II

COSMIC RAYS

INTRODUCTION

THE study of the penetrating radiation now known as cosmic rays has for many years excited a great deal of interest among physicists. This interest is at present on the increase, as indicated by the fact that though one hundred and six papers bearing on this subject were written between about 1907 and 1924, in the next eight years no less than three hundred and seven were published. It is not without wonder that some of the results of these works have reached the ear of the layman and that he should begin to be curious as to what all the fuss over cosmic rays is about. I shall attempt in the following lines to cast a little light on this question.

By way of an introductory definition it may be said that the cosmic radiation is a new type of radiation which is arriving at the earth's surface from somewhere outside of its atmosphere. It is present, as far as we know, at all points on the surface of the earth and has the same intensity, or strength, by night as by day.

This radiation is similar in its properties to the well known X-rays and to the radiation from radioactive substances. One important property of these radiations is their ability to ionize materials through which they pass. Ionization means simply the splitting of a part of the atoms or molecules of a substance into positively and negatively charged particles. This ionizing ability is made use of in studying the radiation and is responsible for its discovery. The ionization is detected or measured by instruments identical in principle with the familiar gold-leaf electroscope. A diagram of a modern cosmic-ray electroscope is presented in

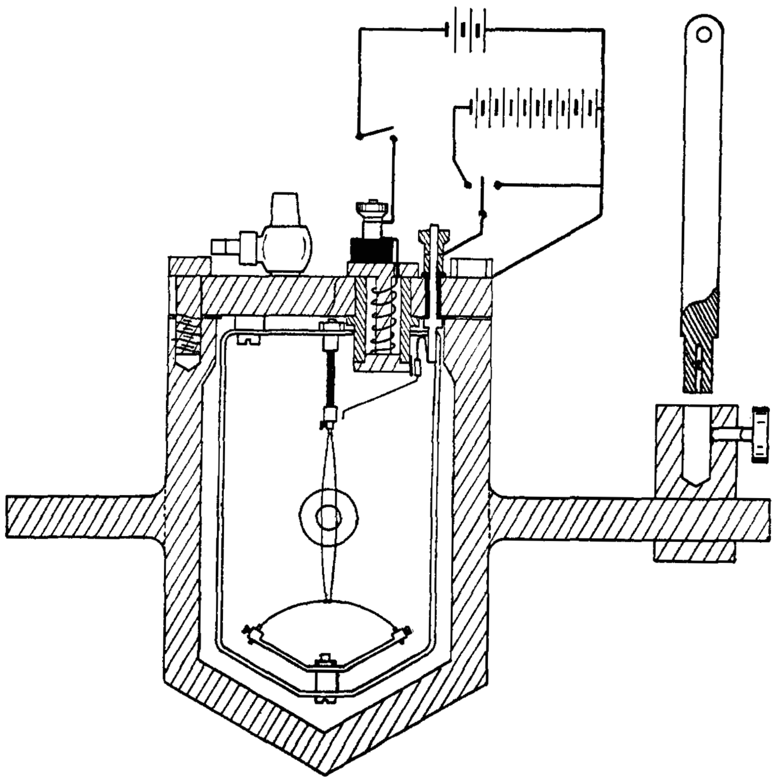

FIGURE 1.

Fig. 1. In this instrument the gold leaves have been replaced by a pair of very fine quartz fibers, coated with platinum to render them conducting. They are attached at their upper ends to an insulating quartz rod, which is in turn supported from the cover of the case. At their lower ends they are attached to a fine insulating quartz bow for

the purpose of maintaining their position in the vertical plane. By means of a movable wire, which can be brought momentarily into contact with the upper ends of the fibers, an electric charge can be placed on them. They will then spread apart under the influence of their mutual electrostatic repulsion, the amount of spreading being a measure of the amount of electricity (quantity of charge) they possess. The fibers are enclosed in an airtight case containing, in this particular instrument, argon gas. Now if an ionizing radiation is falling on the instrument and is generating ions in the gas, the ions of the proper sign will be attracted to the charged fibers and will gradually neutralize their charge. Accordingly, the fibers will be observed gradually to come together, and the rate at which they do so will be a measure of the intensity of the radiation. The motion of the fibers is observed by means of a low-power microscope carrying a measuring scale in its eye piece. It is mounted outside the case, vision into the interior of the instrument being through a small glass window in its side. By means of instruments similar to this the cosmic radiation was discovered and numerous studies have been made of its intensity under various conditions, such as, for example, the way in which the intensity increases with increasing altitude above sea-level.

DISCOVERY AND EARLY EXPERIMENTS

The first step toward the discovery of the cosmic radiation came as early as the year 1900 when Elster and Geitel observed that an electroscope always showed a slow discharge though in the absence of an artificial source of ionizing radiation. It was later shown that this discharge is principally due to the radiation from traces of radioactive materials which are always present in the soil, in building materials, or even in the materials of the electroscope itself. This observation, however, led Gockel in 1910 to take an electroscope up in a balloon for the purpose of making observations on the rate of discharge in what he believed to be a practically radiation-free region. It was known that the radiation from the ground radioactivity should be reduced to a vanishingly small intensity at an altitude of a few thousand feet on account of its absorption by the intervening air. Gockel was surprised to find that the rate of discharge of his electroscope remained roughly constant, where he expected that it would fall to low values, indicating very little radiation. His unexpected result was not at that time believed to indicate more than some hidden source of experimental error. However, the same experiment was repeated by Hess in the next year and constituted the first definite indication of the presence in the atmosphere of this hitherto unsuspected radiation. Hess found that the rate of discharge of his electroscope actually increased considerably as the altitude increased, after going through a minimum value where the radiation from the ground had all been absorbed by the intervening air. This result indicated the presence of radiation coming down from above and being gradually reduced in intensity in the course of its passage through the atmosphere. Numerous experiments of this nature were subsequently performed, all showing the same sort of effect. An example of the curve giving the way the intensity of the radiation increases with increasing altitude is presented in Fig. 2. It will be noted that the rate of discharge of the electroscope (plotted vertically) rises to a value many times higher than that at near sea level as the altitude is increased to about 30,000 feet, and is still increasing rapidly on the upper part of the curve. New experiments, reported last summer, in which an automatic recording electroscope was sent up by a small unmanned balloon showed that the intensity continues to rise up to an altitude of about 100,000 feet. The intensity at this altitude, where practically the entire atmosphere had been left behind, was found to be over one hundred times the intensity at sea-level.

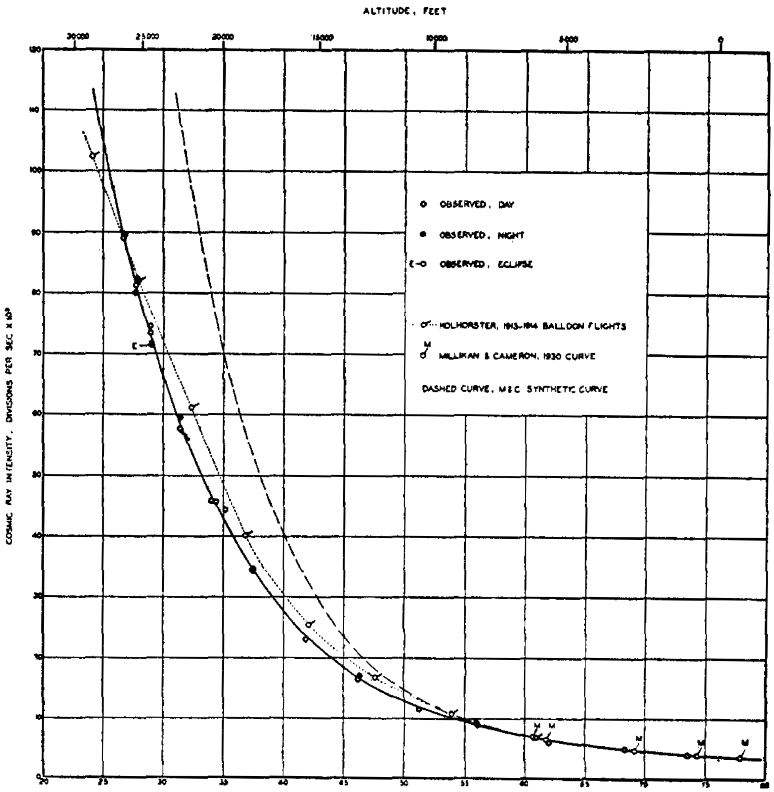

FIGURE 2.

The significance of this result is two-fold. In the first place it seems certain that the radiation is coming down from above. Secondly, from the observed rate of decrease of the intensity it could be concluded that these rays must be enormously more penetrating than any known kinds of ioniz-ing radiations, the most penetrating of which are the gamma-rays from radioactive substances. It is known that the most penetrating, or hardest, gamma-ray would be reduced to about half strength in passing through three hundred feet of air at normal pressure. From inspection of the cosmic-ray curve (Fig. 2) it is seen that it requires a considerably greater amount of air to give the same reduction in intensity, particularly at the lower end of the curve. Accordingly, there is little doubt that one is dealing with a totally different and much more powerful type of radiation than that from any known radioactive substance. From these two observations, namely the increase of intensity with altitude and the great penetrating power, it was only a short step to the conclusion that the radiation must be of extra-terrestrial origin. If it were being produced in the upper atmosphere, then it was necessary either to find there some mechanism by which this powerful radiation is being generated or to assume the presence of some sort of super-radioactive element. Concerning the first possibility, attempts have been made to account for the production of the cosmic rays by invoking the strong electric fields present in thunderstorms. These attempts have met with failure. With regard to the second possible assumption, the presence of new types of radioactive substances giving a more penetrating radiation than those known at the surface of the earth, it seemed extremely unlikely that there could be present in the upper atmosphere elements not also found terrestrially. It is of course definitely known that no natural or artificial substances are sources of radiation with the properties of the cosmic rays. Accordingly, the source of the radiation was placed somewhere outside the earth and its atmosphere. It was placed either in the stars or in the diffuse matter which is observed to fill all space, or at least all the space within reach of the telescopes. The interesting question: the source and the mechanism of production of the radiation, is better deferred until after a discussion of the actual nature of the rays, but it may here be admitted that concerning this question all is mere speculation.

THE NEW EXPERIMENTS

Up to the present point any implication concerning the nature of the cosmic radiation has been avoided, except that it is an ionizing radiation. This was done because there are various possible types of ionizing radiation which the cosmic rays might be, and the attempts to learn just what type they are has been the subject of chief interest in this field during the past few years. There are three principal possible types of radiation: First, there is the so-called gamma-type radiation, where the cosmic rays are assumed to be electro-magnetic waves like gamma-rays, X-rays, ordinary light, etc., but of wave-length shorter than the shortest previously known, namely, gamma-rays. They are assumed to be of still shorter wave-length because it is known from experiments with gamma-rays and X-rays that the penetrating power of this type of radiation becomes greater the smaller the wave-length. The second possibility is that the radiation is composed of rapidly moving electrons. In this case it would be similar to the beta-rays from radioactive substances, but the cosmic-ray electrons would have to be endowed with enormously higher energy than that of the beta-rays to give the observed penetrating power. Finally, it might be supposed that the radiation consisted of some other kind of high-speed particle such as hydrogen or helium nuclei or perhaps even heavier particles.

For many years, in fact until 1928, the cosmic rays were believed to belong to the first type, to be similar to gamma-rays. It was natural to do so, because in the case of the radioactive rays the gamma-rays are much more penetrating than the beta-rays, so that it was thought that the cosmic rays must be a sort of super-gamma-ray. In 1928, however, an experiment was performed by Bothe and Kolhoerster which indicated them to be composed of high-speed particles rather than the previously assumed type. Bothe and Kolhoerster's experiment involved a totally different method from that of the earlier work employing electroscopes. They used a then new device, the Geiger-Müller tube-counter, for detecting and studying the radiation.

To understand this experiment we must consider the process by which radiation such as X-rays, γ-rays or other γ-type radiation is absorbed. In the region of short wavelength the principal manner by which the radiation is weakened, or absorbed, is by a process known as the Compton effect. This effect can be pictured very simply as a collision between a corpuscle of the radiation, a photon, with an electron in the absorbing material. In such a collision momentum and energy are conserved in the same way as in a collision between two perfect billiard balls. In these collisions the photon rebounds from the electron, and in doing so loses more or less of its energy (depending on how nearly head-on the collision), thus causing the absorption of the energy in the photon beam. But what is more important for the present argument is that a portion of the energy of the photon goes into the recoiling electron. This energy gives the electron a certain velocity, and if the collision is favorable and the energy of the photon is high, the recoil electron acquires considerable velocity. Now, on account of the famous $h\nu$ relation that the energy of the photon is proportional to its frequency it is easily computed that photons of the penetrating power of the cosmic rays should be producing very high speed electrons as they pass through absorbing matter. A high speed electron such as a beta-particle from a radioactive substance is capable of penetrating through a certain amount of material. It continually loses speed as it goes until its velocity is finally reduced to zero. In a particular substance, air for instance, the distance it can penetrate depends simply on its initial velocity. It is easily computed that recoil electrons from a photon of the energy of cosmic rays can penetrate considerably more material than β-particles from radioactive sources. It may be calculated that on the average a cosmic recoil electron can pass through six inches of water before it is completely stopped, while the fastest radioactive β-particles are known to be able to penetrate only about half an inch.

Bothe and Kolhoerster devised a method for detecting the presence of these particles in the earth's atmosphere, by the use of the Geiger counter, a relatively simple device which registers high speed electrons. It consists of a tube along the axis of which is stretched a fine wire, the whole being enclosed in an airtight container filled with gas at a pressure of about a tenth of an atmosphere. A source of potential of between one and two thousand volts is connected to the cylinder. The wire is earthed through a high resistance.

If a few ions are formed in the space between the cylinder and the wire, they will acquire considerable velocity under the influence of the relatively strong electric field of this region. Under suitable conditions, which must be satisfied for proper operation, these ions will form new ions when they collide with the molecules of the gas. The new ions thus formed will in turn produce further ions, so that a cumulative process is set up by which an enormous multiplication of ionization results. The entire process takes place in a few hundred thousandths of a second, and is also quickly brought to a stop, probably by formation of a surface charge on the cylinder. Thus a momentary pulse of current is produced whenever a few ions are generated in the interior of the counter, this pulse can be amplified by ordinary vacuum tube amplifiers to sufficient amplitude to be registered on a film, or work some sort of counting device. Hence, if a counter is set up, every time an electron either passes through it or is set off by a γ-ray inside it, it gives a discharge. Now for studying cosmic electrons a single counter is not very satisfactory because it is not possible to distinguish between cosmic electrons and those set off by γ-rays from the surroundings or by radioactive impurities inside the counter. To avoid this difficulty, Bothe and Kolhoerster devised what is known as the coincidence method. They argued, if we put two counters near each other, then if an electron passes through the two we should find impulses occurring simultaneously in the pair. If, further, we put enough absorbing material between them so that no radioactive particles can pass through, we shall be recording only cosmic electrons. Of course a few of the coincidences will occur just by chance, but this fraction is readily found by a separate experiment and allowed for. They set up two counters and found the coincidences. The next thing they were interested in was to find the penetrating power of the electrons, to see if it was in agreement with the value calculated from the frequency of the cosmic rays and the laws of the Compton process. Contrary to expectations, they found that the penetrating power of the electrons was the same as that of the cosmic rays themselves. They expected to find that the electrons would be completely prevented from passing by a screen of six inches of water, or an equivalent amount of other materials. For example, if lead were used, since its density is about eleven times that of water, a screen of this material of one-half inch thickness should suffice. Actually they found that the maximum amount of material which they could put between these counters, about one and one-half inches of gold, whose density is of course even greater than that of lead, only stopped about twenty-five per cent of the electrons. Now from the measurements with the electroscopes it was known that this amount of absorbing material would reduce the cosmic rays themselves by about the same fraction. This result appeared to mean that the electrons were the cosmic rays themselves, and that the ionization found in the electroscope was due to them. Of course these high speed electrons as they go through matter are known to produce ionization, so that the ionization in the electroscopes could as well be explained by them as by photons. Thus according to Bothe and Kolhoerster the cosmic rays were not like γ-rays, but simply a shower of high speed electrons. This meant that the electrons observed at sea-level have to penetrate the entire atmosphere. Now the amount of energy which they need to be able to do this can readily be computed and comes out the enormous value of a billion electron-volts, that is, the energy which the electron acquires when it falls through a potential difference of a billion volts. This is a stupendously great energy, as one is able to realize when one remembers that it is five hundred times the voltage which it has thus far been possible to produce in the laboratory.

Bothe and Kolhoerster's experiment, though it indicated the cosmic rays to be principally high speed electrons, or more exactly, high energy charged particles, since their result would have been obtained as well by protons or heavier particles, was not considered to be conclusive evidence to this effect. A great deal of work has been done since then in attempts definitely to settle this question. What seems to be a conclusive result was announced only a few months ago.

This is the work of one of our leading American physicists, Arthur Compton. The basic idea underlying his work is that if the cosmic rays are charged particles, then their motion, as they proceed toward the earth, should be influenced by the earth's magnetic field. It is well known that moving charged particles are deviated by a magnetic field, while photons remain totally unaffected. Now the earth's magnetic field differs in strength and direction at different points of the earth's surface, being stronger and pointing more downward near the magnetic poles and becoming weaker and more horizontal near the magnetic equator. This change in direction and magnitude of the field might be expected to affect the number of particles which could reach a given locality, because some might be deviated away. The problem was worked out by Lemaître and Vallarta, with the result that if the energy of the particles is not extremely high, then in regions near the magnetic equator (which is near the geographical equator), a portion of the particles is prevented from reaching the surface of the earth. Accordingly one would expect to find that the intensity of the cosmic rays would be less in these regions, since the intensity of the radiation, as measured with an electroscope, must evidently be proportional to the number of ionizing particles which strike it in unit time. Professor Compton and a large group of co-workers have during the past year made a world-wide survey of the cosmic-ray intensity with refinement of technique and thoroughness not previously approached. They found an unmistakable decrease in the cosmic-ray intensity as they approached the magnetic equator, whether in the Eastern or the Western hemisphere. This result showed without much probability of error that the major part at least of the cosmic rays consists of charged particles, and it may be said that this is now the generally accepted view.

The nature of these charged particles is still an open question. Experiments for the purpose of finding an answer are now in progress at several laboratories in this country. Likewise is the question of where the particles originate and how they attain their enormous energies. The older theories of the origin of the rays must of course be discarded since they assumed a gamma-type radiation. The principal suggestion which has been made recently is one due to Lemaître. His theory is bound up with the problem of stellar evolution, so that it would take us too far afield to give anything but the merest outline of his theory. He first points out that there are difficulties with believing that cosmic rays are now being generated in the stars. For one thing, the sun, a typical star, it has been repeatedly shown, is not even a feeble source of the radiation. In addition the stars have atmospheres which would effectively prevent the radiation from escaping from the interior. Furthermore, there are now reasons for believing that the stars were formed by a relatively rapid process of evolution in the remote past (the so-called "fireworks" theory of stellar evolution), rather than by a slow process continuing up to the present day. As Lemaître puts it, "The last two thousand million years are slow evolution: they are the ashes and smoke of bright but very rapid fireworks." For these reasons he believes that the cosmic rays were generated during the original "fireworks" by the disintegration of super-radioactive elements which have long since all disintegrated away. These rays have been wandering around our closed universe ever since, and a small portion of them is still reaching the earth.

There are also a number of other interesting questions which require investigation. For example, we know as yet very little about the exact manner in which the radiation is absorbed. It seems probable that the future investigations in this field will lead not only to a complete understanding of the cosmic rays themselves but will also indirectly yield much new knowledge of atomic physics, particularly of the structure and properties of the nucleus.

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