III

THE RIDDLE OF COSMIC RAYS

"UNIQUE in modern physics for the minuteness of the phenomena, the delicacy of the observations, the adventurous excursions of the observers, the subtlety of the analysis, and the grandeur of the inferences," thus K. K. Darrow describes the study of cosmic rays. It is a subject which offers unaccustomed difficulties in public presentation. The first question that is usually asked is, "What are cosmic rays?" To this we must answer, "We do not know." The next question is, "Where do they come from?" Again the answer is, "We do not know." Their existence is however shown by their effects, and their properties lead us to suspect that they may be bringing us messages of unusual interest.

The presence of cosmic rays is recognized through the electrical conductivity that they impart to air and other gases. This is a property shared in common with X-rays, and the alpha, beta, and gamma rays of radium. That the air is conducting has been recognized ever since the time of Coulomb, a century and a half ago. This he proved by the fact that an electroscope slowly loses its charge even though no current passes through the insulation that supports the gold leaves. Electroscopes precisely similar in principle to that of Coulomb, though of course with various refinements, still form one of the chief means of studying the electrical conductivity of the air.

After the discovery of X-rays and radioactivity, it was supposed that this conductivity of the air was due to rays from radioactive matter distributed in the ground and the atmosphere. Rutherford and Cooke at McGill and McClennan at Toronto tested this hypothesis by surrounding their electroscopes with lead shields. They found as they had anticipated that these shields diminished the conductivity of the air in the electroscopes, due to the absorption of the gamma rays from external radioactive materials. However, after several centimeters of lead had been placed around an electroscope, additional lead produced but little effect. The remaining conductivity was accordingly ascribed to radioactive impurities in the walls of the electroscope itself. Thus it was supposed that the air's conductivity was completely explained.

If this interpretation was the correct one, an electroscope carried above the surface of the earth should register lower conductivity than at the surface. For the radioactive materials which make it conducting are either in the earth itself or in the atmosphere. The rays from radioactive materials in the earth should be absorbed by the lower layers of air and be weaker when they reach an elevated electroscope. Moreover the only radioactive substances in the atmosphere are gases of very high molecular weight, and these should be relatively more abundant at low altitudes than at higher levels. A series of experiments was accordingly carried out to see how the conductivity of the air in an electroscope would vary as it was carried above the ground.

In the first of these experiments the electroscope was carried from the bottom to the top of the Eiffel Tower. It was found, indeed, that its rate of discharge was slower at the higher levels; but the difference was considerably less than had been expected. This unlooked for result stimulated Gockel, Hess, and Kohlhörster to carry on a series of balloon measurements to study the variation of these rays at greater altitudes. It was found that instead of a continuous decrease in intensity, at about a thousand meters above the earth the conductivity of the air reached a minimum, and began to rise at higher altitudes. At 5350 meters Hess found the conductivity several times that at the earth's surface. At 9300 meters (almost six miles) Kohlhörster reports it "many times" as great. Last year's balloon flight by that intrepid Belgian physicist, Piccard, showed that at 16,000 meters, or ten miles, the conductivity of the air increases to a hundred times its value at the earth's surface. Obviously such effects cannot be due either to radioactivity of the earth itself or to a dense radioactive gas in the earth's atmosphere.

In order to account for this rapid increase in conductivity with altitude, Hess suggested in 1912 that it was probably due to highly penetrating radiation entering the earth from outside its atmosphere. Finding no appreciable variation in its intensity at different times of day, he believed that this radiation was probably coming from some remote portion of the cosmos.

One of the most convincing experiments in showing that the conductivity observed in the air is due in large measure to rays from above was performed a few years ago by Millikan and Cameron. They carried an electroscope to a high mountain lake, and observed the conductivity of its air when submerged at various depths below the surface of the water. At the lower depths the conductivity decreased due to the absorption of the ionizing rays by the water. Then they carried the instrument to a lake at a lower altitude, and repeated the experiment. When the electroscope was lowered to a depth in the upper lake such that the total pressure of the atmosphere and the water was the same as in the lower lake, the conductivity in the two locations was found to be the same. That is, as they went down the mountain, the conductivity of the air in the electroscope decreased just as it should if the rays producing the conductivity were being absorbed by the layer of atmosphere through which they were passing. This indicated that the conductivity was due to rays coming from some point higher than the higher lake.

Though Hess's experiments would seem to have been enough, it was these experiments perhaps more than any others which convinced physicists of the real existence of a radiation of a highly penetrating kind coming from high altitudes. American newspapers began to speak of them as the "Millikan rays," not knowing that for more than a decade the same rays had been spoken of in Europe as the "Hess rays." Millikan himself seems first to have been convinced of their reality by these experiments, and gave to them their most commonly used name of *Cosmic Rays.*

NATURE OF THE COSMIC RAYS

We have remarked that the conductivity that cosmic rays give to air is a property shared in common with X-rays and the rays from radioactive substances. Of the latter rays, the alpha rays may be completely absorbed by a piece of paper, and the beta rays will penetrate only a few millimeters of solid matter. The gamma rays, however, can be easily detected through a brick wall. It is thus natural to associate the cosmic rays with the gamma rays from radium. Like them they produce ions in gases, thus making the gases conducting, and like them they are very penetrating. In fact the cosmic rays will penetrate from five to a hundred times as much matter as will the most penetrating form of gamma rays. A closer inspection shows that this similarity to gamma rays holds also for other characteristics. For both types of rays the ionization produced in gases is the same function of the pressure and temperature, and depends in the same way upon the material of the walls. Neither kind of ray is noticeably affected by a magnetic field, though the beta rays and the alpha rays from radium are so affected. Since gamma rays are known to consist of photons, i.e., uncharged particles of the same kind as light, associated with electromagnetic waves, the hypothesis usually made is that cosmic rays are likewise photons.

Whatever the nature of the original cosmic rays, we have direct evidence that the ionization which they produce in air is due to ionizing particles, which appear very much like high speed electrons. This is perhaps best shown by experiments with counting tubes. A counting tube is a device which responds with a sudden rush of electricity every time an ion or a group of ions is produced within it. These counting tubes serve as sensitive means for detecting the presence of cosmic rays. Two or three such tubes are used at a time, the tubes being connected to a single amplifier in such a manner that if an impulse occurs in only one tube nothing happens, but if impulses occur in all of them simultaneously a record is automatically made of the event. The cause of such a coincidence is that an ionizing particle shoots at high speed through all the tubes. If two tubes are placed side by side, comparatively few such "coincidences" occur. If however one is placed over the other, the coincidences are much more frequent. This indicates that the ionizing particles are moving in a vertical direction. Dr. Mott-Smith and Mr. Locher at the Rice Institute have confirmed this conclusion by placing a pair of these counting tubes over a cloud expansion chamber of the type described in the first lecture of this series for making visible the paths of atoms and electrons. They found that when such a vertical coincidence is observed, a vertical track appears at the same time in the expansion chamber.

That these coincidences and vertical tracks are due to the cosmic rays is shown by the manner in which they are absorbed. A block of lead placed beneath the counters has no effect on the coincidences, whereas if the block is placed above, it reduces the number of coincidences in about the same ratio that the same thickness of lead surrounding an electroscope reduces the conductivity due to cosmic rays. We thus conclude that the ions produced by cosmic rays result from the passage of high speed ionizing particles.

Photons do not, to the best of our knowledge, produce ions in this manner. Being electrically neutral, they traverse large thicknesses of matter without losing any of their energy; but when at last they do strike something, they give up a large part or all of the energy they possess. In doing so they give rise to the photoelectrons and recoil electrons described in the second lecture of this series. These electrons in turn ionize the air as they pass through it, until all their energy is spent. The observation that cosmic ray ionization is due to ionizing particles does not thus exclude the view that the original cosmic rays were photons. For though photons would not themselves produce the effects we observe, they would give rise to recoil electrons which might in turn produce the coincidences and the trails in the expansion chamber.

At this point, however, we must describe a beautiful experiment of Bothe and Kohlhörster which has been supposed to rule out the possibility that cosmic rays are photons. They placed two counting tubes, such as we have described, one above the other, and placed a heavy absorbing block of gold *between* the tubes. They found that the coincidences were reduced in practically the same ratio as the cosmic ray ionization due to the same thickness of gold. If the cosmic rays were photons, these coincidences must have been due to passage of the recoil electrons through both chambers. With the gold in between, these electrons should however have been almost all absorbed before they reached the second chamber. For experiments with gamma rays show that the recoil electrons which they produce are much more absorbable than the original gamma rays. The experiment showed that the particles which give rise to the coincidences are absorbed at about the same rate as the cosmic rays themselves. Thus they inferred that the particles must be the cosmic rays.

Though in the case of radium the gamma ray or photon is much more penetrating (about a hundred times) than the recoil electron or beta ray which it ejects from matter, the theories of the absorption of these rays indicate that for photons of sufficiently high energy the penetrating power of the recoil electron should approach close to that of the parent photon. It would not in fact require a great change in our theories to make the two practically the same for the very high energies that the cosmic rays particles are known to have. For this reason the experiment of Bothe and Kohlhörster can hardly be considered a crucial one.

Moreover there are serious difficulties involved in interpreting the ionizing particles which give rise to the coincidences as the original cosmic rays which enter the earth's atmosphere from outside. The tracks which appear in Mott-Smith's and Locher's photographs are like those that would be produced by an electrically charged electron or proton moving with a speed nearly equal to that of light. Electrically neutral particles such as photons or neutrons should not show any trail at all. If the particles are charged, they should be deflected by a magnetic field. Though attempts to deflect these particles by means of powerful electromagnets have been made in vain by Mott-Smith and by Rossi, Curtis has reported a slight effect, and reports from Millikan's laboratory say that they have succeeded in deviating these particles with powerful magnets. Thus it would seem that the ionizing particles are indeed electrically charged, but are moving with very high energy.

If, however, the original cosmic rays are electrically charged, they should be deflected by the earth's magnetic field as they approach the earth. Because of the large size of the earth, the motion of the electron is affected while it is yet a great way off. In fact it has been shown by Epstein that unless the electron has greater energy than that acquired by a fall through ten billion volts it could only strike the earth near the north or south magnetic poles. Various experimenters have tried to find variations in the cosmic ray intensity at different magnetic latitudes on the surface of the earth. Though there is some variation between the results of different investigators, there is certainly no considerable dependence of cosmic ray intensity on latitude. This can only be reconciled with the view that the cosmic rays consist of electrons if we suppose that the energy of these electrons is very great indeed, or that they come not from remote distances, but from the earth's upper atmosphere. In fact the energy required to bring these electrons from interstellar space undeviated by the earth's magnetic field is so great that there is no known source from which it could be derived.

Thus difficulties confront us whether we suppose that the cosmic rays are electrified particles or neutral particles. It is to be hoped that some of the experiments now under way will enable us to choose between the two alternatives.

In the meantime we can say with definiteness that whether photon, electron, or some other kind of particle, the energy associated with each cosmic ray is very much greater than that associated with any of the other rays with which we are familiar. This great energy makes us feel that the solution of the question of their origin and nature is of fundamental importance.

SOURCE OF THE COSMIC RAYS

In searching for a possible origin of the cosmic rays, we note that the fact that the rays are of almost equal intensity day and night, and at different geographic latitudes, means that the origin must be approximately equally distributed in all directions. The earth's atmosphere satisfies this condition. Though the mountain and balloon observations indicate that the source of the rays must be higher than ten miles, there are many interesting atmospheric phenomena which occur at still higher altitudes. There is for example the earth's aurora, which is for the most part more than 100 miles high, and the Kennelly-Heaviside layer of conducting air, so important in radio transmission, which is about 50 miles high. We are at a loss however to suggest any way in which radiations with the characteristics of cosmic rays could be produced in the upper atmosphere. C. T. R. Wilson's suggestion that they might be associated with the electrical discharges occurring in thunderstorms seems to be ruled out by the fact that no significant variation in the intensity of the cosmic rays is found to occur during a storm. We accordingly look farther, keeping in mind however that we have not shown that the atmosphere may not be the origin of these mysterious rays.

It is clear that neither the sun itself, nor any other single heavenly body can be the source of the cosmic rays, for if it were, we should have a large diurnal variation which is in fact not found. Kohlhörster at one time reported a considerable maximum of intensity when the Milky Way is overhead, and thought this meant that the rays are coming from the stars. But later experiments failed to confirm his experimental results, so that this possibility seems to be ruled out. Millikan has suggested that the rays are produced in the cold regions of interstellar space, which would agree well with their uniform intensity at different times of day.

Within the last year, however, Hess and Lindholm and the writer, all working independently, have found a small but apparently definite maximum in the cosmic ray intensity at noon, and a corresponding minimum at midnight. If this is real, it means that the sun has something to do with the cosmic radiation. Thus, for example, if the cosmic rays originate in the portion of space within an effective radius equal approximately to the radius of the solar system, a slight variation of this kind could be explained.

If the cosmic rays come from interstellar space as Millikan has assumed, they would seem to be of very considerable significance in cosmic evolution. For Millikan has pointed out that the energy in the cosmic rays is comparable with that of starlight. Thus if we receive a fair sample of the rays in interstellar space, the cosmic ray energy in the world must be of the same order of magnitude as the heat and light energy radiated by the stars. MacMillan has indeed suggested that this cosmic ray energy forms ultimately the source from which the stars draw their energy during at least a part of their life cycle. It would thus appear that our understanding of the development of the universe is far from complete unless we include the cosmic rays along with the heat energy.

If, on the other hand, the cosmic rays are a local disturbance started in our own atmosphere, we should thus be attaching to them far too great a world significance. Several experiments are now under way with the objective of learning whether such a local explanation is possible.

HOW ARE THE COSMIC RAYS PRODUCED?

From whatever place the cosmic rays come, the process which produces them must be very energetic. If the rays are photons, in order to account for their penetrating power it would seem that each ray must have from thirty million to a billion electron volts of energy (an electron volt is the energy acquired by an electron in falling through a potential difference of one volt). Such energies may be accounted for as due to either the formation of heavier elements out of hydrogen, or to the annihilation of hydrogen atoms themselves. If on the other hand the rays are electrons or protons, the observed penetrations would seem to imply energies as great as several billion electron volts.

It is possible to calculate the energy involved in an atomic change by use of Einstein's equation relating energy and mass. According to this relation, the energy associated with a mass m is mc^2, where m the mass is expressed in grams, c is the velocity of light expressed in centimeters per second, and the energy is in ergs. Using this relation we find that when the mass of a particle changes by as much as the mass of a hydrogen atom, the energy released is almost exactly a billion electron volts.

Millikan has pointed out that if the cosmic rays are photons, the penetrating power of the softest known component of the rays corresponds to about thirty million electron volts, which is just what should be released if four hydrogen atoms of atomic weight 1.008 suddenly coalesce to form a helium atom of weight 4.00. Likewise he ascribes some of the intermediate components to the formation of oxygen, silicon, iron, etc. Thus he pictures the cosmic rays as coming from interstellar space, where heavy atoms are being built from lighter components.

Jeans, on the other hand, also using the photon hypothesis, notes that the most penetrating cosmic rays must have an energy approximately equal to that released when a proton or a hydrogen atom is annihilated. This is a process which he has favored to account for the energy of the stars. The softer components he interprets as secondary rays resulting from these more penetrating primary rays. Jeans thus sees in the cosmic rays a stage of the gradual dissipation of the initial energy of the universe.

If we take the alternative view that the cosmic rays are electrons, or some other form of electrified particle, we are at a loss to know how to account for the immense amount of energy (speaking on an atomic scale) that each ray must possess. We might suppose that some heavy atomic nucleus suddenly disintegrates, and spends all of its energy in ejecting one high energy particle. But such a heavy nucleus we believe to be made of many protons and electrons, and it would be surprising if all of these particles should agree upon a suicide pact and annihilate themselves in one act. No other process has however as yet suggested itself whereby such high speed electrified particles might be produced.

We are thus unable to offer a satisfactory account of the origin of the cosmic rays. It seems likely, however, that they result from some change occurring in an atomic nucleus, for this is our only known source of energy which can come in sufficiently large units. Thus we hope that their further study may enable us to gain new information regarding the structure of that nucleus. In any case, we have here evidence of some kind of process which is liberating immense amounts of energy. We cannot rest until we know where that energy comes from, and find out if possible whether it can be made available to man.

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