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SOME COSMICAL ASPECTS OF RADIOACTIVITY.

BY E. RUTHERFORD.

THE subject of my address this evening quite naturally divides itself into two parts, one dealing with the properties of the radioactive bodies themselves and the other with the distribution of radioactive matter throughout the surface of the earth, and throughout the volume of our atmosphere.

It is the latter division of the subject that I wish more particularly to discuss this evening, but before doing so, it may be advisable to mention briefly some of the more important properties of the radioactive bodies themselves, so that we may be able to judge of the methods employed to detect and measure the minute quantities of radioactive matter scattered throughout the earth and atmosphere.

I shall not speak here of the early history of Radioactivity, which is no doubt well known to most of my audience. As a result of a large amount of detailed investigation, a considerable number of distinct radioactive substances have been isolated. Among the best known of these are uranium, thorium, actinium, radium and polonium, and the numerous substances which arise from their transformation.

Of all the substances separated from uranium or thorium minerals, radium has occupied the most important position. This is partly due to the comparative ease with which it can be chemically isolated and purified, but mainly to its great activity or radiating power, which is about two million times as intense as that of uranium.

The distinguishing feature of radioactive bodies in general, is their power of spontaneously and continuously emitting special types of radiation, of giving out heat, and also in some cases of giving out light. These properties in the case of radioactive substances like uranium and thorium, continue, if not indefinitely, at any rate for periods of time measured by millions of years. In the case of radium, the duration of the activity is shorter, but is still measured by thousands of years. This emission of radiations is spontaneous and is completely independent of control, whether by physical or chemical agencies.

I shall take radium as an example of a typical radioelement, but it must be borne in mind that most of the other active substances possess similar radioactive properties. Radium emits three types of rays, called the α, β and γ rays. The α rays are distinguished by their slight power of penetration of matter. A thin sheet of notepaper suffices to cut off the α radiation completely. These rays have been shown to consist of heavy atoms of matter carrying a positive charge of electricity, expelled from the active substances at a speed of about 20,000 miles per second. It seems probable that the α particle consists either of a charged hydrogen or helium atom, and most probably the latter.

The β rays are more penetrating than the α rays and carry a negative charge of electricity and are projected from the active substance at a speed much greater than that of the α particle. Some of the β particles from radium escape with a speed nearly equal to that of light, or 186,000 miles per second. Their apparent mass is only about one thousandth of that of the α particle, and in fact they are identical with the electrons produced in the cathode ray discharge of a vacuum tube.

The γ rays possess extraordinary penetrating power, passing readily through several inches of iron. It is now fairly certain that the γ rays are ethereal waves similar in character to the well known Röntgen rays, only of a more penetrating kind.

All of these types of radiation possess in common the properties of acting on a photographic plate and of producing phosphorescence in a certain class of substances, but from the point of view of measurement, their most important property is their power of causing the discharge of electricity from electrified bodies. This property is by far the most delicate test of radioactive matter and we shall consequently consider it in some detail. If we take an ordinary well-insulated gold-leaf electroscope and charge it so that the gold leaves diverge widely, it is well known that under ordinary conditions with good insulation, the leaves collapse extremely slowly, and over a few minutes' interval the leaves will appear to be almost stationary. Now bring some radioactive matter near the exposed plate of the electroscope. The leaves at once commence to collapse rapidly. This is due to the loss of charge from the electrified system, and takes place with equal rapidity whether the charge is positive or negative. The mechanism by which this discharge is produced has been most carefully studied, and it is known that the effect is due to the property possessed by these radiations of making the volume of the air surrounding the electroscope, a partial conductor of electricity. The radiations in passing through a gas produce a number of positively and negatively charged carriers or "ions." These ions move in an electric field. If, for example, the electroscope is charged positively, the negative ions are drawn towards the charged system. The discharging effect is thus due to the drawing in of a great number of negatively charged ions to the positively charged conductor or vice versa. The moment the radioactive substance is removed, the rapid movement of the leaves at once ceases.

This property of the radiations of ionizing the air or other gas is an extraordinarily delicate test of the presence of radioactive matter. I bring up near the electroscope a watch glass on which has been evaporated a solution, containing only one millionth of a gram of radium bromide. The leaves collapse in a few seconds. If I place the watch glass on the plate attached to the electroscope, a charge given to the electroscope is almost instantly dissipated. The discharging effect in this case is due mostly to the α rays. This can be shown by placing a sheet of ordinary paper, which absorbs the α rays, over the watch glass —the rate of collapse of the leaves becomes now much slower. The residual discharging effect is then due to the β and γ rays from the small quantity of radium.

From the point of view of measurement, a millionth of a gram of radium produces far too large an effect. In practice, it is found that a quantity of radium measured by one thousand millionth (10^{-9}) of a gram produces an effect of magnitude suitable for accurate measurement. With care, in a suitably designed electroscope, it is possible to measure the presence of one hundredth of this latter amount and in some cases of one thousandth. The electroscope is thus capable of detecting by its increased rate of discharge a quantity of radium measuring 10^{-12} of a gram. As an agent for detecting minutest quantities of radioactive matter, the electroscope is far more sensitive than the spectroscope.

Such measurements do not of themselves throw any light upon the type of radioactive matter which produces the discharge. It would be difficult, for example, to be sure whether the radioactive matter present was radium, actinium or thorium. But there is another property of these substances which allows us to distinguish readily between them. Each of the substances, radium, thorium and actinium gives off steadily a radioactive " emanation " or gas which has very intense radioactive properties. If a current of air, for example, is passed over a thorium or actinium compound and then carried into an electroscope,. a rapid collapse of the leaves is observed. This is due to the radiation from the emanation, which produces a large number of ions in the air with which it is mixed. In the case of radium, the emanation does not escape from a solid compound but is readily released by heat or by solution. I have here a solution of radium in a closed bottle. The emanation has collected in the air space above the solution, and on passing a slow stream of air through the solution into the electroscope, some of this emanation is carried with it, and as you see, causes an extremely rapid discharge of the electroscope. If the emanation were left in the electroscope, it would preserve its discharging power for several weeks. The discharging effect would not be constant but would decrease to half value in four days, to one quarter value in eight days, and so on : and would still be appreciable after a month's interval. In fact, the radium emanation is an unstable substance which breaks up with the emission of α particles. On an average, half of it breaks up in four days. The emanations of thorium and actinium are chemically quite distinct from that of radium and can be at once distinguished from it by the rapid rate at which their activity dies away with time. The emanation of thorium falls to half value in 54 seconds and that of actinium in 3·9 seconds.

The production of the radioactive emanation by radium offers an extremely simple and reliable method of determining not only whether radium is present, but also of measuring accurately the quantity present. Suppose, for example, that we wish to determine the amount of radium present in a given specimen of rock. This is dissolved and placed in an air-tight vessel and left for about one month. During this time the emanation collects in the solution and the air space above it, and reaches a steady equilibrium value where the rate of production of new emanation compensates for the disappearance of emanation due to its further transformation. The solution is then boiled, and the air mixed with emanation is passed into a suitable electroscope and the rate of movement of the gold leaves noted.

If the rate of discharge decreases to half its initial value after about four days, it is certain evidence that the radium emanation is present in the electroscope. The amount of radium in the rock is determined by treating in a similar manner a solution containing a *known* quantity of radium and observing the rate of discharge of the electroscope, produced by the emanation from it. By this method, we are not only able to detect the presence of radium in a substance, but also to determine the amount present with considerable accuracy. In this way, a quantity of radium in a solution of only 10^{-11} gram can be readily measured.

The emanation from radium is an unstable substance and breaks up into another substance which behaves as a solid and has quite distinct radioactive properties. The inside surface of a vessel containing the radium emanation becomes coated with an invisible deposit of radioactive matter. If the emanation is rapidly blown out by a current of air, this "active deposit," as it is called, remains behind. The activity of this deposit is not permanent but decays rapidly with the time. After several hours, the activity decreases in a geometrical progression falling to half value in about 28 minutes. For thorium, the active deposit loses half of its activity in 11 hours, for actinium in 34 minutes. The production of this characteristic active deposit from each emanation offers another very useful method of distinguishing whether thorium, radium or actinium is present.

An interesting property of the active deposit, which we shall see has played a notable part in the analysis of the radioactive state of the atmosphere, is its concentration on a negatively charged conductor in an electric field. The carriers of the active deposit become in some way positively charged and are drawn in to the negative electrode and adhere to it.

RADIOACTIVE STATE OF THE ATMOSPHERE.

I have now passed rapidly over some of the more important properties of radioactive bodies, which have proved of great utility in the attack on the question of the distribution of radioactive matter in the earth and atmosphere. The pioneers in this work were Professors Elster and Geitel, teachers in the Gymnasium of Wolfen-büttel, Germany, and to these investigators we owe a large amount of the information now collected in this important and rapidly growing branch of radioactivity.

Geitel had observed in 1900 that the open air possessed the property of causing a slow discharge of an electroscope, and showed that this effect was due to the production of positive and negative ions in the air. In seeking for a possible cause of this effect, it occurred to Elster and Geitel that it might be due to the presence of some radioactive matter in the atmosphere. They then tried an extremely bold experiment. I have shown you that the emanations from the radioactive bodies produce an active deposit, which can be concentrated on a negatively charged wire. If any radioactive emanation were present in the

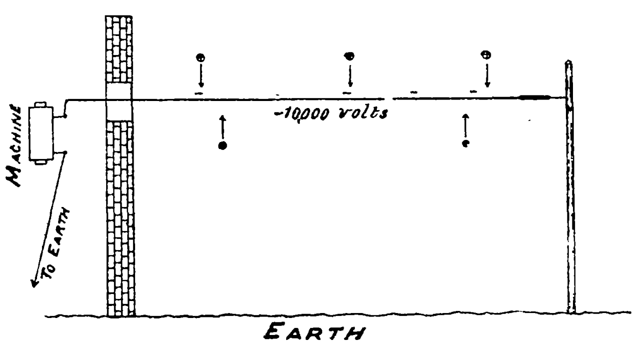

Fig. 1.

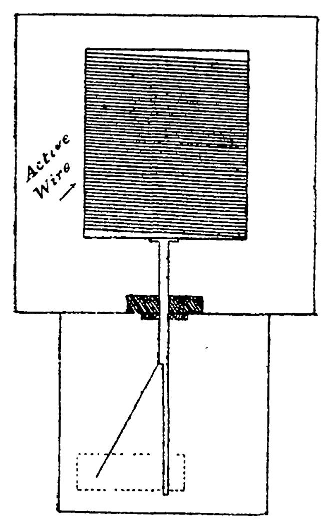

Fig. 2.

atmosphere, the active deposit should collect on a negatively charged wire exposed in it. An insulated wire 20 or 30 metres long (Fig. 1) was strung outside a laboratory window and kept charged negatively to a potential of several thousand volts by means of a battery or electrical machine. After several hours, the wire was rapidly removed, coiled round a frame attached to the electroscope, similar to that shown in Fig. 2, and the rate of discharge of the electroscope observed. The gold leaf was found to collapse rapidly, indicating that some radioactive matter was present upon the wire. The magnitude of this effect was independent of the material of the wire and was conclusively shown to be due entirely to the presence of radioactive matter on its surface.

We must next consider how to determine the *kind* of radioactive matter concentrated upon the wire. In the first place, it is improbable that particles of the solid radioactive bodies like radium, uranium or thorium should be present in the atmosphere. But the emanations from radium, thorium and actinium are gaseous, and if the earth contains these substances, we might reasonably expect that some of the emanation released from them might escape into the atmosphere. We have at once a means of definitely settling this question. If the radium emanation alone is present in the atmosphere, the active deposit collected on the wire should decay at the rate characteristic of radium, *i.e.*, after some hours, the activity should decay exponentially decreasing to half value every 28 minutes. The rate of decay of the active deposit from the air has been shown to be very similar to this, so we conclude that the radium emanation is present in the atmosphere.

The experiment of Elster and Geitel in Germany was repeated by Rutherford and Allan in Montreal and by Professor McLennan in Toronto and the results showed that the air of Canada is as radioactive as that of Germany. Falling rain, or snow is also radioactive, and its activity decays at the characteristic rate to be expected if the falling rain or snow collects upon it the active deposit of radium distributed throughout the atmosphere.

Preliminary experiments showed that most of the radioactive effect of the atmosphere was due to the presence of the radium emanation. Bumstead, in New Haven, and Blanc, in Italy, have however clearly shown that in these localities some thorium emanation is also present. This can be tested in a very simple way. A wire is made active by exposure as negative electrode to the open air for several days. On removal, part of the activity due to the active deposit of radium decays rapidly. After 5 or 6 hours, an activity still remains which decays much more slowly, decreasing to half of its value every 11 hours. This is the rate of decay characteristic of the active deposit of thorium and shows that the thorium emanation must also be present in the atmosphere. In some parts of Italy, Blanc has recently shown that fully 70 per cent. of the activity on the wire must be ascribed to thorium, but apparently the effect due to radium predominates in most other localities.

We may consequently conclude that the atmosphere over the surface of the earth contains everywhere small quantities of the radium and thorium emanation and also the active substances arising from their transformations *in situ* in the atmosphere. The amount of ionization thus produced is small, but can be accurately measured by apparatus specially designed by Ebert for the purpose. By means of a fan driven by a spring motor, a steady current of air is drawn between two concentric cylinders. The inner insulated cylinder is charged and connected with an electroscope. As the ionized air passes between the cylinders, the ions are removed by the strong electric field between them. The rate of discharge of the electroscope serves as a measure of the number of ions per cubic centimetre of the volume of outside air. In the open air, there are usually about 1,500 ions per c.c. of the air; the number is not constant but fluctuates considerably. This number of ions present in the atmosphere is extraordinarily small compared with the number of un-ionized molecules. Each cubic centimetre of air contains about 4×10^{19} molecules, so that on an average only an infinitesimal proportion of the molecules are ionized at one time. While this ionization appears very insignificant, needing a delicate electroscope to detect and measure it, yet it has a very important bearing on the electrical state of the atmosphere.

We must bear in mind that all of us are continuously inhaling the radium and thorium emanations and their products, and ionized air. In addition we are continuously undergoing a type of mild X-ray treatment, for the β and rays from the earth and atmosphere continuously pass into and through our bodies. We are in fact, subjected to a continuous bombardment by the radiations from active matter and are fortunately quite unaware of it. Some have considered that possibly the presence of radioactive matter and ionized air in the atmosphere may play some part in physiological processes, but this is a question quite outside the scope of my address.

An examination of the electrical state of the atmosphere shows that the upper atmosphere is nearly always positively charged, so that the earth must be negatively electrified. There is consequently an electric field normal to the earth which causes a steady movement of the positive ions in the air towards the earth and a corresponding movement of negative ions upwards. The latter must tend to dissipate rapidly the positive electricity in the upper atmosphere.

There are many theories as to the origin and maintenance of the positive charge in the upper atmosphere. One very plausible hypothesis, supposes that the electrical state of the atmosphere largely results from the radioactive matter distributed throughout it. The appearance of positive electricity in the upper atmosphere is in this view due to the effect of falling rain carrying the negative charge to earth ; for it is found that rain is always negatively electrified. The presence of an ionized layer of gas between the upper atmosphere and the earth tends continually to dissipate the positive charge left behind, and this ordinarily prevents the increase of positive electricity to the danger limit, when lightning discharges would pass to the earth. It thus appears probable that the insignificant amount of radioactive matter in the atmosphere plays an important rôle in causing and controlling the electrical state of the atmosphere.

AMOUNT OF RADIUM EMANATION IN THE ATMOSPHERE.

The amount of radium emanation in the air per cubic centimetre of its volume is extremely small but can be measured by several methods. This problem has been attacked by A. S. Eve of Montreal, who found that a cubic kilometre of the atmosphere contains an amount of emanation equivalent to that liberated from about half a gram of radium bromide in radioactive equilibrium. Assuming that the amount of emanation in the air over the land surface of the globe is about the same as in the neighbourhood of Montreal, and that on an average, this distribution is uniform over a height of ten kilometres of the atmosphere, he concluded that the total amount of radium emanation in the atmosphere was equal to that liberated from about 200 tons of radium bromide in equilibrium. It is probable that the amount of radium emanation over the sea is less than that over the land, and is mainly conveyed there by winds from the land, but there is still some uncertainty on that important question.

As I mentioned before, it is extremely improbable that much solid radium in the form of fine particles exists in the air, so that for the supply of emanation to the atmosphere we must look to some external source. We shall now discuss the evidence which leads us to believe that the supply of emanation to the atmosphere is kept up by its steady escape from the surface crust of the earth.

DISTRIBUTION OF RADIOACTIVE MATTER IN THE EARTH'S CRUST.

Elster and Geitel early observed that many caves and cellars, in which the air had been confined for long intervals of time, was unusually rich in the radium emanation. This was shown by the strong activity observed on negatively charged wires exposed in these confined places. Such a result is to be expected if the radium emanation continuously escapes from the soil, for the amount of it present must increase in such confined spaces. This led them to make an examination of the activity of soils. All were found to be active and many gave off the radium emanation. This effect was especially marked in clayey soils. J. J. Thomson and others showed that the water in many deep wells and springs was impregnated with the radium emanation. The presence of the radium emanation is especially marked in many of the hot springs distributed throughout Europe. Elster and Geitel observed that the sediment from certain hot springs in Italy was unusually rich in radium. Blanc showed that the sediment from certain hot springs gave off freely the thorium emanation. A very great deal of work has been done along these lines in the last few years, and radioactive matter has been found to be very widely distributed, in small quantity, over the earth's crust. The continent of North America has not been so systematically examined as Europe, but Boltwood has shown that a large amount of radium emanation is present in the waters from many deep-seated springs in various localities in the United States. McLennan and Burton have shown that the petroleum from the oil wells in Ontario contains a considerable quantity of radium emanation and also a trace of radium.

There appears to be no reasonable doubt that the earth is the source of the emanation in the atmosphere. This emanation escapes from the soil by the process of diffusion, or is borne to the surface in spring water and is then distributed by the winds. On account of the rapidity of the transformation of the emanations of thorium and actinium compared with that of radium, it is to be expected that the radium emanation will predominate in the atmosphere, and it is a matter of some surprise that the thorium emanation is present in such a large amount as is observed in some localities. The emanation of radium must diffuse slowly through the earth, disappearing with time, and it is to be expected, that, apart from deep-seated springs, most of the emanation observed in the air must be derived from a thin skin of the earth's surface not more than a few feet deep.

INTERNAL HEAT OF THE EARTH.

It is thus natural to suppose that there is a very large quantity of radium and other radioactive matter distributed over the surface of the earth. This radioactive matter must be continuously supplying heat to the earth, and it is of great interest to examine the magnitude of this heating effect and its probable bearing on the question of the origin and duration of the earth's internal heat.

In addition to the various properties I have enumerated, radium also gives out heat continuously and uniformly at a rapid rate. A quantity of radium supplies enough heat to melt more than its weight of ice per hour. A pound of radium in the course of a year will emit as much heat as that resulting from the combustion of 100 pounds of good coal. This heat emission of radium and of all the radioactive bodies is in reality a secondary property, for it is a consequence of the bombardment of the active matter by the α particles expelled from its own mass. The β and γ rays produce only a small percentage of the total heating effect. This heating effect of radium must always be proportional to the quantity of radium present and must persist, however sparse may be the distribution of radium throughout the earth's crust. Consequently, there must be a continuous supply of heat to the earth due to the radium and other radioactive matter distributed throughout it. But the heating effect due to a given quantity of radium does not last indefinitely. The radium breaks up into other forms and after 20,000 years only a small fraction of the radium would remain. This difficulty, however, is not serious, for it is now definitely settled that radium is produced from uranium and it is found that in old minerals the amount of radium is always proportional to the amount of uranium.

Now uranium is transformed extremely slowly in comparison with radium, and probably a period of at least one thousand million years would be required before the uranium was half transformed. Consequently, the supply of radium from the breaking up of uranium will keep up the amount of radium in the earth to a nearly constant value for periods measured by hundreds of millions of years.

We shall now consider briefly the ordinarily accepted theory of the origin of the earth's internal heat and of the age of the earth. It is known that the temperature of the earth steadily rises as we proceed from the surface inwards, and on an average rises 1° Fahr. for every fifty feet of descent. From the evidence of volcanic action, it is concluded that the interior of the earth is at a high temperature.

Lord Kelvin attacked this question of the age of the earth by supposing that the earth was originally at a temperature of molten rock and has since that time gradually been cooling by the radiation of heat through the surface into space. According to this theory, the temperature gradient near the surface of the earth has been gradually decreasing. Knowing the temperature gradient to-day, and the average conductivity and specific heat of the materials of the earth, it is possible by the aid of Fourier's celebrated analysis to deduce the interval that has elapsed since the earth was a molten mass. Some of the values of the quantities necessary in the calculation are uncertain within limits, but Lord Kelvin concluded that certainly not more than 100 million years can have elapsed since the surface of the earth was at a temperature capable of supporting animal and vegetable life. In later papers this estimate has been still further reduced, and the age of the earth is put as low as forty million years. I cannot here enter into the intermittent controversy that has raged for nearly half a century between Lord Kelvin on the one hand and the geologists and biologists on the other. The latter initially required a much longer period for the progress of geologic and biologic evolution than that allowed by Kelvin, but there appears to be a general consensus of opinion among geologists and biologists to-day, that a period of 100 million years allows sufficient time for the processes of evolution.

On the assumptions made by Lord Kelvin, there is no doubt of the general accuracy of the deductions. Let us however examine these fundamental premises. The earth is assumed to be a cooling body isolated in space, and it is assumed that there has been no supply of heat to the earth since the cooling began ; for Kelvin has conclusively shown that the heat supplied from ordinary chemical processes, that may be supposed to occur in the earth, is not sufficient to influence materially the conclusion as to the age of the earth's heat. But the discovery of the presence in the earth of active matter like radium which emits heat at a rapid rate, at once suggests the possibility that the earth is not a simple cooling body, but one in which heat is being steadily generated. In 1902, I made some calculations to determine how much radium (or other radioactive matter expressed in terms of radium) would be required to be uniformly distributed throughout the earth in order to maintain the present observed temperature gradient. In such a case, the heat supplied by the radium must exactly compensate for that lost from the earth by conduction to its surface and radiation into space. The calculations are simple, and show that a uniform distribution of radium amounting to only $1{\cdot}7 \times 10^{-13}$ gram of radium per cubic centimetre would suffice. From the data then available, I calculated that the amount of radium present in the earth was probably of the right order of magnitude to produce such a result.

Recently, the Hon. R. J. Strutt has made a number of systematic observations to determine the distribution of radium in the typical rocks of the earth's crust, and has obtained results of remarkable interest. Strutt collected a number of typical rocks, both igneous and sedimentary, obtained from widely different localities, and determined the amount of radium contained in them. The rocks were first of all obtained in solution and placed aside in closed vessels. After a definite time the emanation, generated by the radium contained in them, was boiled out, and passed into a suitable electroscope. The amount of radium in the solution was then determined by comparison with the effect in the electroscope due to the emanation from a standard solution containing a known quantity of radium bromide.

The following table shows the observed amount of radium in grams per cubic centimetre of rock for samples of igneous rocks.

No.	Name of rock	Locality	Density	Radium per gram in grams	Radium per c.c., in grams
1	Granite	Rhodesia	2·63	$9·56 \times 10^{-12}$	$25·2 \times 10^{-12}$
2	"	Lamorna Quarry, Cornwall	2·62	9·35 "	24·5 "
3	Zircon syenite	Brevig, Norway	2·74	9·30 "	25·5 "
4	Granite	Rosemorran, Cornwall (?)	2·62	8·43 "	22·1 "
5	"	Cape of Good Hope	2·67	7·15 "	19·1 "
6	"	Knill's Monument, near Carbis Bay, St. Ives, Cornwall	2·61	6·90 "	18·0 "
7	"	Shap Fell, Westmoreland	2·65	6·63 "	7·6 "
8	Elæolite syenite	Laurdal, Norway	2·70	4·88 "	3·2 "
9	Granite	Haytor, Devonshire ?	2·61	3·69 "	9·64 "
10	Blue ground	Kimberley	3·06	3·37 "	0·3 "
11	Leucite basanite	Mt. Somma, Vesuvius	2·72	3·33 "	9·07 "
12	Hornblende granite	Assouan, Egypt	2·64	2·45 "	6·47 "
13	Pitchstone	Isle of Eigg	2·41	2·06 "	4·97 "
14	Hornblende diorite	Schriesheim, near Heidelberg	2·89	1·98 "	5·73 "
15	Augite syenite	Laurvig, Norway	2·73	1·86 "	5·07 "
16	Peridotite	Isle of Rum	3·15	1·37 "	4·32 "
17	Olivine basalt	Talisker Bay, Skye	2·89	1·32 "	3·82 "
18	Olivine euchrite	Isle of Rum	2·97	1·28 "	3·80 "
19	Basalt	Victoria Falls	2·75	1·26 "	3·46 "
20	Hornblende granite	Mt. Sorrel, Leicestershire	2·71	1·25 "	3·38 "
21	Dolerite	Isle of Canna	2·95	1·24 "	3·65 "
22	Greenstone	Carrick Dû, St Ives	2·99	1·14 "	3·41 "
23	Basalt	Giants' Causeway, Antrim	2·80	1·03 "	2·89 "
24	Serpentine	Cadgwith, Lizard	2·60	1·00 "	2·60 "
25	Granite	Isle of Rum	2·61	0·723 "	1·89 "
26	Olivine rock	Isle of Rum	3·22	0·676 "	2·18 "
27	Dunite	L. Scaivig	3·34	0·664 "	2·22 "
28	Basalt	Ovifak, Disco Island, Greenland	3·01	0·613 "	1·84 "

I mentioned before that about $1·7 \times 10^{-13}$ gram of radium per c.c. distributed uniformly throughout the volume of the earth, would keep up the earth's internal heat. An examination of the above table, however, shows that the surface rocks contain far more radium than this. As we should expect, the radium content varies considerably, but the poorest rock of all, Greenland basalt, contains more than ten times this estimate, while the average rock contains fifty or sixty times as much. An examination of the sedimentary rocks shows an average amount of radium somewhat smaller than that of the igneous rocks, but still of the same order of magnitude. Strutt considers that 5×10^{-12} gram of radium per c.c. is a fair average for the surface rocks of the earth—a quantity thirty times greater than that required to maintain the present temperature gradient. This is a surprising result, for although of necessity only a small number of rocks have been examined, yet we must consider that the results obtained by Strutt probably give the right order of magnitude for the distribution of radium in the earth's crust. It will be observed that very few rocks from the American continent figure on the above list. This omission will no doubt be soon rectified by other observers. It is of interest to note that Eve and MacIntosh of McGill University have recently examined the amount of radium in the typical rocks in the neighbourhood of Montreal, and have obtained an average value in substantial agreement with Strutt. By calculations based on the intensity of the penetrating or γ radiation at the earth's surface, Eve has deduced a value of the amount of radioactive matter in the earth's crust even greater than the average value found by Strutt. Not only therefore is the apparent amount of radium in the earth's crust sufficient to account for the maintenance of the earth's internal heat, but if uniformly distributed throughout its mass, there is far more than is required. The latter assumption would lead to the conclusion that the earth is growing hotter instead of colder—an explanation not likely to be regarded with favour. In order to get round this difficulty, Strutt suggests that the distribution of radioactive matter is not uniform throughout the earth, but is confined to a thin surface shell of the earth. Assuming the distribution of radium found by experiment to be uniform throughout this shell, it can readily be shown that its thickness is about 45 miles. In support of this explanation he cites the results of Milne, the seismologist, who concludes from an examination of the velocity of propagation of earth tremors through the earth, that there is a fairly abrupt transition of the material of the earth's crust at a depth of 30 miles. Below this depth, the material appears to be uniform, and transmits earth tremors at quite a different rate from the surface rocks.

On the assumption that radium is confined to a shell 45 miles deep, it is easy to calculate the temperature of the earth as we proceed downwards. The results are shown in Fig. 3.

The temperature should rise to about 1,500° C. at a depth of 45 miles. The temperature of the interior mass of the earth below this depth must be uniform and equal to 1,500° C.

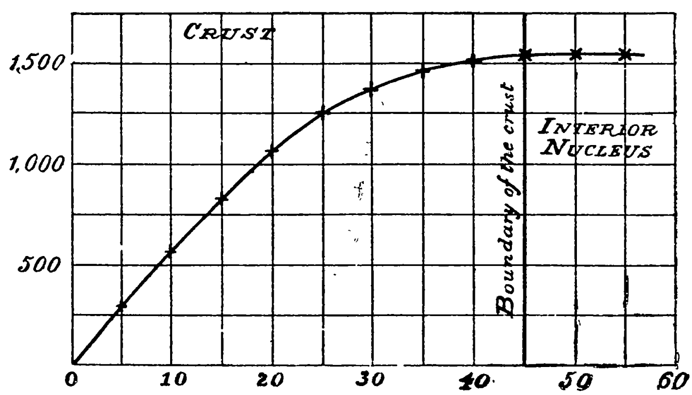

FIG. 3.

It is difficult at present to advance satisfactory reasons why this superficial distribution of radium should occur. Temperature can have little if any effect, for Bronson has conclusively shown that the radiating power of radium is not altered by exposure to a temperature of 1,600° C.

There is another interesting point raised by Strutt in regard to the internal temperature of the moon. The latter is supposed to have been initially separated from the earth's surface, and should thus contain the same average amount of radium as that found in the earth's crust. If this be the case, it can readily be deduced that the temperature gradient in the moon should be about eight times greater than in our earth. Taking into consideration that the force of gravity is small at the moon's surface, the conditions would appear to be very favourable for volcanic action in the moon. This is contrary to the general opinion that the lunar craters are extinct, but as Strutt points out, this view rests chiefly on an *a priori* conviction that the moon has no internal heat. Professor W. H. Pickering has pointed out that close students of the moon believe that changes are still occurring there.

I hope that I have made clear to you how the study of radioactivity has profoundly altered our views of the earth's internal heat. The conclusions advanced are by no means completely proved, but sufficient has been done to cast grave doubt on the validity of the older theories of the origin and variation of the earth's internal heat.

AGE OF RADIOACTIVE MINERALS.

This new point of view of regarding the supply of the earth's heat does not throw any definite light on the problem of the age of the earth. This want, however, is supplied by taking into account still another very remarkable property of radium. In addition to its property of radiating and of emitting an emanation, radium also steadily produces from itself another stable element, helium. This property of radium was first shown by Ramsay and Soddy, and has been amply confirmed by other investigators. The weight of evidence at the present time points to the conclusion that the α particle, expelled from radium and its products, is in reality a helium atom, which at the moment of its expulsion carries a positive charge of electricity. Whatever may be the position of helium in the general scheme of radioactive transformations, there is no doubt that radium produces helium at a slow but constant rate. The rate of production of helium has not yet been measured with accuracy, but it is probable that one gram of radium will produce per year about one tenth of a cubic centimetre of helium at standard pressure and temperature.

This rare gas helium, which next to hydrogen, has the lightest atom known to chemists, has had an unusually dramatic history. It was first discovered in the sun by means of the spectroscope by Lockyer in 1868, and hence its name. It was not found in the earth until 1895, when Ramsay showed that the gases liberated from the mineral cleveite, showed the spectrum previously attributed to helium in the sun. Now it is a very interesting fact that helium is only found in quantity in the radioactive minerals. The presence of helium in these minerals was at first considered very remarkable, but is at once explained if the helium is produced in the mineral by the radium or other radioactive matter contained in it. Consider, for example, a very dense radioactive mineral from which the helium continuously generated by the radium cannot escape. The amount of helium in the mineral will steadily increase with time, and the total amount present should be proportional to the age of the mineral and the amount of radium contained in it. I have here some crystals of a new mineral, thorianite, found a few years ago in Ceylon, which contains about 12 per cent of uranium and about 70 per cent. of thorium. This mineral on heating evolves a remarkably large quantity of helium—more than 10 c.c. per gram of the mineral. Now it is almost certain that the helium stored up in this mineral has been produced by the breaking up of the radium, contained in it since the formation of the mineral. Assuming the rate of production of helium by radium already mentioned, it can be calculated with some confidence that the mineral thorianite is at least 500 million years old, *i.e.*, this interval of time must have elapsed since the formation of the mineral in the earth's crust. This is a minimum estimate, for probably some of the helium has in the course of ages escaped from the mineral. A similar result is obtained from consideration of other primary radioactive minerals. Most of them are apparently about 500 to 1,000 million years old.

When the constants involved in these calculations are accurately determined, I feel great confidence that this method will prove of the utmost value in determining with accuracy the age of the radioactive minerals and indirectly of the geologic strata in which they are found.

CONCLUSION.

I have so far confined my attention to the earth and her satellite the moon. Is there any evidence of the presence of radium or other radioactive matter in the sun or in the stars? We may say at once that no definite evidence has yet been observed. From the similarity of the chemical constitution of the sun with our earth, we should expect the sun to contain radioactive matter also. The large amount of helium observed in the sun indirectly supports such a conclusion. Strutt found that stony meteors contained about as much radium as the surface rocks of the earth, indicating that these visitors from other systems also have their share of radium.

There is no obvious reason for supposing that the sun, at any rate during the initial stages of its condensation, contained much more radioactive matter than the earth. According to the condensation hypothesis of Kelvin and Helmholtz, the heat of the sun is derived from the gradual concentration of its material due to gravitation. On this hypothesis, Kelvin considers it improbable that the sun will continue to shine at its present brilliancy for a period more than 12 million years and probably much less. There is one possibility, however, which may greatly extend the estimate of the duration of the sun's heat. At the enormous temperature of the sun, it is possible that ordinary matter may become radioactive, *i.e.*, it may break up into simpler forms, with the evolution of a great quantity of heat. If ordinary matter, in undergoing such change, emitted as much heat as radium in its transformation, this new source of heat would allow the sun to shine for a much longer period than the older theory allows. This is only a speculation, but one that must be taken seriously into consideration in coming to a decision of the probable duration of the sun's heat, and consequently of the time for habitation of our globe.