Further Investigation of the Penetrating Radiation.

Thesis
by
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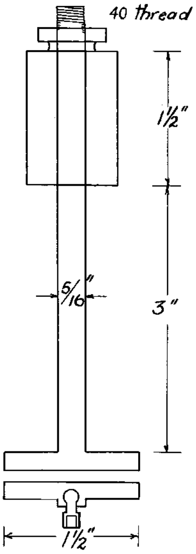
At the time when the experiments to be described were planned, a decided lack of agreement appeared to exist between the results of various observers. All were agreed that the ionization in closed vessels increased with altitude but there was a considerable variation in the rates of increase announced. Furthermore, screening experiments by Kolhorster in Switzerland led him to support more strongly than ever an extremely penetrating radiation of extra-terrestrial origin, while the results obtained by Millikan and Otis were interpreted by them as indicating that all or by far the greater part of the effect was due to radiation of no extraordinary penetration.

The course to be pursued was not hard to see. If doubt were to be cast upon the experiments of Kolhörster it would be on two principal counts in all probabliity. First, the screening experiments in water were made in shallow places at low altitudes where the whole effect is small in comparison with that due to other causes of ionization. Second, in the experiments in the glacier one could not be entirely sure that specious results were not obtained as a result of rocks and waste matter contained in the ice. Hence we planned to go to the highest altitudes available where deep, snow-fed lakes could be found and to use the lake water as screening material.

APPARATUS

In the work to be described three electroscopes of a modified Wulf type were used. Details of the const-



Adjustable Air Condenser.

ruction are given in the following table.

	No.1	No. 2	No.3
Height	22.5 cm.	35.0	29.6
Diameter	11.4	20.0	15.0
Thickness of walls	1.8 mm.	2 mm.	3mm.
Volume effective for ionization	1893 cc.	11326 cc.	3211 cc.
Capacity of fibres	1.41 esu.	1.41	1.10 esu.
Reduction constant	1.45		.665
Sensitivity (approx) volts per scale div.	1.8	2.	1.8

The ionization chamber is of brass in all cases except that the top of No. 1 is cast zinc.

To determine the capacities of the fibre systems the following procedure was adopted. An apparatus was constructed (see fig.) which consisted of a small plane condenser with the upper plate movable. The lower plate fastened directly to the charging rod of the instrument by a ball joint. The upper plate was mounted in a rigidly-held, tight-fitting bearing so that it could be raised or lowered at will. A micrometer screw enabled the distance between the plates to be altered by any given amount. The plates were adjusted accurately parallel to one another by lowering the upper one and pressing them together. The ball joint on the lower then permitted it to rotate until they were completely in contact.

The capacity of this condenser is given by the following formula, where t is the thickness of the plates, r the radius of the plates, and d the distance apart.

$$C = \frac{r^2}{4a} + \frac{r}{4\pi}\log\frac{16\pi r(a+t)}{a^2} + \frac{rt}{4\pi a}\log\frac{(a+t)}{t} + \frac{1}{4\pi}$$

The procedure involved finding first the capacity of the fibres plus the charging rod plus the condenser in the extended position. Call all this C_0. C_0 was charged to a potential V_1 , read on a voltmeter. Then while C_0 was isolated from the source of potential the upper plate was lowered to within a distance d of the lower. Then the fibres came together somewhat and indicated a potential V_2 . Hence if C_c is the capacity of the small condenser when the plates are a distance d apart, we have $(C_0 + C_c) V_2 = C_0 V_1$. and hence C_0 could be determined. In the second part of the problem two distinct methods were used. In the first the fibres alone were charged to a high potential, about 300 volts, by connecting them to the battery through the charging rod and then earthing the rod. This potential was read from the voltmeter. Then the rod was swung back into contact with the fibres and the final potential determined from the position of the fibres. In the other method the fibres and rod were initially uncharged, the rod being just beyond the charging position. Then the rod alone was charged to a given potential read on the voltmeter. Then this charge was spread over the fibres and rod, the final voltage being read from the position of the fibres. Since the combined capacity had been determined in the first part of the determination, the capacity of the fibres alone was readily calculated.

The method of measurement was precisely that used by Otis EXCEPT THAT MUCH LONGER PERIODS OF OBSERVATION WERE GENERALLY USED. At various times the insulation of the fibres was tested by the guard ring method described by Otis and no leak could ever be detected so that in most cases this precaution was abandoned. AS IN OTIS' WORK, A CALIBRATION CURVE WAS DRAWN FOR EACH READING TO AVOID ERRORS DUE TO CHANGING CHARACTERISTICS OF THE INSTRUMENT. That saturation was obtained was best indicated by the fact that for long observations where the potential fell to as low as 50 volts, the ionization was not appreciably less than for an observation under the same circumstances lasting only one-fifth of the time.

COTTONWOOD LAKES TRIP.

In the summer of 1924, the author with the help of Mr. C.H.Prescott Jr., and Mr. Alvin Viney, organized and conducted an expedition to the Cottonwood lakes in the Sierra Nevada mountains. The lake chosen for the work was at an elevation of 11200 feet.

The apparatus used was electroscope No. 2. This instrument consisted of the frame and fibres of No. 1 enclosed ina large brass ionization chamber (volume about 11 litres.) The increased ionization due to the much larger volume was expected to increase the accuracy of the readings especially over short time intervals. In practise, however, the instrument proved undesirable for the following reasons:

1. Temperature changes caused convection currents inside the electroscope which greatly disturbed the measurements. 2. It was difficult to obtain saturation. 3. The electroscope was heavy and bulky. 4. Due to the large ratio of volume to area of walls and other causes

the ionization produced with this instrument per cc. per second was much smaller than with the others used and hence the relative error was large.

On account of these difficulties combined with inclement weather, wholly satisfactory results were not obtained and the experience in organization for high altitude work gained through this trip was, no doubt, the most valuable result of the expedition. Nevertheless the observations showed quite clearly;—
1. A decided increase in ionization with altitude.
2. No variation with time of day. 3. A considerable decrease in ionization when the electroscope was read over the water. 4. AN APPRECIABLE DECREASE IN IONIZATION AT DEPTHS BELOW ONE METRE OF WATER INDICATING THE PRESENCE OF A RADIATION MORE PENETRATING THAN ORDINARY GAMMA RAYS.

A series of 13 one-hour consecutive readings taken with the same instrument on Mt. Wilson(altitude 1760 m.) in the latter part of August 1924, also checked points Nos. 1 and 2 above.

LAKES MUIR AND ARROWHEAD.

In the winter of 1924-25 a new electroscope, No. 3, was constructed, tested and calibrated and in August 1925 a second expedition organized consisting of Dr. Millikan, Dr. Oldenberg, Mr. Prescott, Mr. Glenn Millikan and the author. The work this time was carried on at Muir Lake on Lone Pine Creek near the base of Mt. Whitney at an elevation of 11783 feet. A folding canvas pontoon furnished by the Military

Department of the Institute was used for transportation on the water. For the underwater readings the electroscopes weresuspended from a small raft anchored in about 40 metres of water. Granite cliffs varying in height from five hundred to two thousand feet at a distances up to three-fourths of a mile surrounded the lake on three sides. The lake itself was about one-fourth of a mile in diameter and roughly circular in shape.

On the return from Muir Lake, readings were also taken for a day on a large flat rock in the desert near Lone Pine at an altitude of about 5500 feet.

Finally the Muir Lake observations were repeated at Lake Arrowhead in the San Baernardino mountains at an altitude of 5125 feet. The depth of the lake at the point of observation was about 50 metres.

RESULTS.

The results of the underwater readings are collected in Table 1.

For our purposes it is convenient to regard the atmosphere as the equivalent of 10.33 metres of water and to consider a given locality, such as Muir Lake, in terms of the water equivalent of the air above this point. The pressure due to a layer of air of thickness dH is $dp = -\rho\, dH$ where ρ is the density. But $\rho = k\, p/T$. Then $\frac{dp}{p} = -k \frac{dH}{T}$

T is a function of H but to avoid complication we will assume it to be a constant and substitute a suitable mean value over the region H concerned when we eval-

Table No. 1

Electroscope No. 3

Muir Lake

	surface	.45m	1m	2.8m	3m	5m	10m	15m	20m
	13.3	9.7	7.7	6.0	5.45	4.9	4.0	3.6	3.6
	13.2		7.8	5.8		4.6	4.0		3.7
means	13.25	9.7	7.75	5.9	5.45	4.75	4.0	3.6	3.65

Arrowhead

	surface	.7m	1m	1.1m	3m	5m	15m
	7.0	5.8	5.5	5.15	4.85	4.4	3.7
	7.2				4.9		
	7.5						
	6.9						
	7.2						
means	7.0	5.8	5.5	5.15	4.9	4.4	3.7

Electroscope No. 1

Muir Lake

	surface	.45m	1m	2.8m	3m	10m	20m
	16.5	13.5	11.0	9.0	9.2	7.8	7.2
	15.8						
	15.9						
means	16.1	13.5	11.0	9.0	9.2	7.8	7.2

Arrowhead

	surface	.6m	1m	3m	5m	10m	20m
	10.5	9.35	9.6	8.6	8.3	7.8	7.5
	11.0		9.2	8.45			
means	10.75	9.35	9.4	8.5	8.3	7.8	7.5

uate the integral. Then $\log p = -\frac{kH}{T} + A$

or $p = Ae^{-\frac{kH}{T}}$. Now when $p = 76 \times 13.6$ and $T = 273$

$\rho = .001293$

$\therefore k = \frac{\rho T}{p} = 34.2 \times 10^{-5}.$

Therefore $p = Ae^{-34.2\,H/T}$ if H is measured in km.

But when $H = 0$, $p = 10.33$

Hence $A = 10.33$ and $p = 10.33\,e^{-34.2\,H/T}$.

where T is the mean temperature over the height H.

Now we assume the following temperature distribution.

H (km)	t (C)	T (abs)
0	22	295
1	18	291
2	14	287
3	10	283
4	6	279
5	2	275

This distribution, corrected for the average ground temperature, corresponds closely to that observed experimentally in balloons near Paris, according to the Smithsonian tables.

The curve connecting altitude with depth of water, shows Muir Lake at a depth of 6.75 metres of water below the surface of the air, Lone Pine 8.5 m., Arrowhead 8.6 m., and Pasadena 9.98 m.

Now Muir Lake and Arrowhead differ on this scale by almost exactly 2 metres. Hence whenever we have a reading in Muir Lake two metres below one at Arrowhead we should expect them to agree. Consequently it is very reassuring to find in the four possible instances where this point could be tested, pointed out by arrows in Table 1, the beautiful confirmation shown there.

The results of the water work are also displayed in the two curves. It will be noticed that at both Muir Lake and Arrowhead, readings taken at the surface come above the curves and this is to be expected because the readings at the surface must be partly due to local radiation of ordinary penetration. Below one metre, however, we should have only the ionization contributed by the instrument itself and the penetrating radiation. This is because the radiation which has the penetration of gamma rays is so reduced as to be practically negligible by one metre of water. The extraordinarily good agreement of the results testifies to the correctness of these views as well as to the validity of the readings themselves.

COMPUTATION OF ABSORPTION COEFFICIENT.

In computating the absorption coefficient from the above data, two alternatives present themselves. In the first place, we may assume that the radiation comes into our atmosphere as a beam of parallel rays or on the other hand, we may assume that the rays are incident to the surface of the atmosphere equally in all directions. In the first case we would use the well known law of absorption $I = I_0 e^{-\mu d}$

If the radiation did come into our atmosphere as a parallel beam of rays, however, we should expect well-marked variations with the time of day. For, on account of the earth's rotation on its axis, when the rays are coming in at an angle of θ degrees say, with the vertical, they would have to go through a layer $d/\cos\theta$, where d is the vertical height of the atmosphere at the point in question. Even if the source of the radiation is not a small region of the heavens but a band such as the Milky Way, we should expect easily observable variations in the intensity measured at Muir Lake or Mt. Whitney. Now this point has been repeatedly tested not only in the present experiments but also by Otis on Mt. Whitney and by Otis and Millikan on Pike's Peak, and we have never been able to find any indication of a regular variation. Consequently we appear to be justified in using the second alternative given above.

Consider the radiation coming from above only, and let its intensity at the surface be I_o. Then the part of I_o due to the radiation included in a cone-shaped shell whose angle with the vertical is θ and of anglular thickness $d\theta$ is,

$$\frac{I_o H}{\cos\theta} \; \frac{2\pi H \tan\theta}{H^2/\cos^2\theta}$$

The intensity at the depth H in the absorbing medium due to this part of the radiation is

$$dI = 2\pi I_o \sin\theta \, d\theta \, e^{-\mu H \sec\theta}$$

$$I/I_o = 2\pi \int_0^{\pi/2} \sin\theta \, e^{-\mu H \sec\theta} \, d\theta$$

Now put $\sec\theta = x$

Then $\sec\theta \tan\theta \, d\theta = dx$

$$d\theta = \frac{dx}{x\sqrt{x^2-1}} \qquad \sin\theta = \frac{\sqrt{x^2-1}}{x}$$

$$I/I_o = 2\pi \int_1^\infty \frac{\sqrt{x^2-1}}{x} \, e^{-\mu H x} \, \frac{dx}{x\sqrt{x^2-1}}$$

$$= 2\pi \int_1^\infty \frac{1}{x^2} \, e^{-\mu H x} \, dx.$$

Values of the integral $I/I_o = \int_1^\infty x^{-2} e^{-zx} \, dx$ are given by Gold - Proc. Roy. Soc. A - 82, 62 1909 and these were used in this computation.

The method of determining the absorption coefficient was to select the most reliable observation near the top of each curve and to see what value of μ best represented the other readings when compared with it. A little calculation shows that the radiation becomes more penetrating with depth. In other words, the radiation is not homogeneous but consists of a spectrum of wave lengths. For both instrumentsthe upper portion of the curves gave $\mu =$ 0.30 per metre of water and the lower ends gave $\mu =$ 0.18. Electroscope No. 3 was more sensitive however, and gave somewhat more reliable results throughout as a superficial examination of the data shows. These coefficients, of course, characterize the radiation only throughout the region studied. We might expect still softer components t at higher altitudes.

RESULTS OF LEAD SCREENING

In addition to the under water observations, the same lead screen used by Otis, enabled us to obtain additional information. The lead was used with Electroscope No.1 only and was the equivalent of 55 cm. of water. The results of these experiments are collected in the following table.

Table No. 2

Cosmic Rays inside 4.8 cm. lead.

	Pasadena altitude 305 m.	Lone Pine altitude 1676 m.	Muir Lake altitude 3590 m.	Pike's Peak altitude 4298 m.
Ions per cc. per sec. unshielded	13.0	16.7	20.0	23.7
Shielded with 4.8 cm. lead	9.0	10.1	11.8	12.6
External radiations after screening	1.6	2.7	4.4	5.2
Cosmic Rays after screening (theoretical)	1.3	2.4	4.1	4.9
Cosmic Rays after screening (obs.)	1.32	2.2	4.08	5.0

The first and second lines contain the readings without, and with the lead shield respectively. From the latter values we subtract 7.4 I which we found due to the walls of the electroscope alone, obtaining the values given in the third line. These figures consequently represent the whole effect inside the shield of all external radiations of any kind. Now all the experiments with the lead were made with a view to having the surroundings as nearly the same as possible. In every case the instrument was placed either on granite rocks or on soil which was largely decomposed granite. Consequently we should not expect a large variation in the effect due to the surroundings After consulting as many authorities as possible we took 3 I as a fair mean value and assumed that this amount might be attributed to local causes in all these places. Now the amount of this radiation which will penetrate the shield is just 0.3 I. Hence we subtract 0.3I from the last figures given and obtain the values given in the fourth line which we call the "theoretical" values of the cosmical rays after penetrating the lead.

However we have a possibilityof getting these values in another, quite independent way, and these we call "observed." They are obtained by taking the readings on the curve at each location, subtracting 7.4 I and calculating how much of the resulting radiation would penetrate the lead, using the coefficient

.30 per metre of water and the formula $I = I_0 e^{-\mu d}$ since now the shape of the shield ap proximates to a sphere and most of the radiation goes through very nearly perpendicularly. This calculation gives surprisingly good agreement with the preceding results as the table shows. Our one assumption of a constant value for the local, softer radiation is not a serious one, since it could be altered considerably without affecting the agreement very much.

SOFT RADIATIONS

Millikan and Otis, in commenting on the results of their Pike's Peak work called attention to the large part played by soft radiations in the total effect observed. The following table, No. 3, is designed to exhibit as strikingly as possible the properties of these softer radiations and to suggest how they may be accounted for. Some of the Millikan-Otis results are included in the last column for completeness.

The first line gives the directly observed results in each location. The second series of values is taken from the curve and includes of course in addition to the cosmic rays, the zero value of the electroscope. The difference of the first two series then must give the ionization due to the softer rays. It is difficult to escape the conclusion that we have here a stimulated radiation of some sort. If we make the same assumption which led to the very satisfactory conclusion in the previous section, namely that 3 I are due to local causes, we have a residue in every case which increases markedly with altitude. It is interesting to notice

Table No. 3

Soft Radiations

Electroscope No. 1

	Pasadena	Lone Pine	Muir Lake	Pike's Peak
Direct Observation	13.0	16.7	20.0	23.7
Cosmic Rays (from curve)	8.95	10.0	12.2	13.3
Soft Rays	4.05	6.7	7.8	10.4
Stimulated Soft Rays (assumed)	1.05	3.7	4.8	7.4
Stimulating Cosmic Rays (observed)	1.55	2.6	4.8	5.9

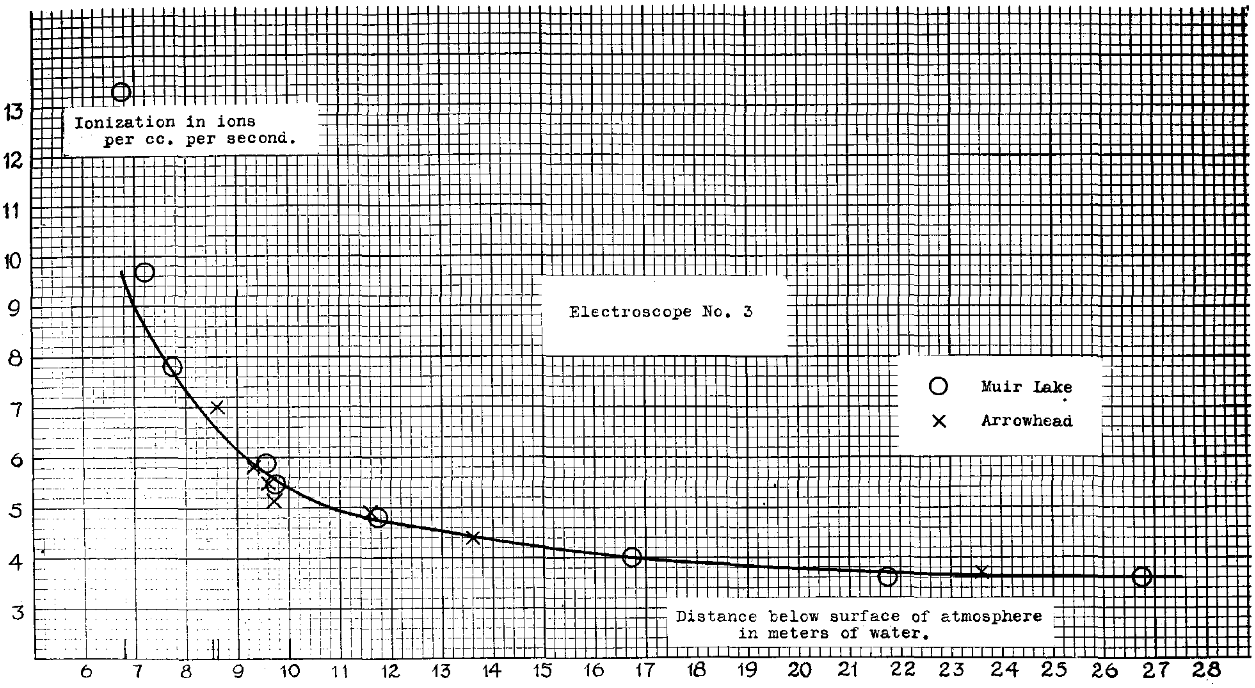
by comparison with the last series of values given, that the increase is roughly proportional to the intensity of the cosmic rays. It would seem probable, therefore, in addition to the radiation with the penetration of gamma rays which we attribute to the radioactivity of the surroundings, THAT THERE IS A CONSIDERABLE QUANTITY OF RADIATION OF ABOUT THE SAME PENETRATION, STIMULATED IN SOME WAY BY THE PRIMARY, MORE PENETRATING RADIATION.

SUMMARY

1. The present work seems to us to furnish conclusive evidence to show that a penetrating radiation does exist which
   a. increases in a perfectly definite way with altitude.
   b. is much more penetrating than any known radiation.

2. Although no very elaborate tests of this point have been made, we have been able to detect no variation of any kind.

3. In addition to the penetrating radiation assumed to be of cosmical origin, there is present in relatively large amounts, softer radiation with about the penetration of ordinary gamma rays. It is suggested that this is in part a secondary radiation stimulated by the primary, and some evidence is presented which seems to confirm this suggestion.


Ionization in ions per cc. per second.
Electroscope No. 3
Muir Lake
Arrowhead
Distance below surface of atmosphere in meters of water.
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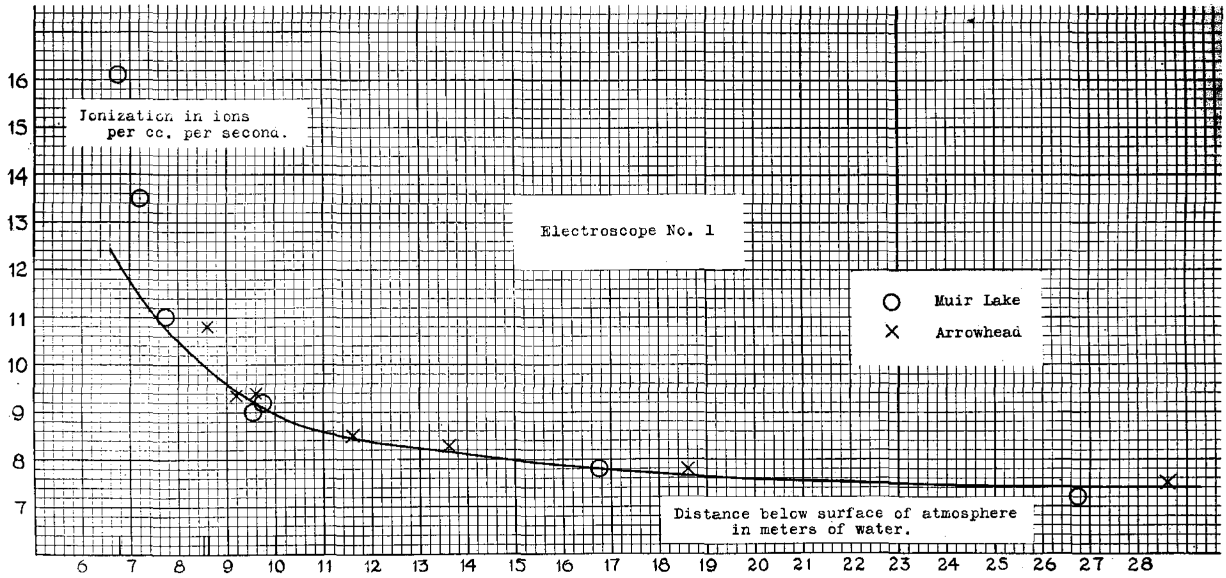
Ionization in ions per cc. per second.
Electroscope No. 1
Muir Lake
Arrowhead
Distance below surface of atmosphere in meters of water.
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