**Physics.** — *The Earthmagnetic effect and the Corpuscular Nature of (Cosmic) Ultra-radiation.* IV. By J. CLAY. (Communicated by Prof. P. ZEEMAN.)

(Communicated at the meeting of December 17, 1932).

§ 1. In our previous communications [1]) II and III the variation of intensity of the ultrarays on the Earth's surface was given. The true value of the effect was yet subject to some doubt, since others did not find a variation in other parts of the Earth. MILLIKAN [2]) found nearly no variation between Pasadena and Churchill. BOTHE and KOLHÖRSTER [3]) only found a doubtful variation between Hamburg and Spitzbergen, CORLIN [4]) has given a discussion on this subject.

The observations to be discussed in the present paper were performed with two instruments constructed by Dr. STEINKE. They were first compared at Amsterdam. Then one of the two was mounted on board the motorship "Christiaan Huygens", where the observations were made by Dr. BERLAGE during the journey from Genoa to Batavia. The instrument consisted of an ionisation chamber of 22 Liters filled with carbon dioxyde under a pressure of 11 atmospheres and surrounded by a shield of 13 cm iron. The wall of the chamber is at a potential of 130 Volt. The needle in the ionisation chamber is connected with an electrometer. The ionisation current, which thus charges up the electrometer, is gradually compensated by a known charge of opposite sign induced on it. The sensitivity of the electrometer was such that, if the charge had not been compensated, the deflection would have been a hundred and eighty scale divisions for one hour. At the end of every hour, the needle is photographed, so that its position may be read from the photograph with an accuracy of one tenth of a division. The measurements at concerning the instrument may be considered accurate to 1 $^0/_{00}$. With this instrument continuous one hour observations were performed, the result of which is given in the graph.

The falling off of intensity confirms our observations of the previous voyages. However the present observations are much more accurate and more detailed. Point *A* is the mean of 100 observations at Amsterdam, *B* the mean of our previous observation at Bandoeng reduced to sea level.

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[1]) Proc. Roy. Acad. of Amsterdam XXXI p. 1091 (1928) XXXIII p. 711 (1930). Die Naturw. **20** p. 687 (1932).

[2]) R. MILLIKAN, Phys. Rev. **36** p. 1596 (1930).

[3]) W. BOTHE and W. KOLHÖRSTER, Berl. Ber. **26** (1930).

[4]) A. CORLIN, Lund. Obs. Circ. **1** p. 3 (1931).

The values are plotted according to magnetic coordinates [1]), and measured from the reduced magnetic North pole (78° N.L. and 69 W.L.). That the minimum of our curve deviates a little from the magnetic equator thus defined may be due to the fact that the dipole in the Earth does not quite coincide with the Earth's centre. In reality the acline is more to the South.

Points from $G$ to $P$ are six hour means, from $P$ to $S$ twelve hour means. In the latter case there were over 200 hour observations, therefore the

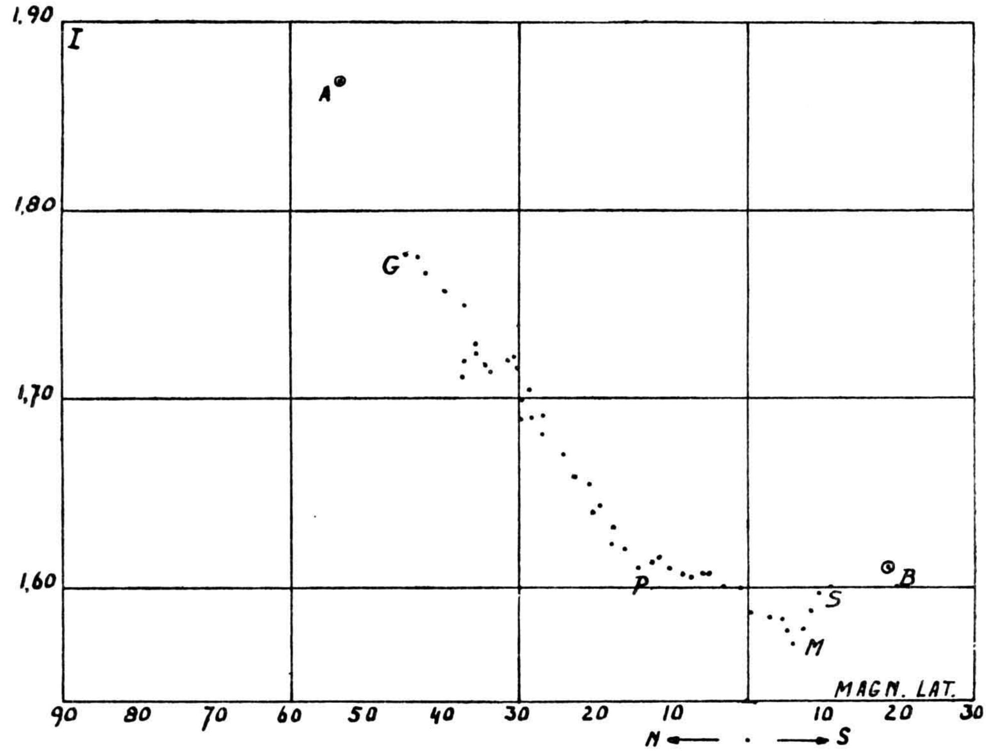


Fig. 1. Variation of the intensity of the Ultra-radiation with the Earth magnetic latitude.

values are very accurate (there is only a barometric influence between Suez and Batavia of 0.2 %).

Combining these results with those of MILLIKAN and of BOTHE and KOLHÖRSTER and with the recent data of BENNETT [2]) and his collaborators — the latter reduced to our initial value — because their shield had a different thickness, we obtain an intensity curve, which runs horizontal from the Pole to $A$, then diminishes towards the magnetic equator by 16 % and after crossing this equator again increases towards the South Pole, according to COMPTON's observations [3]) (Fig. 2).

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[1]) J. BARTELS, Handbuch der Experimental Physik 25[1] p. 586.

[2]) R. D. BENNETT, C. S. Phys. Rev. 42 p. 446 (1932).

[3]) A. H. COMPTON, Phys. Rev. 41 p. 681 (1932).

We may conclude from this that the ultraradiation is a charged corpuscular radiaton as we shall show more in detail in the following.

§ 2. Let us first consider the balance of arguments for and against this conception:

1°. The absorption experiments by BOTHE and KOLHÖRSTER [1]) give arguments in favour of corpuscular rays, but do not exclude the possibility that the rays they have measured would be secondary corpuscular radiation from primary gamma rays. ROSSI's experiments would moreover be against monochromatic gamma radiation [2]).

Of the fact that the absorption coefficient for these counter experiments has the same value as for the primary radiation JOHNSON [3]) has given a beautiful explanation.

2°. REGENER's [4]) absorption measurements in great depths of water suggest gamma radiation because of the character of the intensity decrease, but the possibility of corpuscular radiation is not excluded, since corpuscular rays with a Maxwellian distribution of energy might show a similar decrease of intensity at great depths.

3°. REGENER's [5]) measurements at high altitude, where it is found that at 2.5 cm of mercury the ionisation still increases are against the conception of monochromatic primary gamma radiation producing corpuscular rays of high range, coming from the outside of the atmosphere.

4°. STREET and JOHNSON's [6]) experiments with double and triple coincidences in connection with absorption in lead strongly point to corpuscular rays and are against gamma rays.

5°. The influence of the earthmagnetic field decidedly shows the corpuscular nature of the rays and is against primary gamma radiation, since for a noticeable effect the paths of the corpuscular rays must be so long, that it seems impossible that they have originated from primary gamma rays at such a high altitude above the Earth.

Until recently there was some doubt as to whether the corpuscular rays could have an energy sufficient to pass through the Earth's atmosphere. But the experiments by SKOBELZYN [7]), by MILLIKAN, ANDERSON [8]) and by KUNZE [9]) show that even the secondary rays (e.g. for pairs originating from the wall of the expansion chamber) may have energies of $10^9$ e. Volt.

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[1]) W. BOTHE and W. KOLHÖRSTER, Z. f. Ph. **56** p. 751 (1929).

[2]) ROSSI, Phys. Rev. **36** p. 606 (1930).

[3]) THOMAS H. JOHNSON, Phys. Rev. **41** p. 845 (1932).

[4]) E. REGENER, Die Naturw. **17** p. 183 (1929). Z. f. Phys. **74** p. 433 (1932).

[5]) E. REGENER, Die Naturw. **20** p. 695 (1932).

[6]) J. C. STREET and TH. J. JOHNSON, Phys. Rev. **42** p. 142 (1932).

[7]) SKOBELZYN, Z. f. Phys. **54** p. 686 (1929).

[8]) R. MILLIKAN and C. ANDERSON, Phys. Rev. **39** p. 325 (1932). C. ANDERSON **41** p. **321** (1932)

[9]) PAUL KUNZE, Z. f. Phys. **79** p. 203 (1932).

One may briefly summarise the situation as follows:

| | gamma | corpuscular |
|---|---|---|
| 1⁰. Absorption measurements BOTHE, KOLHÖRSTER, ROSSI | | for |
| 2⁰. Absorption measurements REGENER in water | for | |
| 3⁰. Ionisation curve in upper atmosphere to 28 km. REGENER | against | |
| 4⁰. Measurements by STREET and JOHNSON with double and triple coincidences | against | for |
| 5⁰. Influence of earthmagnetic field on intensity | against | for |

§ 3. Assuming now *a system of corpuscular rays of all energies from zero to infinity to be incident on the Earth*, then there are two limitations for incidence on the Earth's surface at the bottom of the atmosphere: in the first place the limitation imposed by STÖRMER [1]) forbidden spaces, and in the second place the limitation imposed by the thickness of the atmosphere, necessitating for the primary radiation a lower limit corresponding to the loss of energy through the atmosphere. Below this limit no radiation will reach the Earth's surface.

In order to determine, how large the energy of the primary corpuscles must be, if they are to reach the Earth's surface through the atmosphere, we may follow different methods.

1⁰. From JOHNSON's [2]) calculations based on SCHINDLER's [3]) determinations of transition effects follows that in air there are on the average 2.5 secondary corpuscular rays (secondaries) in equilibrium with every primary. The energy of these secondaries is 1.3 times the energy of secondaries in iron. In iron the energy of secondaries is, on the *average*, $2.5 \times 10^8$ e. Volt, according to ANDERSON's photographs, where one has to consider especially the pairs which certainly originate in the iron walls of the chamber. Hence the secondaries in air would have an energy of $3.2 \times 10^8$ e. Volt. If this energy be used for ionisation, this requires 1200 e. Volt per cm.

These rays may therefore pass through $2.6 \times 10^5$ cm of air. For the entire atmosphere of the hight $8.0 \times 10^5$ cm, reduced to 76 cm of mercury, this amounts to $2.5 \times \frac{8.0}{2.6} \times 3.2 \times 10^8 = 2.5 \times 10^9$ e. Volt for the total energy of the secondaries accompanying one primary. To this is to be added the direct ionisation energy of the primary through the atmosphere, which is $1.0 \times 10^9$ e. Volt. The total *minimum* energy lost directly and indirectly by one primary passing through the atmosphere is therefore $3.5 \times 10^9$. In order to account for the fact that primaries are not only

[1]) CARL STÖRMER, Ergebnisse der Kosmischen Physik I p. 1—86 (1932).
W. HEISENBERG, Ann. d. Phys. 5e F. **13** p. 430 (1932).

[2]) TH. H. JOHNSON, Phys. Rev. **41** p. 545 (1932).

[3]) H. SCHINDLER, Z. f. Physik **72** p. 625 (1931).

incident in the vertical, but also in other directions one must take a factor of about 1.6, and thus the necessary energy would be on *the average* $5.6 = 10^9$ e. Volt.

2°. One may also carry out an estimate according to a different method, making use of the impulses of ionisation occurring in ionisation chambers according to observations by STEINKE and SCHINDLER [1]) and by MESSERSCHMIDT [2]). They find that from lead corpuscles are emitted with an energie of $10^9$ e. Volt and perhaps still more. They further state, that after covering up with 10 cm of lead, and additional 10 cm of lead still gives an increase in the number of impulses, hence one may conclude that the range of the corpuscles under consideration is between 10 and 20 cm of lead.

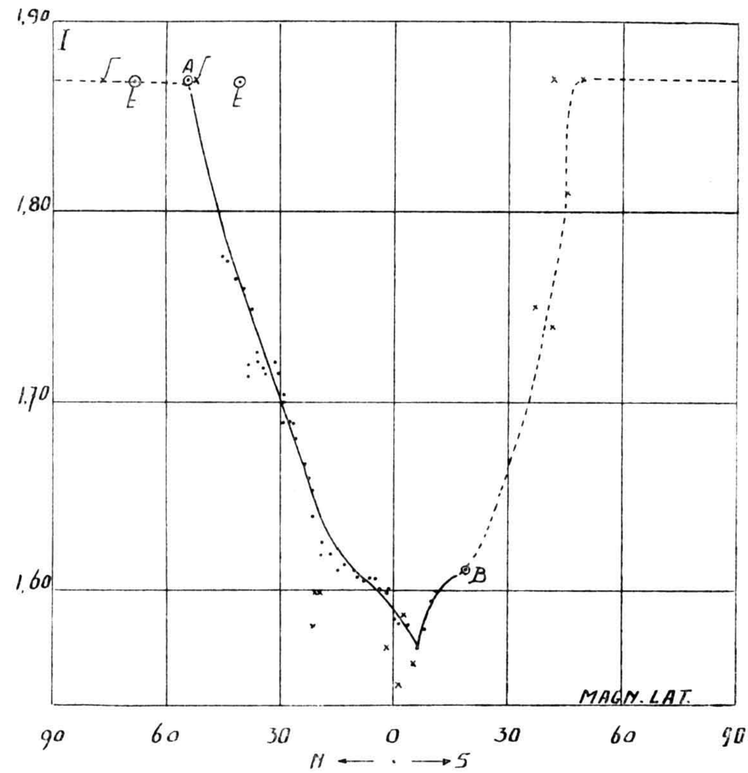


Fig. 2. Comparison with the results of other Observators.

X Observations of A. H. COMPTON

X „ „ W. BOTHE and W. KOLHÖRSTER.

⊙ „ „ R. MILLIKAN and CAMERON.

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1) E. STEINKE and H. SCHINDLER, Z. f. Phys. **75** p. 115 (1932).
2) W. MESSERSCHMIDT, Z. f. Ph. **78** p. 78 (1932).

This estimate is further confirmed by our previous measurements [1]) on absorption in lead, which show that the *local radiation*, which we consider as secondary radiation from the air (because radioactive radiations were cut off by these experiments), is screened off by about 15 cm of lead.

Assuming that the impulses of $10^9$ e. Volt originate in the inner surface layer of the lead, the corresponding sets of corpuscles will have a range of about 20 cm of lead or 232 cm of water, so that 10 meters of water would correspond to $4.2 \times 10^9$ e. Volt. For a corpuscle to penetrate the atmosphere would therefore require a minimum energy of $4.2 \times 10^9$ e. Volt, and, taking different directions, an average energy of $6.7 \times 10^9$ e. Volt.

We know that the most penetrating radiation measured by REGENER [2]) is still present at depths greater than 240 meters of water, so that these rays must have energies of more than $100 \times 10^9$ e. Volt.

The part penetrating the atmosphere, as we saw, must have energies of at least $3.5 \times 10^9$ e. Volt. But according to STÖRMER's theory the forbidden space for rays of this energy intersects the Earth's surface at 46° magnetic latitude. Rays of all directions require, on the average, $6 \times 10^9$ e. Volt, and the STÖRMER forbidden boundary for these rays intersects the Earth's surface at 34° magnetic latitude. This means that from the pole downwards to 46° magnetic latitude, the whole of the spectrum of corpuscular rays from about $4 \times 10^9$ onward to higher energies will penetrate. But from 46° on towards the magnetic equator, the energy spectrum, at its lower end gets more limited, until, at the equator the lower limit is $10 \times 10^9$.

We may further interpret REGENER's hardest component under 80 meters of water by assuming that these rays have an exponential distribution of energy, since, the absorption curve gives a true picture of the spectrum of ranges, hence of the energy spectrum, if energy is assumed to be proportional to range. An exponential absorption then corresponds to an exponential distribution of energy.

Thus an ionisation curve $e^{-\mu x}$, where the absorption coefficient, according to REGENER [3]) has the value $=$ 0.020 per meter of water, leads to an energy distribution $e^{-\frac{\varepsilon}{3 \cdot 10^{10}}}$ as follows from the result just obtained that a range of 10 meters of water corresponds to an energy of $6 \times 10^9$ e. Volt.

§ 4. We now obtain the following picture. We plot the spectrum of these rays in $N = N_0 \, e^{-\frac{\varepsilon}{3 \cdot 10^{10}}}$ in fig. 3, where $N$ is plotted vertically and $\varepsilon$ horizontally. The part of the spectrum *ABC*, cut off at *A*, occurs about uniformly from the magnetic pole to 46°, so that between the pole and

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[1]) Proc. Roy. Acad. Amsterdam XXXI p. 1091 (1928)

[2]) E. REGENER, Z. f. Ph. **74** p. 433 (1932).

[3]) E. REGENER, Z. f. Ph. 74, p. 433 (1932).

46° a very little change of intensity of ionisation is to be expected, as is confirmed by many measurements, as indicated above. At 46° the STÖRMER

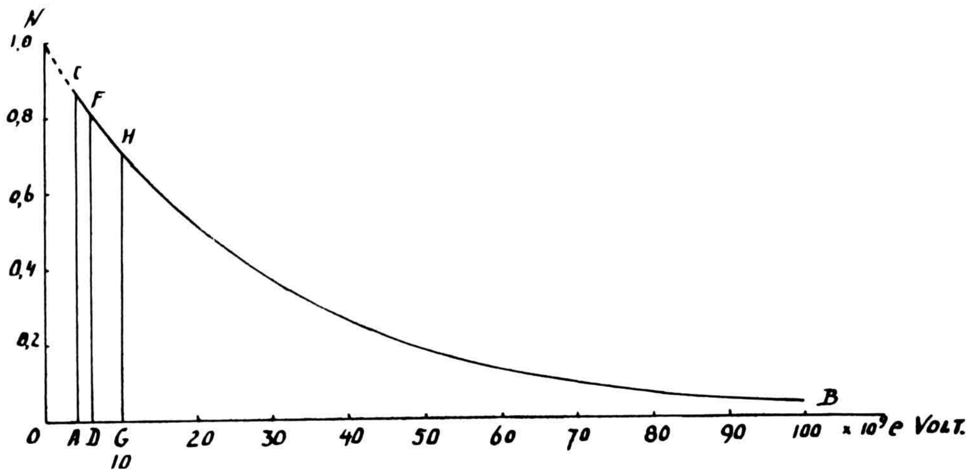


Fig. 3. Distribution of the number of corpuscles over their energie and the variation of their ionisation with magnetic latitude. The part of the graph between *O* and *A* will be discussed later.

boundary for $4 \times 10^9$ e. Volt begins. Between 46° and 34° the rays between $4 \times 10^9$ and $6 \times 10^9$ e. Volt, which may reach the Earth's surface from various directions of space, will gradually be eliminated on account of STÖRMER's limitation. Proceeding from 34° further towards the magnetic equator, rays of energy larger than $6 \times 10^9$ are gradually eliminated, until at the equator everything below $10 \times 10^9$ e. Volt has been cut off.

Calculating the number of particles which is eliminated between 34° northern magnetic latitude and equator, one obtains a decrease of 12 % (area *DFHG*), whereas our observations yield a decrease of 9 % (one may expect the ionisation per $cm^3$ to be proportional to the number of corpuscular rays left). For the decrease from 46° to the equator (energy limit from $4 \times 10^9$ to $10 \times 10^9$) we calculate a decrease of 18 % (area *ACHG*), whereas our observations give a decrease in ionisation of 12 %. Our observations of 1928 have given 12 % and in 1929 11 %. A better agreement could hardly be expected, the more since in the simple picture followed here, the distribution outside STÖRMER's forbidden space for a certain energy has been assumed to be homogeneous, which does not follow from STÖRMER's theory, but is intended only as a rather rough approximation.

We may summarise the results in the following table. (See page 1289).

It may be expected that the observed difference would have been somewhat larger, if we could have observed at the points of maximum horizontal intensity, which occurs in the South Chinese Sea near Indo-China. We intend to persue the same calculation with Maxwellian

| Magn. Lat. $\varphi$ | Observed variation between $\varphi^\circ$ and 0° M.L. $\frac{dI}{I_\varphi}$ | | | Decrease of *primary* radiation calculated $\frac{dI}{I_\varphi}$ |
|---|---|---|---|---|
| | 1928 | 1929 | 1932 | |
| 43° | 0.12 | 0.11 | 0.12 | 0.18 |
| 33° | 0.09 | 0.08 | 0.09 | 0.12 |

distribution which will be especially for the lowest energies of another and more probable form.

The mean energy to be expected at the Earth's surface (lower limit $6 \times 10^9$ e. Volt) according to the spectral distribution of fig. 3 is calculated $30 \times 10^9$ e. Volt, whereas JOHNSON concludes from ANDERSON's experiments to a mean energy of $22 \times 10^9$ e. Volts for a primary ray, which therefore outside the atmosphere would have been $28 \times 10^9$ e. Volt.

§ 5. In conclusion, it will be clear that, if the above explanation is correct, the radiation will gradually become harder, as one passes from 46° latitude towards the magnetic equator. Indeed there are in my former observations three cases which show this. In the voyages of 1928 and 1929, the 8 cm iron shield surrounding electrometer was removed now and then and the difference was measured. This difference always increased with the distance from the equator [1]).

| | dI (1928) | dI′ (1929) | magn. latitude |
|---|---|---|---|
| Suez canal | 0.48 | 0.36 | 29° |
| Red Sea, North | | 0.31 | 21° |
| Red Sea, South | 0.32 | | 15° |
| Gulf of Aden | 0.18 | | 8° |
| Indian Ocean | | 0.26 | 6° |

The values, though not accurate, certainly show the variation expected.

The third case is the following. In 1927 BÜTTNER [2]) has measured the absorption for 3 cm of lead with a KOLHÖRSTER apparatus at an altitude of 3470 meters. It is a curious coincidence that I happened to measure in the same year the absorption also for 3 cm of lead at 3024 meters with an identical apparatus. BÜTTNER found 17.4 $10^{-3}$ $cm^{-1}$ of lead at about 50° *N* magnetic latitude, and I obtained 11.8 $10^{-3}$ $cm^{-1}$ at 18° *S* magnetic latitude.

It is to be regretted that the absorption measurements in water just published by BENADE [3]) cannot be compared with those of REGENER, since

[1]) Proc. Roy. Acad. of Amsterdam XXXI p. 1091 (1928). XXXIII p. 711 (1930).

[2]) K. BÜTTNER, Z. Geophys. **3** p. 161 en 237 (1927).

[3]) J. BENADE, Phys. Rev. **42** p. 290 (1932).

they were made at different altitudes. At any rate it may be seen that the upper parts of their curves do not coincide, but the lower parts do, as is to be expected.

§ 6. We have reached the conclusion *that the ultra-radiation incident on the Earth is a charged corpuscular radiation, in all probability of a* MAXWELL *distribution of which the hardest end is approximately exponential with a mean energy of about* $3 \times 10^{10}$ *e. Volt, which is cut off at the lower limit of* $4 \times 10^{9}$ *e. Volt by the atmosphere, whereas between 50° magnetic latitude and the magnetic equator an additional 16 percent is cut off at the lowest side in consequence of* STÖRMER's *forbidden spaces.*

*In the atmosphere this primary radiation produces a secondary radiation of positive rays (protons and perhaps neutrons) of great energie and of negative rays and some of these rays will give on their turn a tertiary radiation. The paths of these rays depend on the pressure of the air.*

On this base it is possible also to give an explanation of the ionisatie-curve of REGENER [1]) in the stratosphere and of the high conductivity of the upper layers of the atmosphere, which I will give in a following paper.

The interpretation of a MAXWELL distribution being correct, one might ask, what is the source of such an enormous electron temperature, a problem which might be of interest for astrophysics. I suppose they must originate from the hot stars of the MILKY system.

It will be of much value to investigate more in detail the intensity and range distribution from about 50° latitude to the equator, and, especially to measure the ionisation in the upper atmosphere according to REGENER's method.

A determination of the direction from which the primary rays originate will involve serious difficulties on account of the appreciable curvature of the rays in the earthmagnetic field. Only the rays with highest energies will be suited for this purpose.

In conclusion we wish to express our cordial thanks to Dr. BERLAGE for his careful help for the measurements and to Dr. H. ZANSTRA for valuable help in various fruitful discussions and calculations. Further to the Direction and Inspection of the Steamship Company "Nederland" for their readiness in giving facilities and to Captain MÖRZER BRUINS, First Officer STEEN and members of the Crew of the M.S. "Christiaan Huygens" for their active help.

*Amsterdam,* December 10, 1932.

*Natuurkundig Laboratorium.*

[1]) E. REGENER, die Naturw. **20**, p. 695 (1932).