MODERN NORWEGIAN RESEARCHES ON THE AURORA BOREALIS

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I have the honour in this lecture to give you a short report on the Norwegian researches on the *aurora borealis* during the last thirty years.*

Here in Canada you ought to be well acquainted with these remarkable phenomena whose real nature has been a great mystery until the last few years. I think it is not too pretentious to say that most of this mystery has been elucidated by the Norwegian researches. One of the reasons for the success of these researches is the very favourable situation of Norway for the observation of the aurora. If you look at a chart of the frequency of the aurora, you will see lines passing through the regions where the frequency is the same and the thickest of them, corresponding to the maximum frequency, lies over northern Norway. Here at the Alten Fjord you have the well known observation place Bossekop where numerous expeditions have studied the aurora and where the conditions for studying it are also most excellent. The great extent of Norway north and south has also been most important for studying the different types of aurora and their occurrence and movements during magnetic storms.

The interest in these remarkable phenomena has been most lively ever since the middle ages. Thus we find in the old saga Kongespeilet (The Kings Mirror) of the thirteenth century a description of the aurora with an attempt at explanation remarkable for that time.

In modern times, during the second part of the last century, Sophus Tromholt spent most of his life collecting all Norwegian observations regarding the aurora from the earliest times up to 1878. This has been published since his death by Professor Schroeter at the cost of the Videnskabsselskabet and the Nansenfondet in Christiania.

The new epoch in the researches on the aurora began with the beautiful experiments of my late colleague Professor Kristian Birkeland. It was just at the time of the discovery of the Röntgen rays, and physicists all over the world were interested in experimenting with cathode rays. Birkeland made a series of experiments with these rays in magnetic fields. He discovered an interesting phenomenon which he called the suction of cathode rays towards a magnetic

*See *Les aurores boréales, Conférence faite à la Sorbonne le 14 décembre* 1923 par Carl Størmer. Livre du Cinquantenaire de la Société Française de Physique, Paris, 1925.

pole. A magnetic pole has an effect on a beam of parallel cathode rays analogous to that of a lens upon a beam of light, namely to make them converge towards a point.

This phenomenon led him in 1896 to the idea that the aurora borealis was due to a similar effect of the earth's magnetism on cathode rays coming from the sun. In order to test his hypothesis, Birkeland exposed a small spherical electromagnet to a stream of cathode rays and the result was most promising. In 1900 he describes his experiment in the following words:

"If the little globe was unmagnetized, only the half of it that was exposed to cathode rays was shining with an evenly distributed light. As soon as the globe was rendered magnetic the rays were thrown away from the surface of the globe except at certain places near the magnetic poles (Fig. 1). Both near the north pole and near the south pole the rays come down to the little earth-model in inclined striated wedges of light, and these wedges can be seen outside the globe up to 5 centimetres from its surface. These luminous wedges strike the surface of the model and produce two luminous narrow bands, one near the north pole and one near the south pole. Each of these bands stretches along the latitude of 70° from a point directly opposite the cathode and along the afternoon and night side of the earth-model, the cathode being considered as the sun. No corresponding light is seen on the morning and afternoon side of the globe."

During the following years Birkeland made a long series of similar experiments, which showed a striking resemblance to the aurora belts.

Birkeland has published the results of his experiments on cathode rays and of his extended studies of magnetic storms in two large volumes,* a work which certainly will be of great importance for future researches.

His later experiments were made with a large glass reservoir having a volume of about 1000 liters. In Fig. 2 are shown a series of photographs of the artificial aurora belts at the poles of the magnetic globe. When the magnetization is weaker, the phenomena are quite different.

At the beginning of 1903 I became extremely interested in Birkeland's experiments and in his theory of the aurora; knowing that the phenomenon of the suction of cathode rays towards a magnetic pole had been mathematically treated by Poincaré, I thought it might be worth while to find by mathematical methods the trajectories of electric corpuscles in the magnetic field of the earth, hoping in this way to find again not only the details of Birkeland's experiments but also the principal features of aurora and of magnetic storms.

When one has to solve a problem as difficult as that of the aurora borealis, it is nearly hopeless to begin with the most general assumptions. The only reasonable way, it seemed to me, was to start from a series of simplifying hypotheses and to attempt to solve the mathematical problem in this ideal case. Afterwards, when the first simplified problem was solved, one could go on to

*See *The norwegian aurora polaris expedition* 1902-1903, New York, Longmans Green & Co., 1913.

solve the aurora problem under more general assumptions approaching more nearly the real conditions in nature.

As a simplifying hypothesis I first consider the motions of the earth and the sun as negligible, so that only their relative positions come into consideration. It is furthermore assumed that the force acting on the corpuscles is only the earth's magnetism, and for simplicity the magnetic field is considered to be that of a uniformly magnetized sphere,—or, what amounts to the same thing, to be that of an elementary magnet at the earth's centre with its magnetic axis coinciding with that of the earth. Thus we neglect in this first approximation the mutual action between the electric corpuscles as well as the action of the sun's magnetic field.

Nevertheless it is surprising how many details of the auroral phenomena we can explain by these simplified hypotheses.

The mathematical treatment and solution of the resulting problem, viz., to find the trajectories of electric corpuscles in the field of an elementary magnet, is itself a very heavy task. It is impossible in this short lecture to give a more detailed report on my mathematical researches on this problem during the years 1903-1907. Only a few of the more striking results will be mentioned. The differential equations which determine the trajectories are herewith given:

$$\frac{d^2x}{ds^2} = \frac{1}{r^3}\left[3yz\frac{dz}{ds} - (3z^2 - r^2)\frac{dy}{ds}\right],$$

$$\frac{d^2y}{ds^2} = \frac{1}{r^3}\left[(3z^2 - r^2)\frac{dx}{ds} - 3xz\frac{dz}{ds}\right],$$

$$\frac{d^2z}{ds^2} = \frac{1}{r^3}\left[3xz\frac{dy}{ds} - 3yz\frac{dx}{ds}\right].$$

The elementary magnet (Fig. 3) is at the origin of the system of coordinates and the unit of length C is chosen equal to the square root of $\frac{M}{H\rho}$. M is the moment of the magnet and $H\rho$ is a product characteristic of the corpuscles. The arc of the trajectory is s, which is chosen as independent variable.

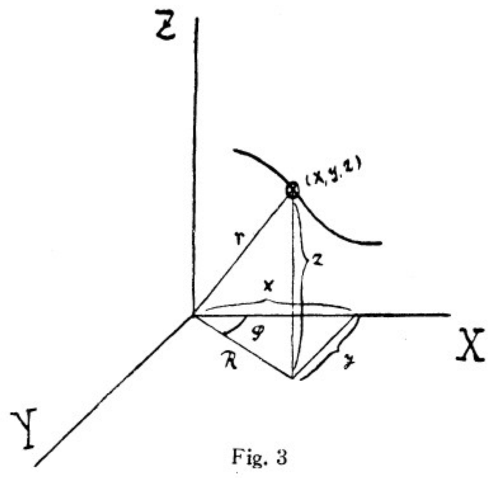

Fig. 3

If in place of x and y one introduces the polar coordinates R and ϕ where $x=R\cos\phi$, $y=R\sin\phi$ it will be found that it is possible to integrate one of the resulting equations. This introduces a constant of integration γ, and we are led to the transformed system:

$$R^2\frac{d\phi}{ds}=2\gamma+\frac{R^2}{r^3}$$

and

$$\frac{d^2R}{ds^2}=\tfrac{1}{2}\frac{\partial Q}{\partial R},\quad \frac{d^2z}{ds^2}=\tfrac{1}{2}\frac{\partial Q}{\partial z},\quad \left(\frac{dR}{ds}\right)^2+\left(\frac{dz}{ds}\right)^2=Q,$$

where

$$Q=1-\left[\frac{2\gamma}{R}+\frac{R}{r^3}\right]^2.$$

This system not only can be interpreted in a very useful mechanical manner, but it is also very convenient for numerical integration.

We will only give a geometrical consequence of the equation for the angle ϕ. It is easily seen that $R\frac{d\phi}{ds}$ is the sine of a certain angle θ and thus we obtain the formula:

$$\sin\theta=\frac{2\gamma}{R}+\frac{R}{r^3}.$$

Now $\sin\theta$ along the trajectory is confined to the interval -1 to $+1$. The trajectory corresponding to a given value of γ must then be limited to the region of space where

$$-1\leqq\frac{2\gamma}{R}+\frac{R}{r^3}\leqq 1.$$

To each value of γ thus corresponds a region Q_γ to which all trajectories corresponding to this value of γ are confined.

In Fig. 4 is given a series of regions Q_γ. The upper row represents their sections cut by a plane through the magnetic axis. The regions are described by the white parts when rotated about the magnetic axis.

From this consequence of the differential equations which I already found in 1904 we can make an interesting application to the aurora. In this case the earth is very small compared with the dimensions of the regions Q_γ and thus we see that these regions strike the earth only in the polar regions, this corresponding to the fact that the aurora generally is confined to these regions.

To obtain further information about the trajectories a mechanical interpretation of the system in R and z, followed by a general discussion of the trajectories directly from the differential equations themselves, was made. In this discussion I found a most valuable aid in the methods of numerical integration of differential equations. In fact the mathematical methods gave the qualitative results, and the numerical methods gave quantitative results which could be directly applied to nature.

More than 5000 hours were spent on numerical calculations and in this extended work I received most valuable assistance from several young students of mathematics; the results were illustrated by wire models giving the shape in space of the calculated trajectories.*

The trajectories in the magnetic equatorial plane can be found exactly by elliptic functions. In space the trajectories must be found by numerical integration.

In Fig. 5 is shown a wire model of trajectories issuing from two separate points towards the elementary magnet placed in the centre of the little sphere. Fig. 6 shows the coincidence between this calculation and one of Birkeland's experiments.

For application to the *aurora borealis* the orbits which strike the little sphere are of special interest. The nearer the orbits come the more they take the spiral shape like the one resembling the geodetic lines on a narrow cone of revolution (Fig. 7). The orbits approach the elementary magnet in a corkscrew spiral of ever narrowing windings, reach a minimum distance from the magnet, then recede. The more this minimum distance approaches zero, the more the trajectory approaches an orbit of a special kind passing through the elementary magnet, an orbit which I have termed the "trajectory through the origin".

In Fig. 8 we have a series of trajectories of this kind corresponding to cathode rays coming from the sun and reaching the earth in the north polar regions. A corresponding wire-model of the trajectories in the neighbourhood of the magnetic globe is given in Fig. 9. It is apparent that the points of precipitation are located on the afternoon and night side, corresponding to Birkeland's experiments.

These points of precipitation lie about the magnetic axis in a sort of spiral the form of which is in full agreement with experiment.

Also another series of Birkeland's experiments can be easily explained by the mathematical theory. For instance, the remarkable form of the luminous wedges of light going down towards the magnetic poles of the sphere are demonstrated (Fig. 10); this corresponds to the characteristic form of the region Q_γ to which the trajectories are confined.

A further application to the aurora of the numerical results on the trajectories yields a limitation towards the magnetic axis. Corpuscles coming from the sun cannot strike the earth too near the axis. Thus we get auroral zones in the form of belts around the magnetic axis, the northern ones of which correspond to the zone of maximum frequency of the aurora borealis.

The formation of auroral rays and of auroral curtains are also easily explained, but for the details I must refer to my published papers.

Since the magnetic axis of the earth is rotating with the earth, the relative positions of this axis to the sun are ever changing. This gives a continual varia-

*See *Sur les trajectoires des corpuscules électrisés dans l'espace*, etc. Archives des Sciences Physiques et Naturelles, Genève 1907 and *Résultats des calculs numériques*, etc., I, II, III, Videnskabsselskabets skrifter 1913, Christiania.

tion of the initial conditions for the different orbits and corresponding fluctuations in the auroral phenomena.

This is especially so in the case of auroral curtains; the special conditions conducive to these curtains rapidly pass away and thus cause the short duration of these beautiful displays.

In spite of this fine harmony between theory and observation the agreement is incomplete in one respect: that is, the dimensions of the calculated and the observed auroral belts are not in accord, if the cathode rays are causing the aurora. Here the fact that we have neglected the mutual action of the corpuscles on each other is probably the cause.

For the cathode rays the angular radius of the auroral zone proves to be about 3° instead of 23°; and during magnetic storms the angular distance of the aurora from the magnetic axis can be even much greater, say to 30° or 40°.

To take into account this mutual action of streams of cathode rays is a very difficult problem, especially because these streams move in the earth's magnetic field where the problem of finding the trajectory of a single corpuscle is already so difficult.

I have only succeeded in obtaining one interesting result, and this is the following: If one assumes, corresponding to Birkeland's experiments and the theory of the trajectories, that a temporary corpuscular ring may exist in the earth's magnetic equator far out in space, the magnetic action of such a ring will draw the aurora away from the magnetic axis. A calculation I undertook in 1911 showed that a corpuscular ring can draw the auroral belt, even for cathode rays, from its theoretical position down to the real position without exercising greater magnetic effects on the earth than about a thousandth part of the earth's magnetism. If the ring is stronger, however, the aurora can be drawn even much farther away from the magnetic axis, and then the magnetic action of the ring on the earth will be of the order of that which we observe during magnetic storms. This is in accordance with the fact that during such storms the aurora is seen much farther south than usually.

It is very interesting that Carlheim Gyllensköld* and Ad. Schmidt† have both been led to assume the existence of such a corpuscular ring through their studies of great magnetic storms, what Birkeland had already found, and noted in his above mentioned work: *The Norwegian aurora polaris expedition 1902-1903.*

You see that the theoretical researches on the aurora are still in their infancy, and that one has a series of most difficult and attractive problems for future researches.

Now I must pass to the other phase of my own researches, which began in 1909 and which are still in progress. This is the study of the aurora by means of photography, especially the exact determination of its height and position in space. I was naturally led to these researches by my theoretical studies. It was necessary to try to confirm the theoretical results by observations, and

*See *Norrskenet och solens atmosfär*, Populae astronomisk tidsskrift. Stockholm, 1920, p. 124.

†See Encyclopädie der Mathematischen Wissenschaften, Bd. VI, 1, 10 Ad. Schmidt: *Erdmagnetismus*, p. 394.

the only reliable method seemed to me to be the photographic. When I began the work in 1909, the results obtained hitherto by this method were very poor. Only a single photograph with relatively short exposure, 7 seconds, had been obtained in 1892 by Brendel in Bossekop. I systematically tried a series of objectives and plates on auroras and found that a little "kinolens" with aperture 25 mm. and focal distance 50 mm., together with plates "Lumière, *etiquette violette*" solved the problem. I succeeded in taking good pictures of strong auroras with an exposure of less than one second.

In 1910 and 1913, I made expeditions to Bossekop in order to photograph the aurora and determine its height and position by simultaneous photographs from two stations connected by telephone. The method is very practical, but requires much work afterwards in measuring and calculating the photograms. Bossekop is situated in the northern part of Norway at about 70° latitude.

During the last expedition in particular I obtained a great many excellent photograms with a base of about 27 kilometers. On each plate was photographed at the same time as the aurora the face of a watch, and thus the exact time and the exposure could be seen later, on the negative, a very useful arrangement.

Fig. 11 shows an arch with the constellation *Cygnus* in the background The arch was faint and quiet which allowed a relatively long exposure. Height about 120 km.

In Fig. 12, we have a series of bands with *Vega* as reference star. Altitude about 105 km.

In Fig. 13 is an arch where curtains begin to develop to the right. Altitude of inferior border about 100 km.

Other curtains are seen in Fig. 14, with *Vega* in the background. The aurora descends to about 90 km.

Very beautiful draperies together with *Venus* are seen in Fig. 15. Altitude of lower border about 100 km. The draperies stretch to a distance of 700 km. from Bossekop towards the west.

In Figs. 16 and 17 are shown two stages of the development of an auroral curtain, each with an exposure of a few seconds. The altitude of the lower border is between 95 and 100 km. and the vertical extension between 15 and 20 km.

Lastly Fig. 18 shows a remarkable aurora which has the form of a luminous surface; height between 90 and 100 km: great horizontal extension and a very small vertical one.

The results of all the determinations of height are seen in Fig. 19, each altitude being marked by a dot. One sees how well marked is the lower limit of about 87 to 90 km. The maximum altitude is about 350 km.

The next year 1914, Krogness and Vegard made a great number of determinations of height in the same region, and by the same method. Their results were essentially the same. They have also made extended studies of the distribution of intensity with height for the different forms of the aurora.

Both my own report of the expedition of 1913 and the results obtained by Krogness and Vegard in 1914 are published in *Geofysiske publikationer*, Christiania (Vol. I).

After the extensive work done in Bossekop, it was of the greatest interest to study and measure the altitude of the aurora in other places also, especially further south. For this purpose I have since 1911 had a series of stations in southern Norway, where several hundred photograms have been obtained. Fig. 20 shows some of the base lines, the lengths varying between 27 and 258 km. There follow some interesting single pictures of auroras taken from these stations.

In Fig. 21 is a corona of the night of March 7 to 8, 1918. The constellation of the *Great Bear* is seen in the background.

During the night of March 22 to 23, 1920, an exceptionally great aurora was seen over Europe, Canada and the United States. I had 7 stations in action and more than 600 photographs were secured, among these about 40 coronas. Some pictures of coronas taken on that night are given here. Fig. 22 was taken early in the evening, the display being reddish in colour.

Another shown in Fig. 23, was yellow green. This was taken at 2 o'clock in the morning; finally a very beautiful one of blue colour is represented in Fig. 24. Of this blue corona, which occurred about 4 o'clock in the morning, I secured twelve very successful pictures well adapted to determine the position of the point of radiation.

Now we shall pass to the photograms and the determination of height.

Very fine rays observed March 4, 1920, are seen in Fig. 25. The lower border of these rays was at a height of 106 to 111 km.; the summits reached about 300 km.

During the remarkable aurora on the night of March 22 to 23, 1920, a great number of interesting photograms were taken both from two and from three stations simultaneously.

Fig. 26 shows one taken from 3 stations, which gives a good idea of the exactitude attained. A discussion of this case* has shown that the relative error in the determination of height probably does not exceed two per cent.

On this night we obtained highly interesting records of the altitude of auroral rays.

For instance, the rays shown in Fig. 27, photographed with a base of 66 km., had summits which surpassed 600 km. altitude.

A later picture of the same rays is seen in Fig. 28. (The stars are marked by arrows).

In Fig. 29 are shown rays to the west of Scotland photographed from Christiania, Oscarsborg and Horten simultaneously: foot 400 km., summit 600 km.

In Fig. 30 we have rays whose summits reached the enormous altitude of 750 km.

*See *Notes relatives aux aurores boréales*, Geofysiske publikationer, Christiania, 1922, Vol. II, no. 8.

On the same night I also measured aurora curtains down to 83 km. (Fig. 31). The reference stars were *Castor* and *Pollux*, and the base was 64 km.

All the photographs collected during the last 11 years from my stations in southern Norway are now measured and auroral heights and distances calculated. They will shortly be published in an extended report.* I shall here give some of the preliminary results:

As regards the distribution of the calculated heights (Fig. 32); a comparison with those obtained from my Bossekop expedition of 1913 shows that the auroral rays seen in southern Norway are very much higher than at Bossekop. On the other hand the lower limit of auroral curtains is lower in southern Norway than in Bossekop.

Fig. 33 exhibits the geographical distribution of the arches over Scandinavia.

The time is already so far advanced that I must pass rapidly over the later work on the aurora, that is to say, the photographing of the auroral spectrum and the possible artificial reproduction of it. As you know, my colleague, Professor Vegard has succeeded in photographing with great dispersion the spectrum of the aurora in northern Norway. He has obtained about 35 lines, of which all have been identified with lines of nitrogen except five, including the well known green aurora line. No traces of hydrogen and helium lines were found; but Vegard has not as yet photographed auroras of a height greater than about 160 km. The facts just mentioned led Vegard to a new hypothesis regarding the upper air, a hypothesis which he tried to verify last winter in the laboratory of Kammerlingh Onnes at Leyden. His experiments were most interesting, and he found that the spectrum of solid nitrogen when bombarded by cathode rays was of the same type as the characteristic auroral spectrum.

Vegard thought that he had by these experiments confirmed his hypothesis about the upper atmosphere, but recent experiments by Professor McLennan on solid nitrogen have thrown some doubt on this conclusion, and judgment must be reserved until more data are available.†

At all events Vegard has here opened up a new field of research which will certainly give rise to many new and valuable suggestions for solving the remaining mysteries of the aurora borealis.

I hope that the researches which have been carried on with so much ardour by Norwegian scientists, may also stimulate interest in these remarkable auroral phenomena here in Canada which is so admirably situated for an extended study of these beautiful displays.

**Resultats des mesures photogrammétriques des aurores boréales observés dans la Norvège méridionale de 1911 à 1922*, Geofysiske publikationer, Oslo, 1926, Vol. IV, No. 7.

†"Nature", Vol. 115, March 14th, 1925, p. 382 and Vegard's paper in Skrifter utgit av Det Norske Videnskabsakademi i Oslo, Math. Naturv. Klasse No. 9, 1925.

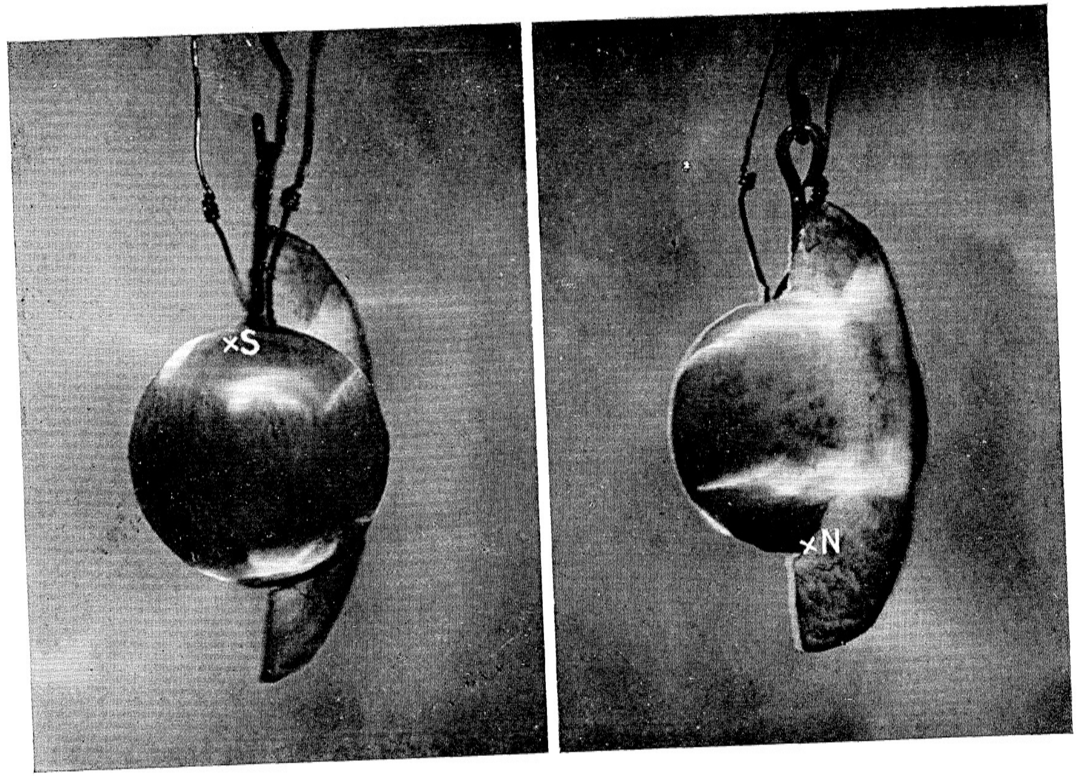

Fig. 1

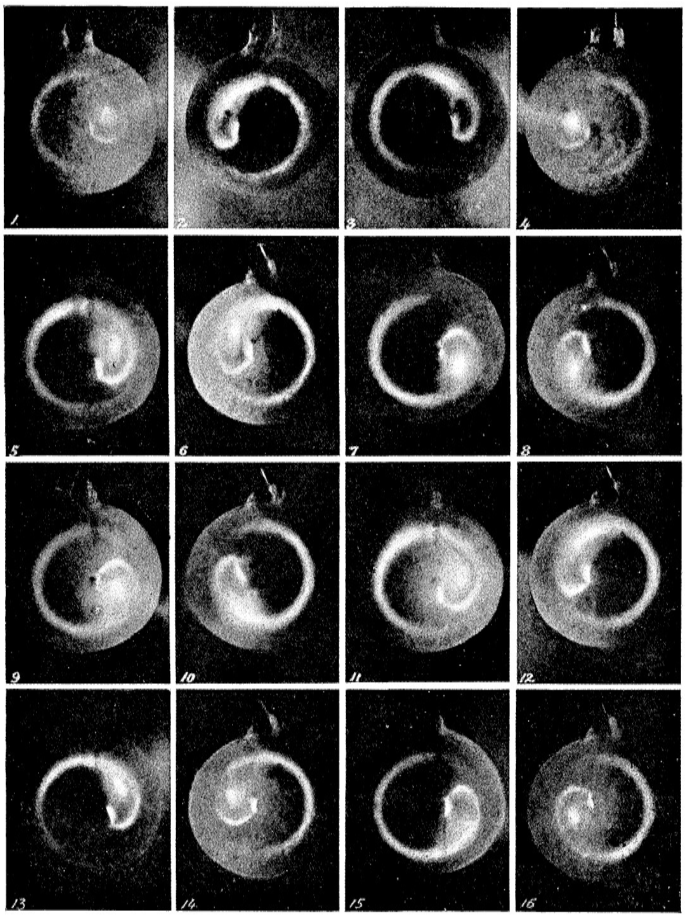

Fig. 2

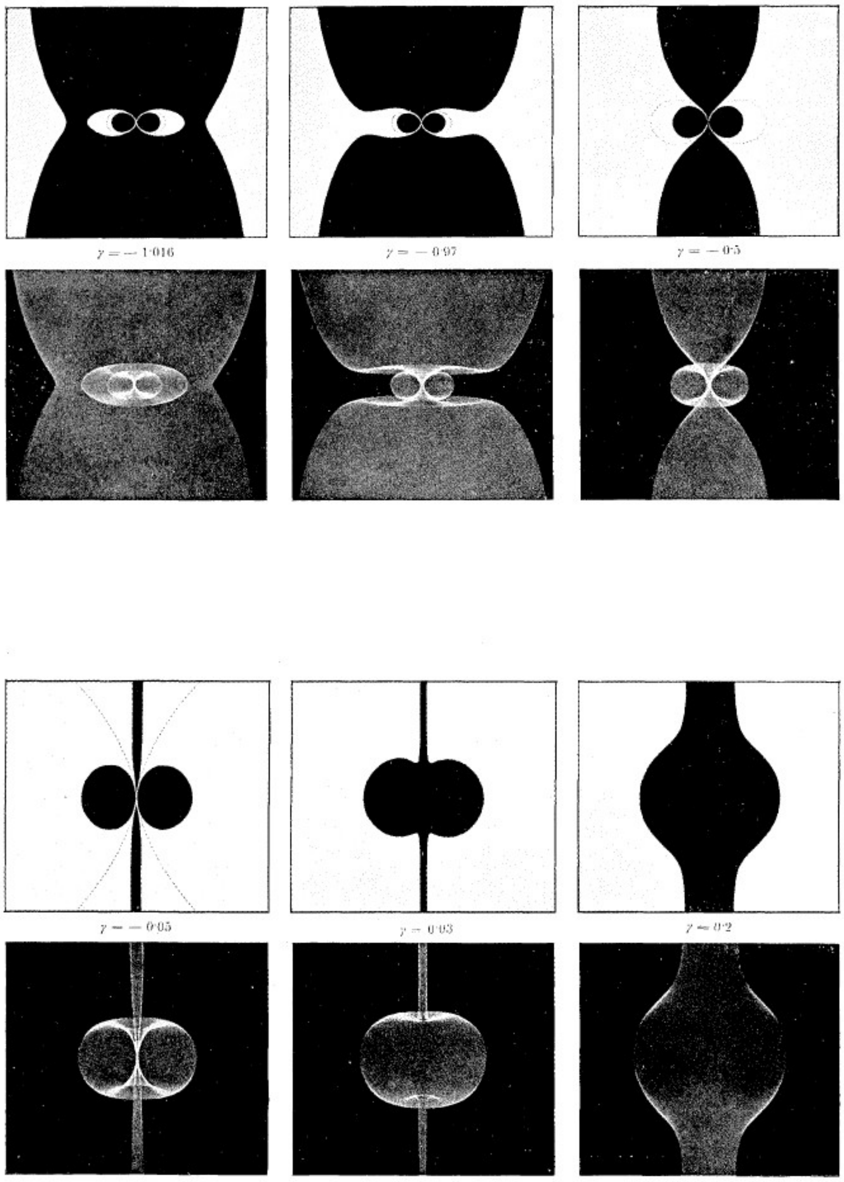
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Fig. 4

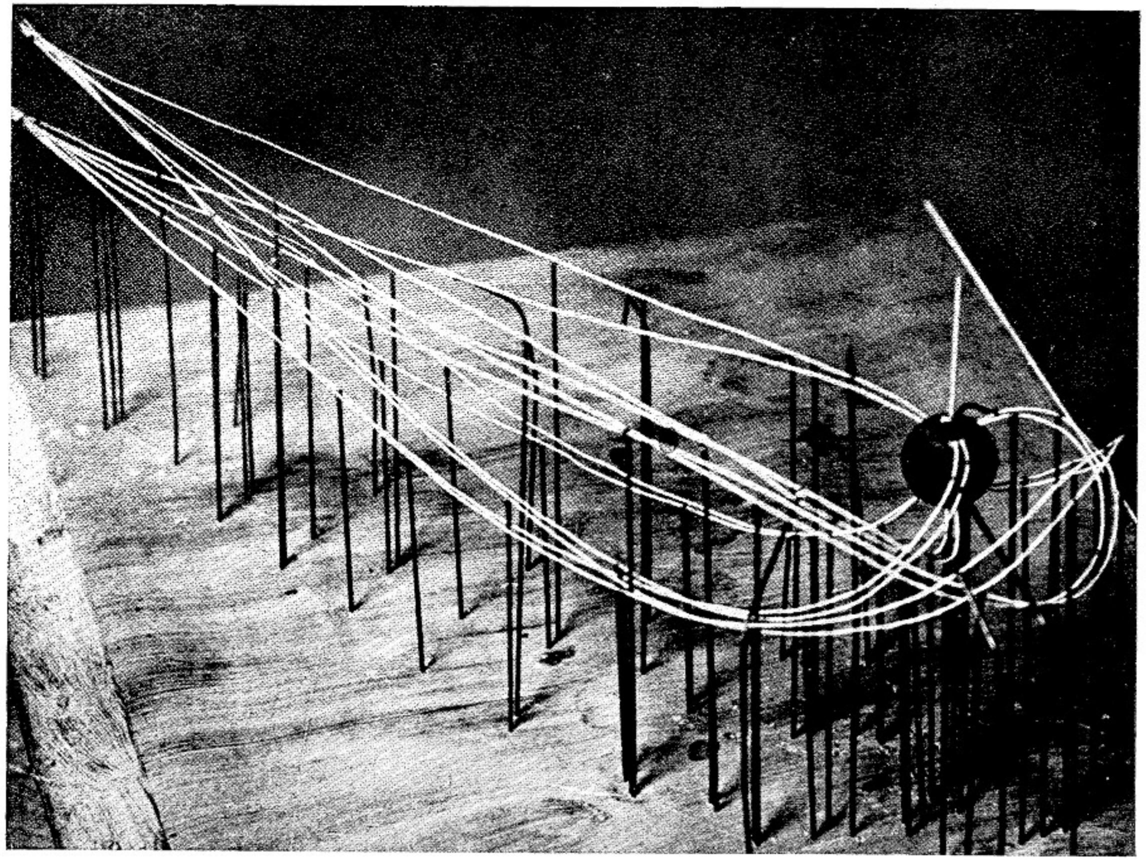

Fig 5

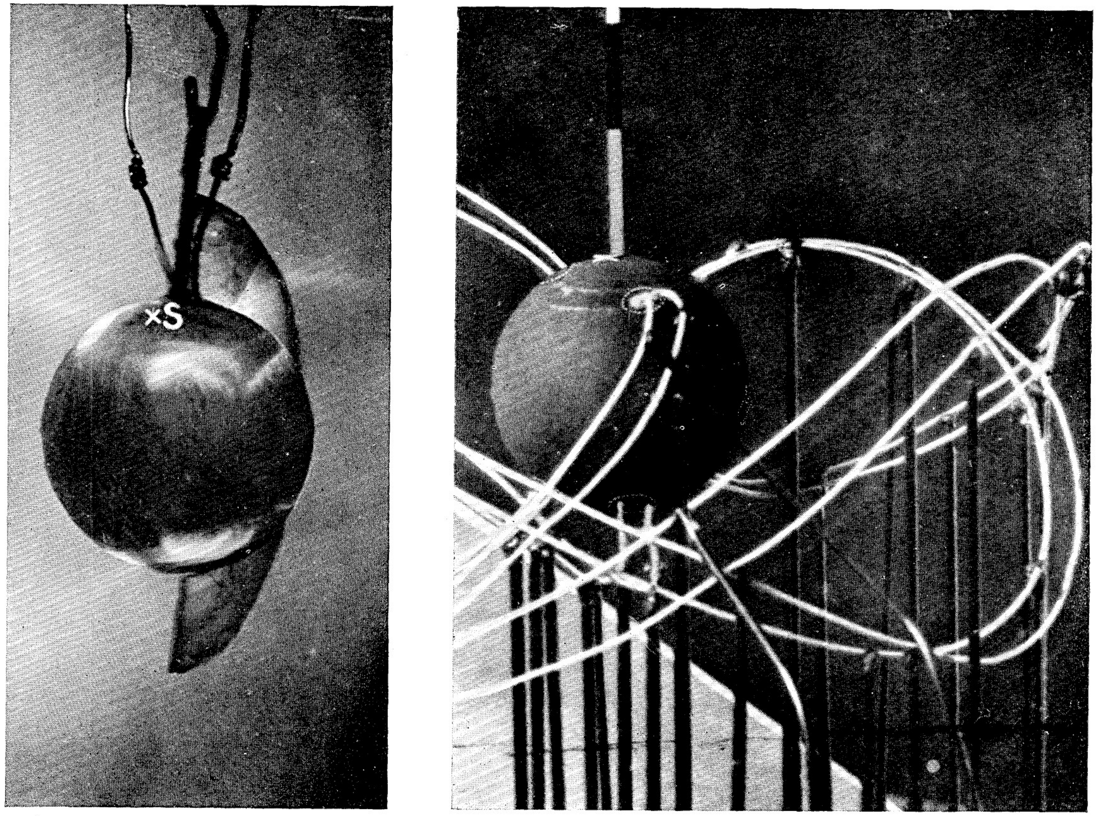

Fig. 6

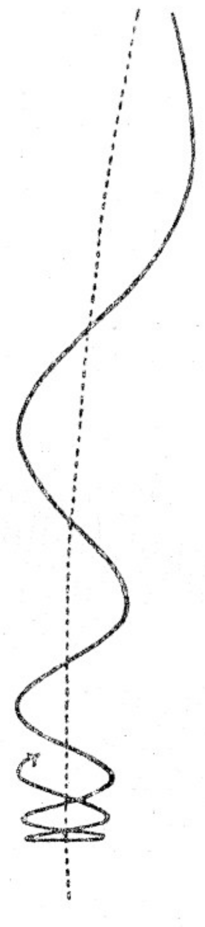

Fig. 7

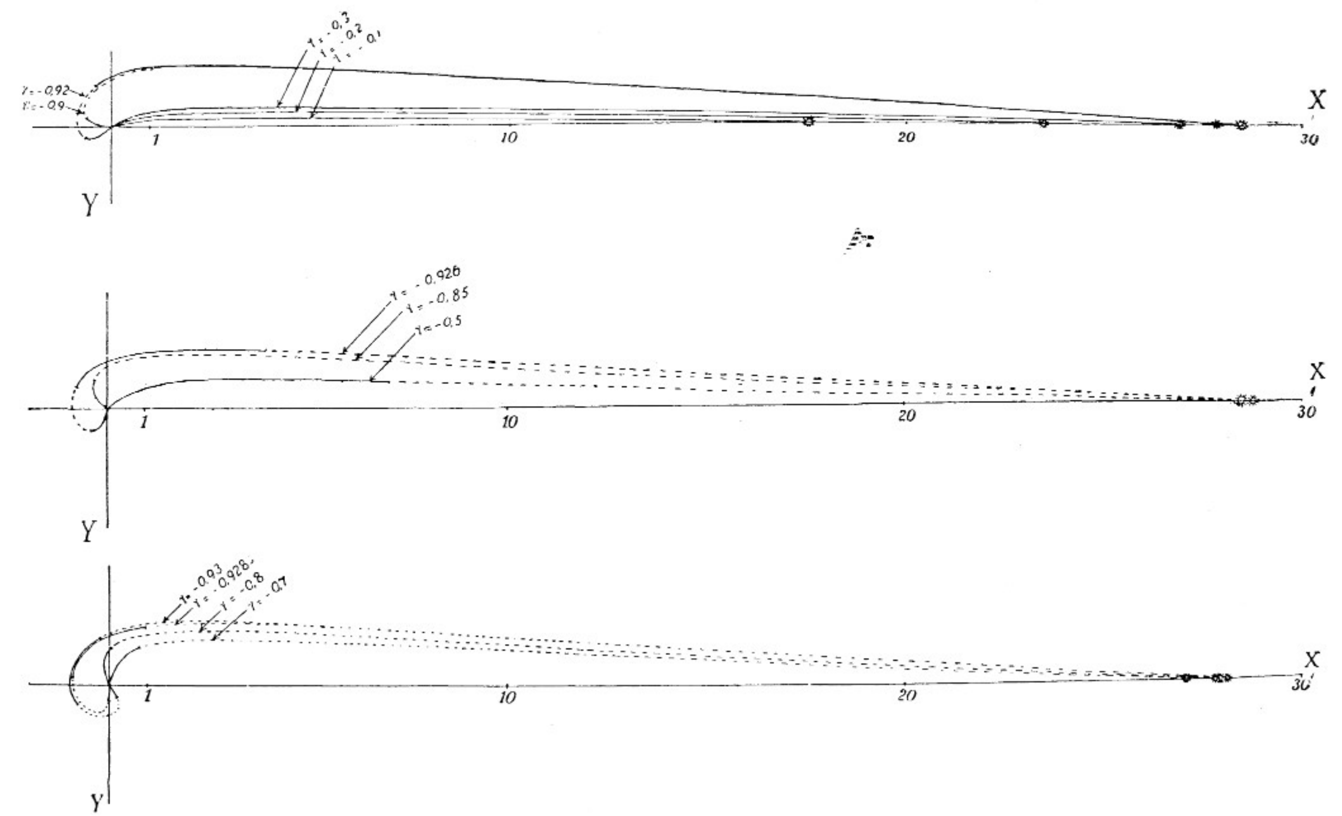
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Fig. 8

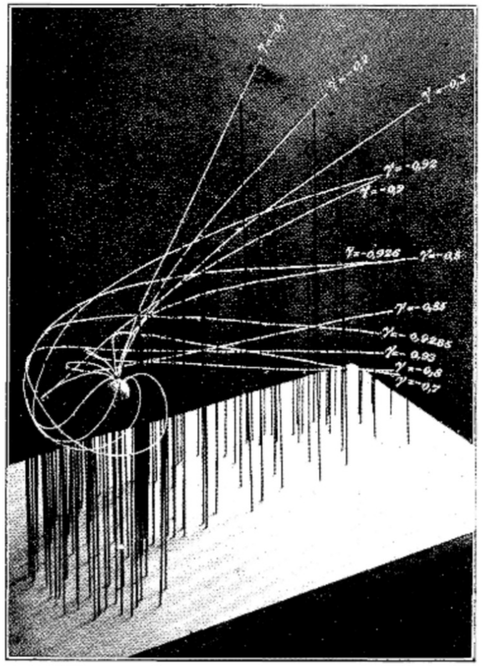

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Fig. 9

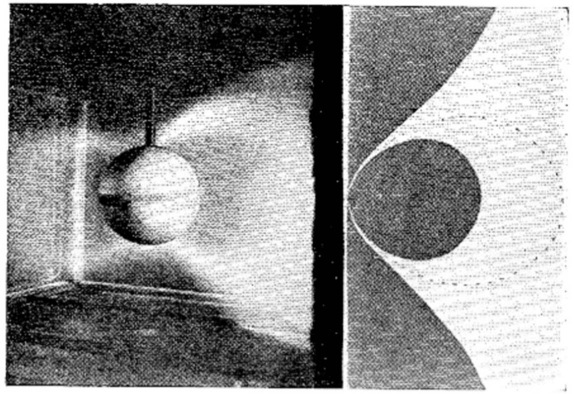


Fig. 10

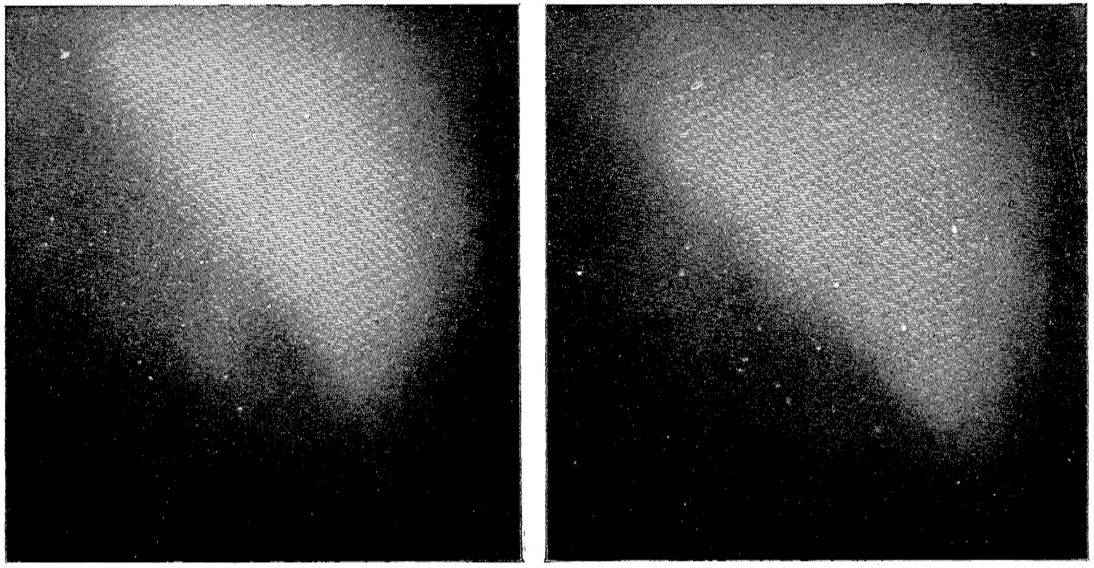


Fig. 11

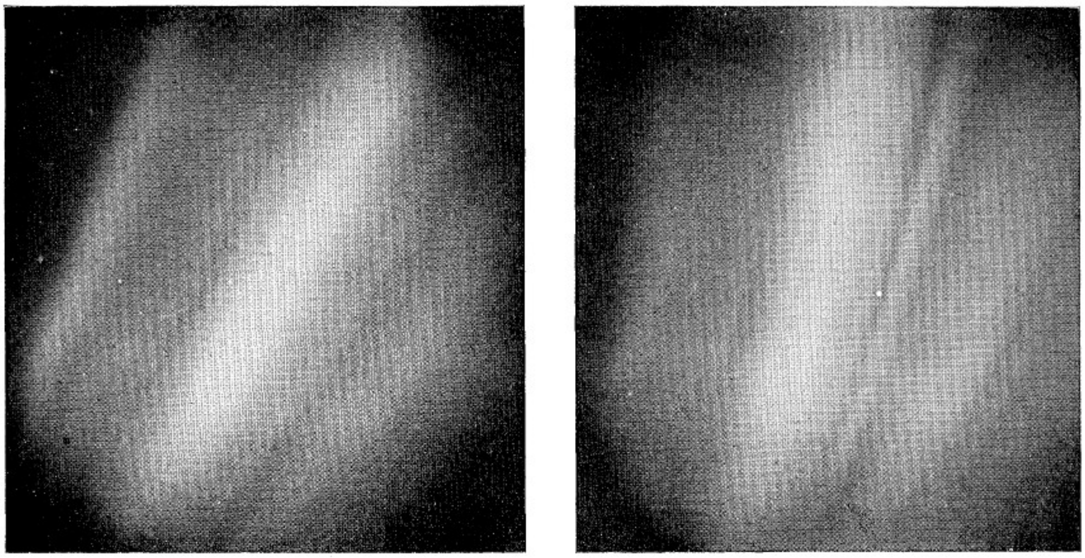


Fig. 12

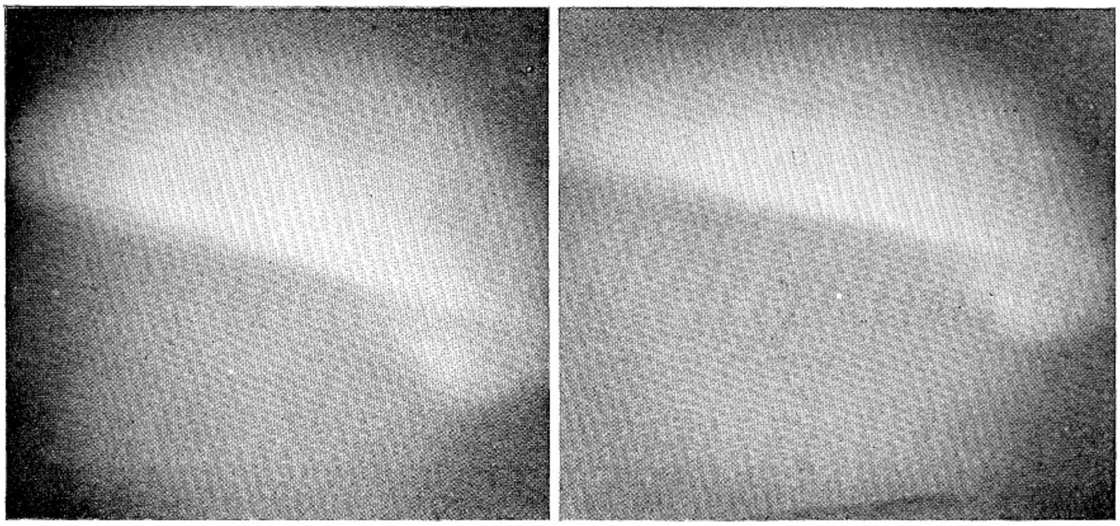


Fig. 13

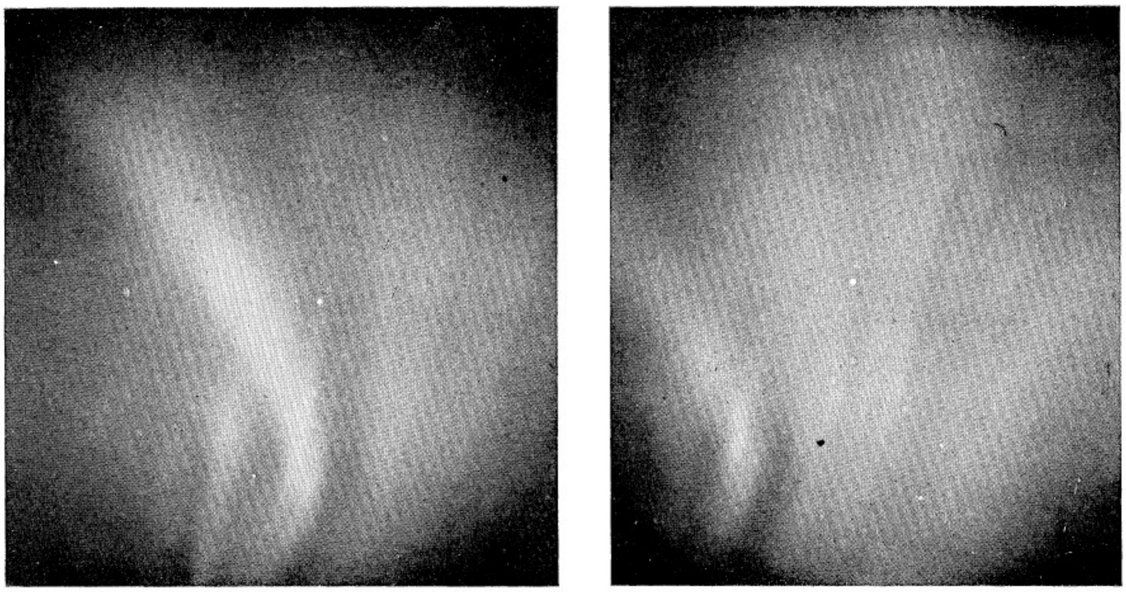


Fig. 14

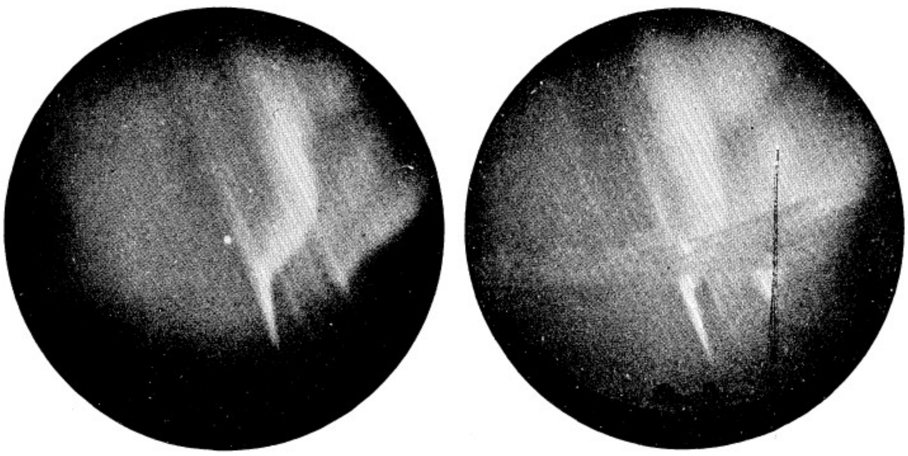


Fig. 15

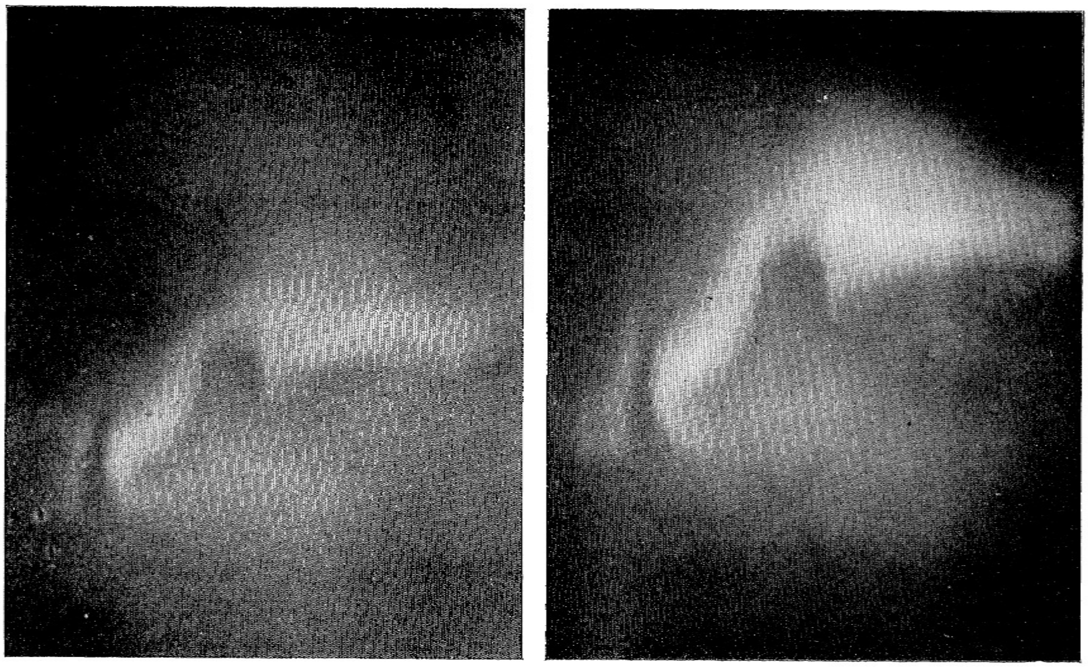
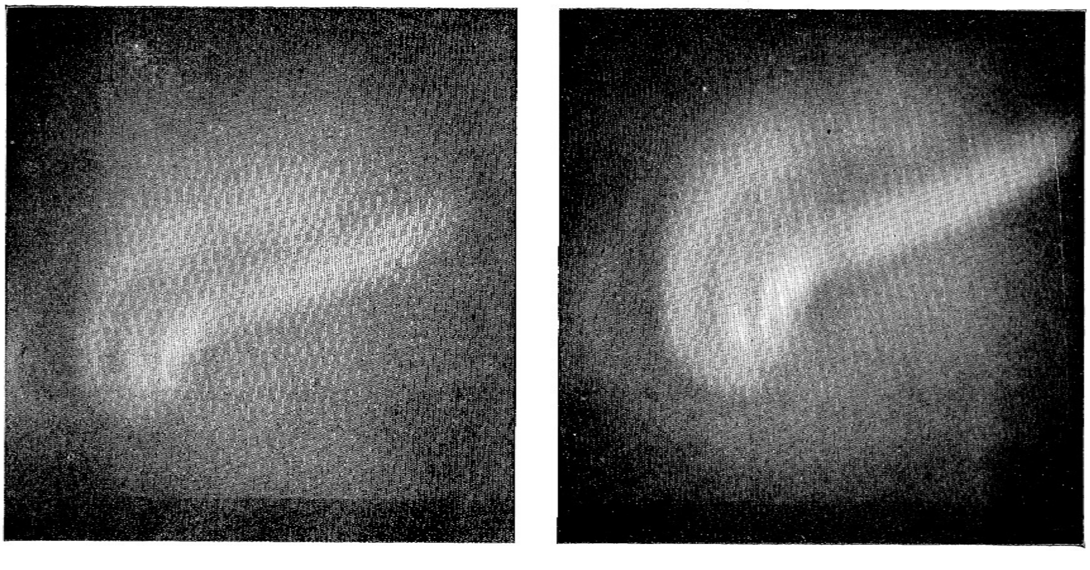


Fig. 16



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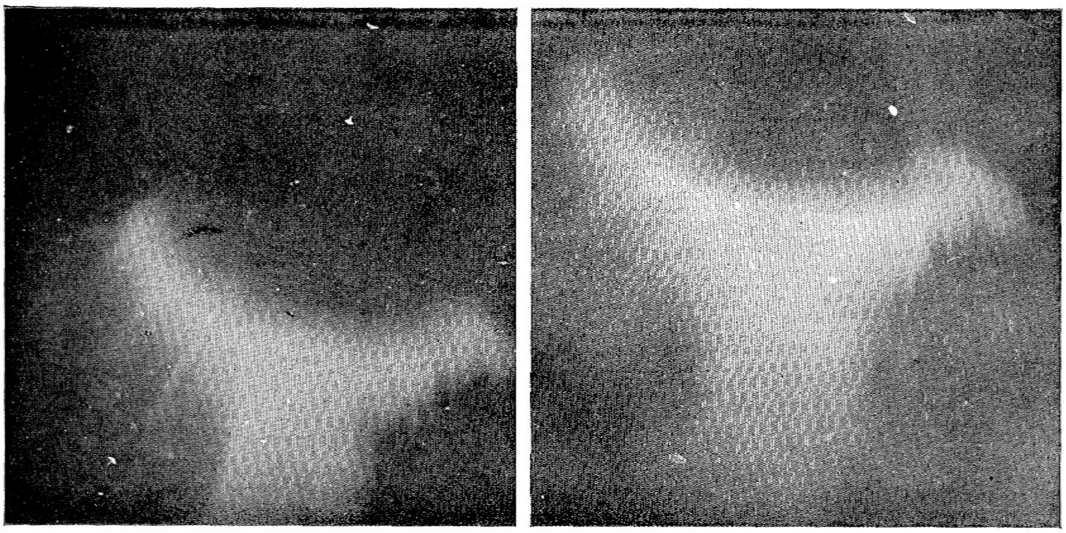

Fig. 18

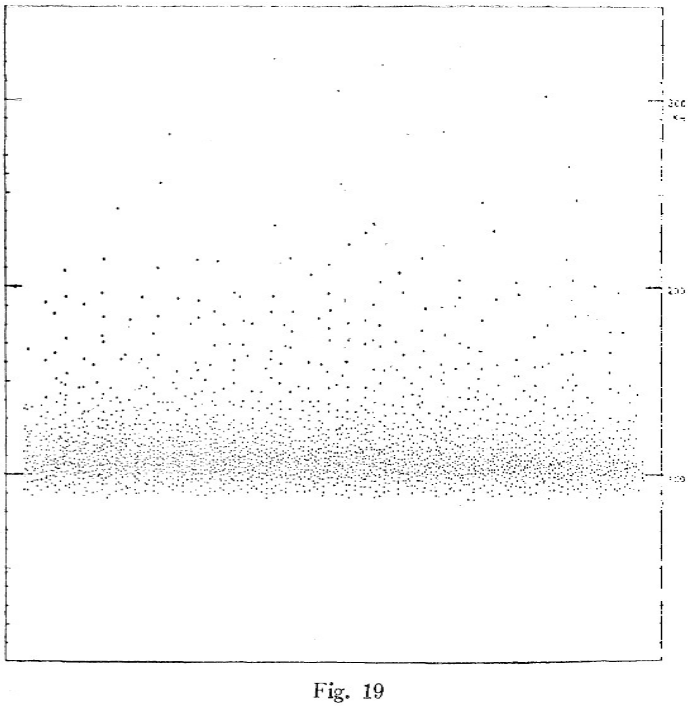

Fig. 19

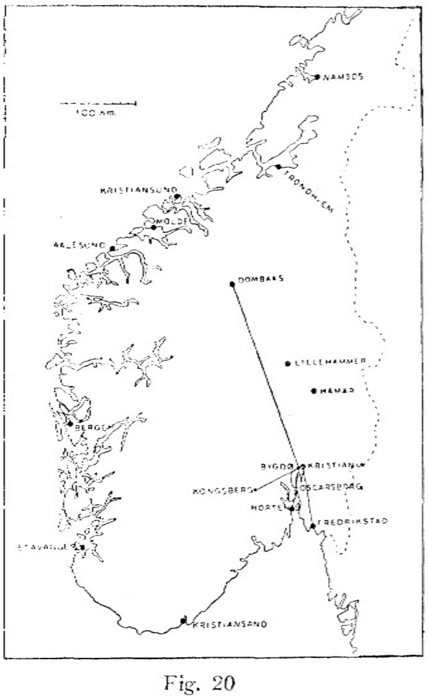

Fig. 20

Fig. 21

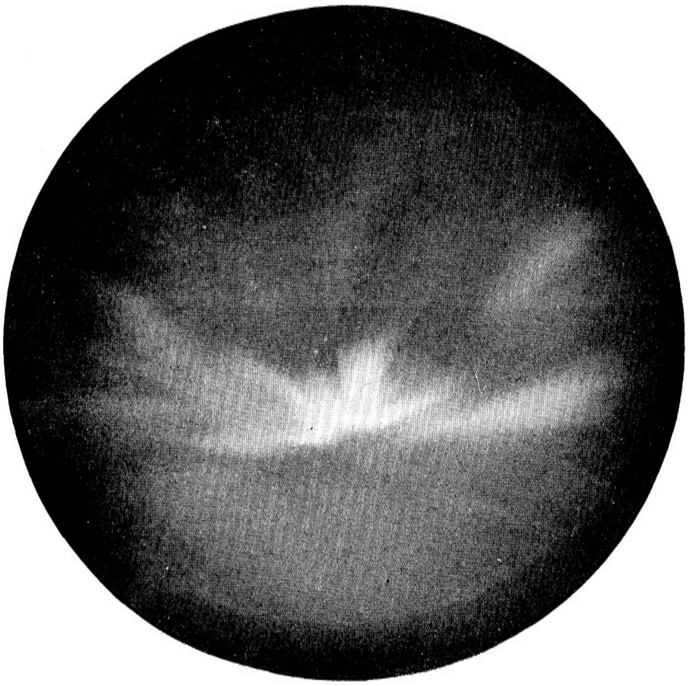

Fig. 22

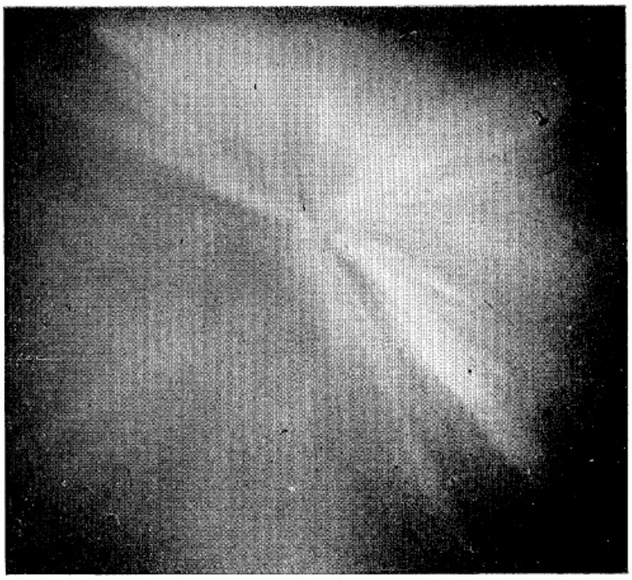

Fig. 23

Fig. 24

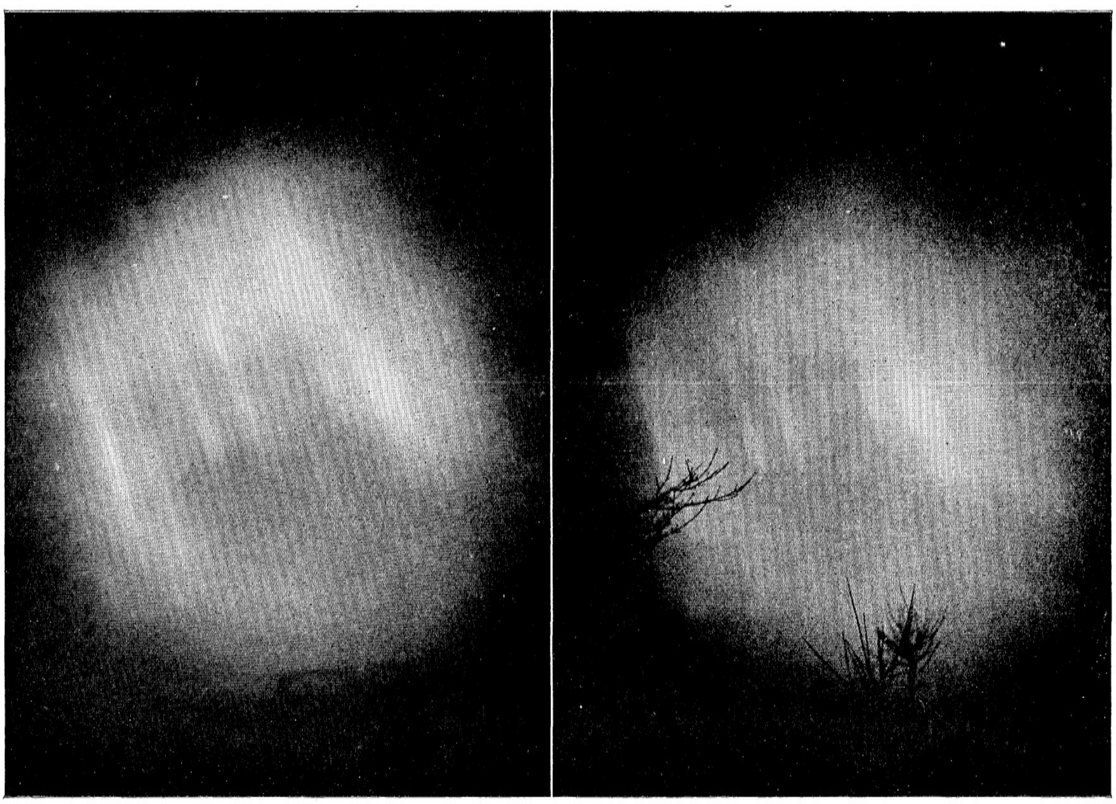

Fig 25

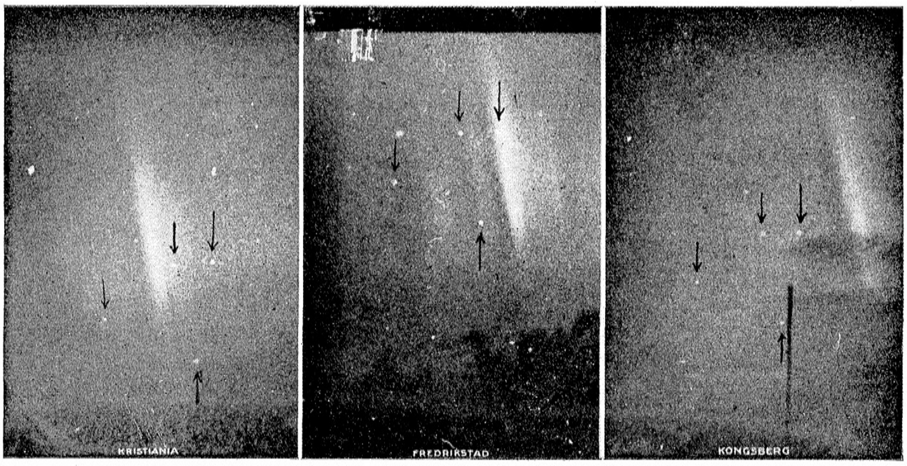

Fig. 26

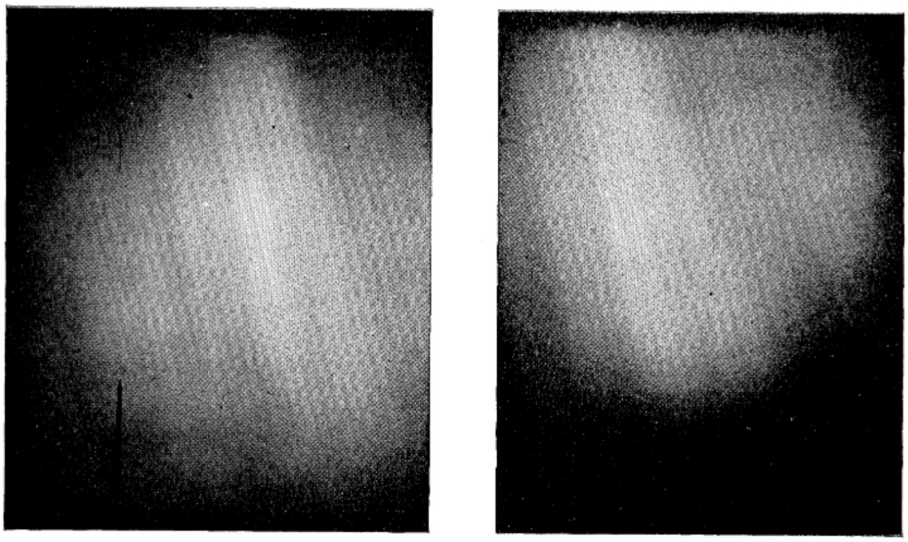

Fig. 27

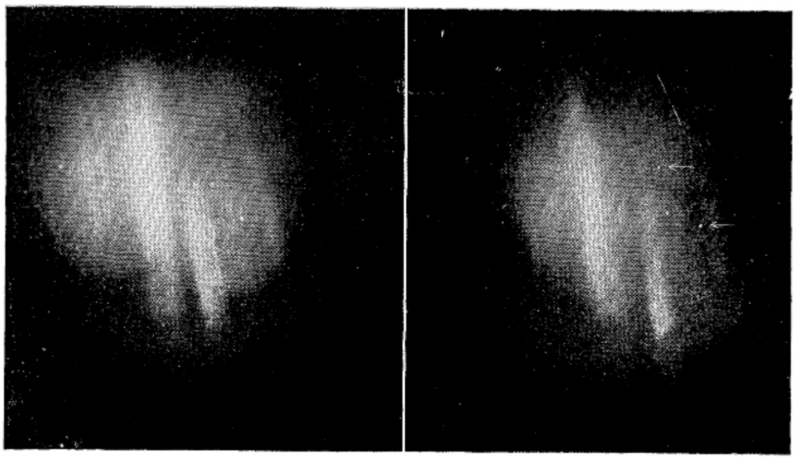

Fig. 28

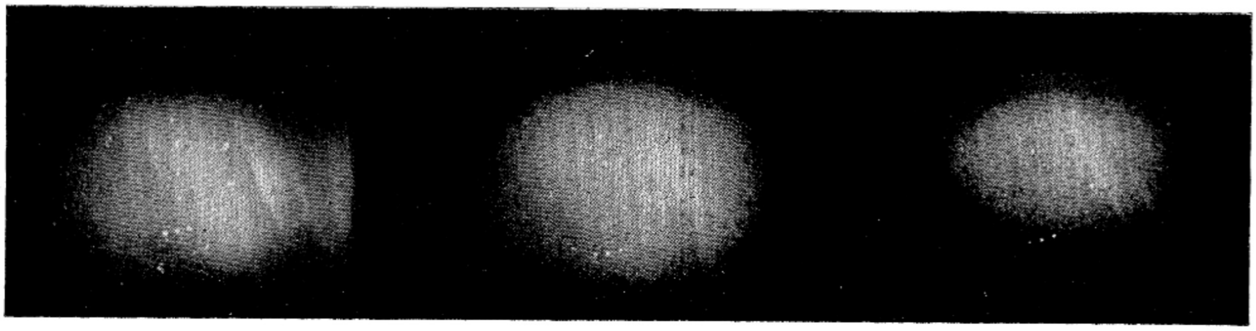

Fig. 29

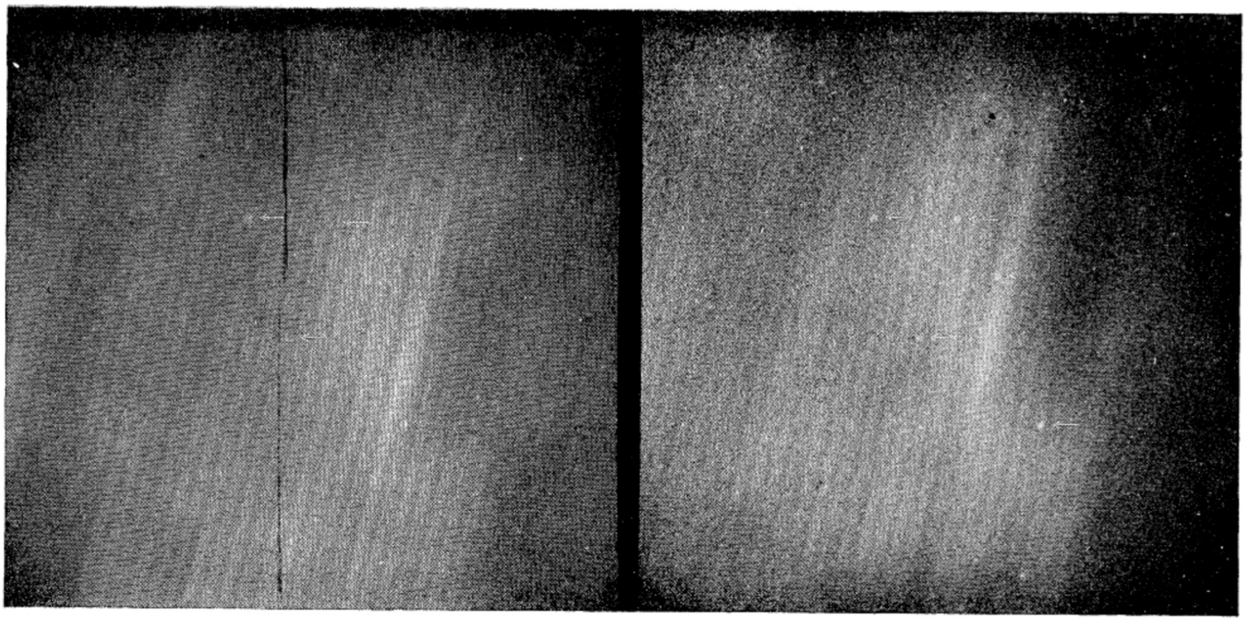

Fig. 30

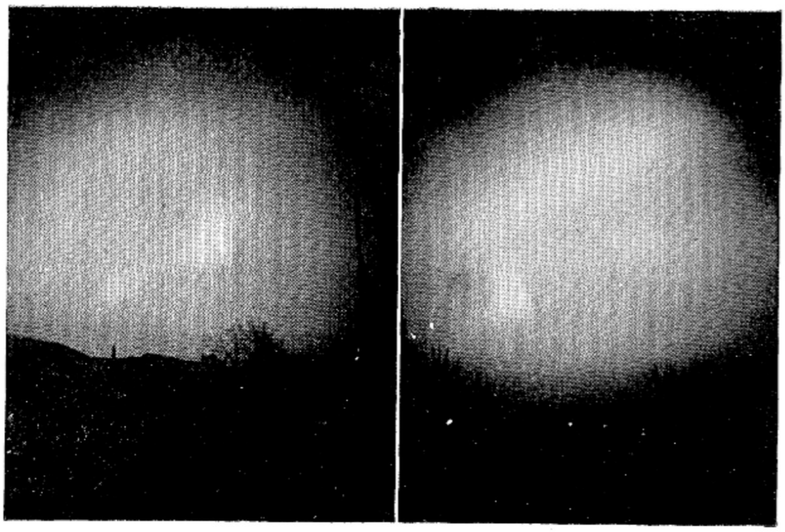

Fig. 31

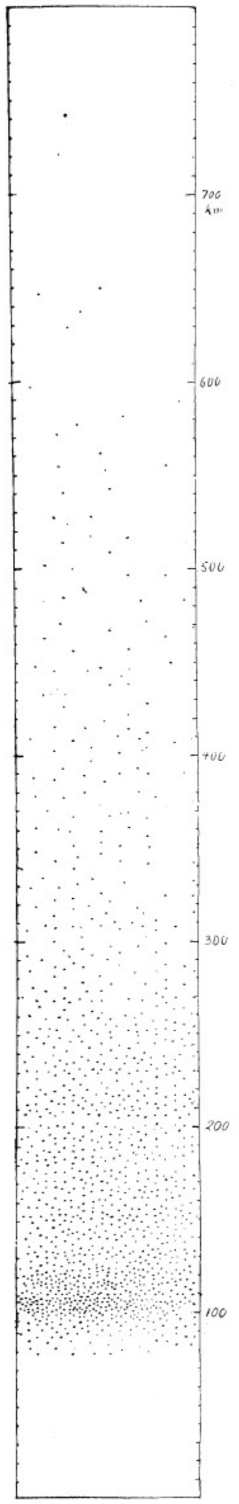

Fig 32

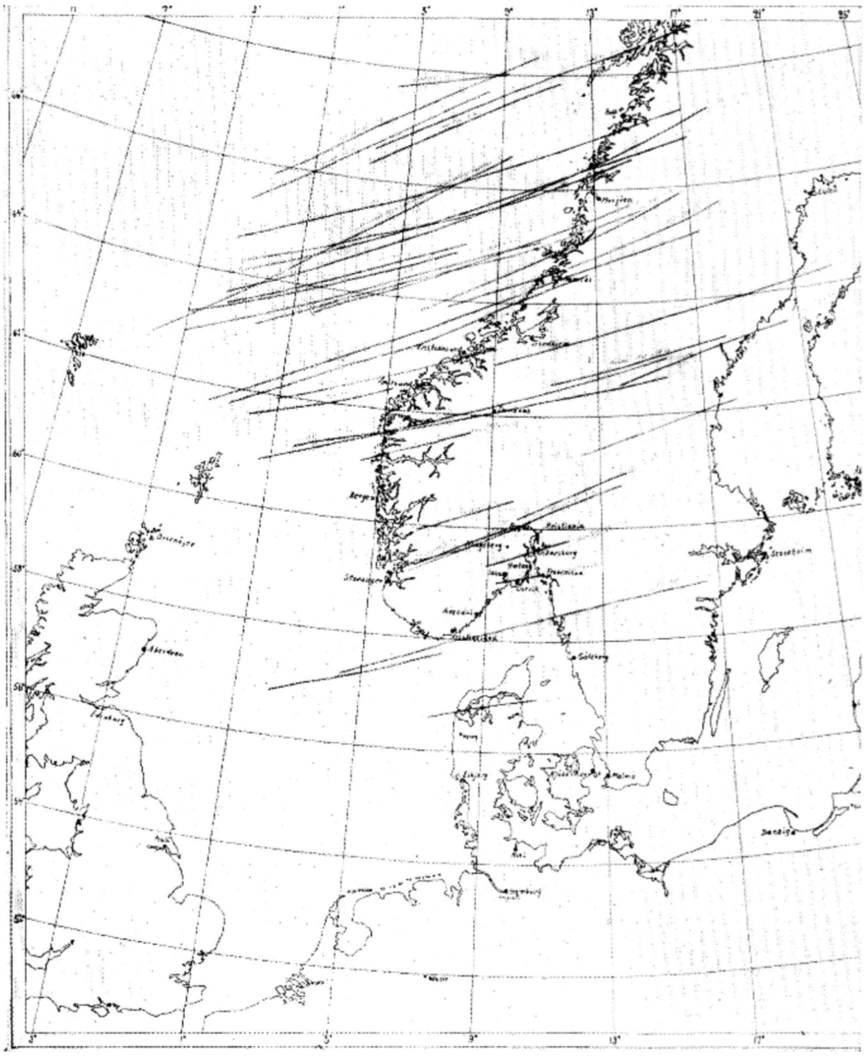

Fig. 33