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Photographic Investigation of Flame Movements in Gaseous Explosions. Parts IV, V, and VI

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X. *Photographic Investigation of Flame Movements in Gaseous Explosions. Parts IV, V, and VI.*

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[Plates 13–20.]

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Contents.

Introduction.

In Part III of our previous memoir* upon " Flame Movements in Carbonic Oxide-Oxygen Explosions " experiments were described showing certain effects of superimposed " shock waves " upon flame-velocities up to the development of detonation in such explosions. Also the phenomenon of " spin " in the detonation of carbonic oxide-oxygen mixtures, first observed in 1926 by C. Campbell and D. W. Woodhead, was illustrated, but its further discussion deferred pending the accumulation of more experimental evidence.

In reviewing the experiments in ' Nature '† the late Professor H. B. Dixon said they had revealed how shock waves catching up an accelerating flame, and *vice versa*, may impose a succession of " uniform movements " upon it, and how such waves ahead of the flame may set up " detonation " in explosions, a point of which, though formerly he had doubted, he had now been quite convinced.

In conversations and correspondence which we had with him on the subject up to shortly before his death in September, 1930, Dixon repeatedly urged upon us the importance of continuing the investigation because of its having shown the necessity of some revision in the classic conception of detonation. Accordingly, having considerably

* ' Phil. Trans.,' A, vol. 228, pp. 223–234 (1929).

† ' Nature,' vol. 124, p. 580 (1929).

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advanced our experimental studies since the publication of our previous memoir, we propose describing in this one a selection of the further photographic evidence now available.

Ever since MALLARD and LE CHATELIER'S researches fifty years ago upon the development of gaseous explosions, it has been generally supposed that the initial phase of "slow uniform movement" and the final attainment of "detonation" represent two fundamentally different modes of flame propagation, *i.e.*, the former by conduction of heat between the burning and the unburnt medium, and the latter by adiabatic compression due to the propagation of a shock wave through the medium.

With regard to the initial phase, which is supposed to be exemplified by a "weak" mixture ignited near the *open* end of a horizontal tube,* while undoubtedly "conduction" plays an important and often predominant part, other factors, such as expansion of the hot combustion products, convection currents and the intensity of the source of ignition, also come into operation according to circumstance. Indeed with "strong" mixtures —*i.e.*, those well removed from one or other of the limits of the "inflammable range" of a given combustible gas and air (or oxygen)—it not infrequently happens either that the velocity of the initial "uniform slow movement" in a particular case at given temperature and pressure may vary with circumstances (*e.g.*, the intensity of ignition) or in some cases (especially oxygen mixtures) it may be of such brief duration as to be practically non-existent. It can scarcely now be regarded as "constant" for a particular mixture at given temperature and pressure, and is empirical only, having no fundamental significance.

Except perhaps with the "weakest" mixtures, the initial uniform flame movement is soon rapidly accelerated (sometimes becoming "vibratory" also) until, with sufficiently "strong" mixtures, detonation is set up. And it seems probable that, as H. B. DIXON first demonstrated, detonation is distinguishable from the initial phase of an explosion not merely by a much faster propagation of ignition but also by a much more intensive combustion in the flame front. Indeed there is now much evidence for supposing that, while during the initial uniform movement only a relatively small portion of the explosive medium is burnt in the flame front itself, the opposite occurs in detonation.

DIXON'S researches also showed that on an explosive mixture being ignited by an electric spark, the suddenly inflamed gases expand causing a "compression wave" to be transmitted through the medium in all directions; also that, apart from any combustion so initiated, the mere passage of the spark itself sets up such a wave. And many of the beautiful explosion photographs which he published in 1903† showed how potent is the influence of such "compression waves" in accelerating both flame speeds and combustion.

For purposes of exposition, it is sometimes convenient to distinguish between explosion

* See, however, observations made on pp. 368 and 369 in connection with Photograph No. 1 herein.

† 'Phil. Trans.,' A, vol. 200, pp. 315–352 (1903).

flames according as they are travelling through a medium with velocities *less* or *greater* than those of compression waves that may have been produced in it. And it should be remembered that when such waves are initiated by " detonators " their speed usually exceeds greatly that of sound in the medium. And, as will be seen from some of the photographs included herein, there is a practical difference according as an advancing flame is either overtaking, or being overtaken by, a compression wave that may be simultaneously travelling through the medium.

Another material point which most observers are now agreed upon is that " compression waves " may and do originate automatically either in, or just behind, the flame front of a burning medium whenever anything occurs to enhance its chemical activity. Otherwise it would be difficult to account for the continuous rapid acceleration of the flame front between the initial phase of " uniform slow movement " and the final phase of " detonation " which has been demonstrated in cases where special precautions have been taken to exclude the influences of extraneous " compression waves." From this point of view, the possibility of continuous auto-acceleration is inherent from the outset in all explosion flames, and is soon manifested in " strong " mixtures.

As already stated, although it had long been doubted whether detonation could be set up in a sufficiently explosive medium by invisible " shock waves " ahead of the flame itself—and as recently as 1928 Dr. W. PAYMAN published experiments from which he concluded that, with the mixtures and conditions employed, the detonation wave always appears to have its origin behind the flame front*—our former experiments (1929) had proved such " ignitions ahead " of the flame to be possible ; and as those described herein show it to be by no means an unusual occurrence, the issue may now be regarded as definitely decided in the affirmative. Also, in other directions, our experiments have elucidated the influence of shock waves upon flame movements generally, as well as the character of the " predetonation " stage and the phenomena associated with " spin " in detonation.

The Photographs.—It should be understood that all the photographs included in this memoir have been obtained by the Fraser High Speed Photographic Machines, specially designed for this work, and fully described in our previous memoir† (*q.v.*). In the smaller of the two machines the drum is capable of giving any desired constant vertical film speed up to a 100, and in the larger machine up to 200 metres per second, and both of them have been used in these further experiments.

In interpreting the photographs it should be remembered that, in each case, while the film was moving vertically with some known constant velocity the flame was travelling horizontally along a glass tube (closed at the firing end—but open at the other) so that the graph traced by the flame was the resultant of the two velocities. Time is represented by length, and the portion of the tube photographed (usually about 1·5 metres) by width, in the photographs. In many cases the tracks of invisible " shock "

* ' Proc. Roy. Soc.,' A, vol. 120, pp. 90–109 (1928).

† *Loc. cit.*, pp. 198 to 201.

or "compression" waves are indicated thereon by white (continuous or dotted) lines and arrows. Each photograph has been selected from some hundreds obtained during the research because of its showing some typical characteristic movement or behaviour of flame during a particular phase of a gaseous explosion. The dark lines running lengthwise in each are due to a series of reference marks at regular intervals of 20 centimetres along the outside of the glass tube. A time-scale in milliseconds is also shown in each case.

General Procedure.—Except where otherwise stated, the explosive medium used in Parts IV or V was always a $2CO + O_2$ mixture saturated with water vapour at room temperature (18 to 20° C.); it was chosen, not only on account of the high actinic properties of its flame, but also because of the comparatively moderate speed of its initial flame movements, both of which features make it an ideal medium for our purpose. The normal velocity of its initial flame movements when ignited by the application of a small gas flame at the open end of a tube of the same internal diameter as those used in our experiments is *circa* 2·2 metres per sec. In Part VI various other media were also employed as will be indicated in the text.

In all experiments the explosive medium was fired at room temperature and barometric pressure either at or towards the closed end of a tube of stated length and internal diameter, the other end being open to the atmosphere both at the moment of firing and during the subsequent explosion. As the apparatus and firing arrangements often had to be varied from one experiment to another, so as to ensure the desired changes in the experimental conditions, it will be necessary to indicate these diagrammatically in connection with the text. It should be understood that special precautions were always taken to ensure the utmost uniformity throughout in the internal diameter of the explosion tubes employed; also, whenever it was necessary to build up an explosion tube in sections joints between two glass sections were always effected with the greatest possible accuracy by grinding the two surfaces flat till they fitted together quite truly, and securing the joint by an external brass sleeve cemented "vacuum-tight" on to the outer wall of the glass tubing. Joints between metal and glass sections were made by other special devices which ensured the same perfect tightness and uniformity of tube diameter.

The following symbols will be used in the tables and text :—

S_1, S_2, etc.—Flame speeds in metres per second, up to "detonation."
V_d = forward flame speed, in metres per second, in detonation.
W_1, W_2, etc. = compression or shock waves.
S_{w1}, S_{w2} = speeds in metres per second of compression or shock waves.
t = time in seconds, or milliseconds, as stated.
l_1 = total length of explosion tube employed.
l_2 = length of tube actually photographed.
d_a, d_b, etc. = "detonators" of graded strength.

Part IV.—*The Effects of Shock Waves from Detonators upon the Movements of Explosion Flames.*

[Plates 13–15.]

Although an explosive mixture is usually ignited by either an electric spark or a steady gas flame, the firing in it of a "fuse head" or "detonator" will do equally well. A "fuse head" consists of some suitable explosive "igniting" composition in which insulated firing wires are embedded, and which on electrical ignition merely gives a spurt of flame with very little noise. In a "detonator" such a "fuse head" is encased in a layer of some detonating material which on ignition gives a large volume of flame accompanied by an intense "shock wave." The initial velocity of such a "shock wave" exceeds that of sound in the medium in different ratios according to the strength of the "detonator" employed; but afterwards it diminishes, and with a long enough run would eventually fall to that of sound in the medium. In the present experiments both "fuse heads" and "detonators" of increasing strength (d_a, d_b, d_c, etc.), all of which were made for us by Messrs. Nobels Explosives, Limited, were employed for the purpose. They were compound detonators containing tetryl as the main charge with an initiating charge of lead azide, and a small top charge of lead styphnate, for igniting and binding purposes, respectively.

The "detonators" were also used to initiate a "shock wave" in a zone of inert gas (nitrogen) behind where the explosive medium itself was simultaneously ignited by an electric spark, in such wise as to cause the resultant flame to be followed and eventually overtaken by the "shock wave."

A typical selection from many experiments made under such conditions will now be described, in conjunction with the relative photographs. All of them were made in an explosion tube of 1·3 cm. internal diameter, but of varying length according to circumstances; the arrangements in each particular experiment are shown in figs. 1 to 4 inclusive.

No. 1.—In this "control" experiment of the series, the object of which was to show the normal development of flame in the medium uncomplicated by "compression waves," ignition was effected by a condenser discharge (0·0065 m.f. at 10,000 volts = 0·325 Joule) at a point only 0·5 cm. from the closed end of the explosion tube (see fig. 1), the other end being open; $l_1 = 1 \cdot 5$ metres, practically the whole of which was photographed. Any compression wave set up by the spark would thus pass through and out of the explosive medium far ahead of the much more slowly moving flame. The photograph shows that the latter started off with a nearly uniform S_1 of 30 metres per sec., which was maintained for a distance of about 0·4 metre. Then a phase of continuous and non-vibratory acceleration set in, which doubtless would have culminated in detonation had the tube been long enough. This phase was marked by a continuous increase in the luminosity of the flame whose velocity had reached 560 metres per sec. after a total run of 1·4 metres. There was no evidence in the photograph of any movement *en masse* of the medium during the initial "uniform" movement as the flame passed through it.

Another noteworthy feature is that the initial uniform flame speed of 30 metres per second was some 13 times greater than it would have been had the end of the tube

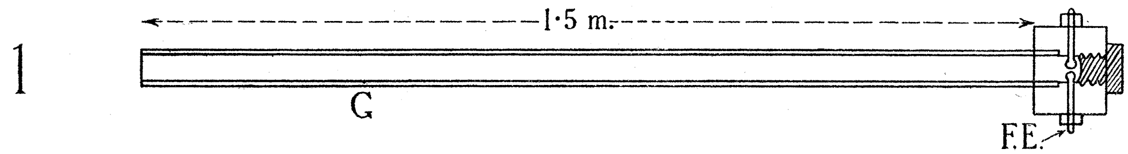


Fig. 1.

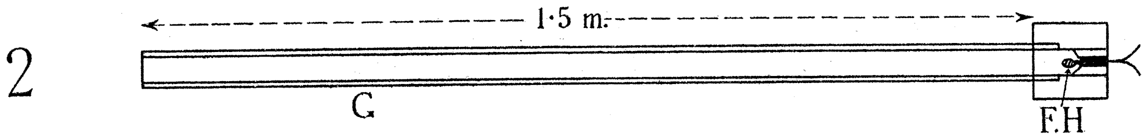


Fig. 2.

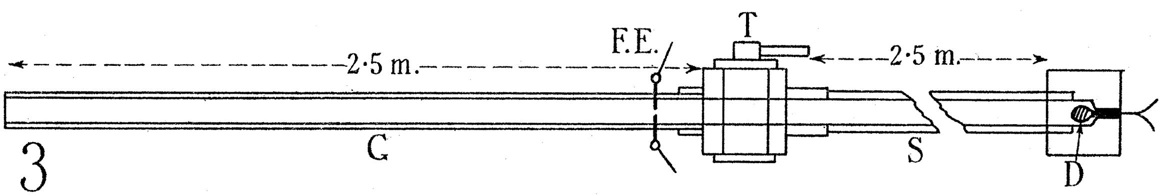


Fig. 3.

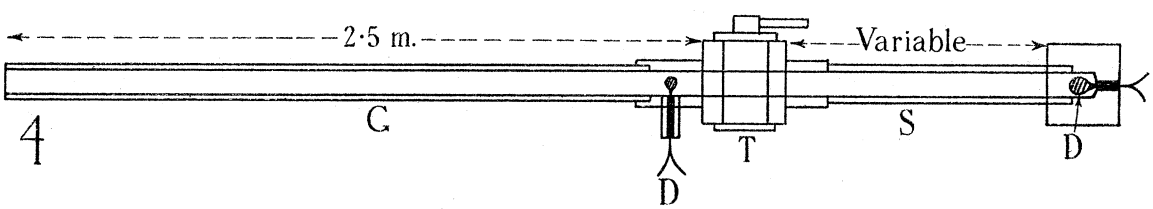


Fig. 4.

D = Detonator. G = Glass tube. F.E. = Firing electrodes. F.H = Fuse head. S = Steel tube. T = Tap.

adjacent to the source of ignition been open, so as to allow of the hot expanding products of combustion escaping therefrom. Indeed from the photograph it will be seen that not only did the whole column of gas remain practically stationary in the tube but also an equally stationary layer of it remained luminous in the neighbourhood of the igniting spark, throughout the experiment. And it seems likely that the initial flame speed observed in such conditions represents more truly the initial uniform speed "by conduction" than does that observed in a similar tube open at one end, when ignition is effected thereat. For in the latter circumstance, the speed measurement must always be affected to some extent by the escape of hot products from the open end.

No. 2.—In this experiment ignition was effected by a "fuse head" 0·5 cm. from the closed end of the tube (fig. 2) of $l_1 = 1 \cdot 5$ metres. The initial velocity S_w, of the compression wave sent out by the initiator was between 400 and 500 metres per sec. The flame itself started off with a S_1 of 500, gradually increasing to 650 metres per sec. during the first 0·8 metre run, after which a rapid acceleration and increase in luminosity abruptly set in. By the time the flame had reached the end of the tube, its speed had attained 1,700 metres per sec., or nearly that of detonation, without its ever having been overtaken by the following compression wave, whose velocity was always less than its own.

No. 3.—In this experiment ($l = 1 \cdot 5$ metres) ignition was effected, at the same point as before, by a "detonator" d_b, the compression wave from which had an initial velocity S_w, of 800, thereafter falling to about 600, metres per sec. The flame started off with S_1 between 700 and 800, which was soon accelerated fairly uniformly up to 1,040 metres per sec. by the time the flame had reached the other end of the tube.

No. 4.—In this and following experiment, ignition was effected (see fig. 3) by the minimum requisite high-tension spark at a point 2·5 metres from the closed end of the tube, a "detonator" d_b being simultaneously fired at a point right up against the closed end, the intervening space being filled with nitrogen, and the tap (of same bore as the tube) separating the latter from the explosion medium being opened just before firing. By this device, a compression wave ($S_{w1} = 760$ metres per sec.) was set up by the detonator 2·5 metres behind the explosive medium. Total $l_1 = 2 \cdot 5$ metres, of which only 1·5 metres were photographed.

A feebly luminous flame started off from the igniting spark with a uniform S_1 of 38·6 metres per sec., but after about 3·3 millisecs. it was overtaken, and its velocity abruptly accelerated to $S_2 = 308$ metres per sec., by the compression wave which, after passing through the flame, emerged from the front thereof at a point about 0·2 metres from the firing point, and continued ahead of the flame along an invisible track indicated in the photograph by the white dotted line. Meanwhile the flame, following hard after it, with further rapid self-acceleration, soon all but overtook it, after a total run of about 1·2 metres, whereupon an ignition occurred at a point in the track of the compression wave a little (4·25 cm.) ahead of the flame, whereby "detonation" was set up, a strong "retonation wave" being sent back through the incandescent medium at the coalescence of the two flames.

In this connection it should be stated that our experiments have also shown that, speaking generally, (1) the faster such a flame is travelling at the time of its being overtaken by a shock wave of given intensity, the smaller is the ratio of the flame-velocity change effected, and (2) the faster the velocity of the overtaking shock wave, the greater the ratio (S_2/S_1) of the sudden velocity change effected in an explosion flame of given velocity. Thus, for example, in different experiments, the following have been found :—

S_1 Explosion Flame when overtaken.	S_w Overtaking Shock Wave.	S_2 Explosion Flame.	S_2/S_1
Metres per sec.	Metres per sec.	Metres per sec.	
82·0	790	283	3·4
38·6	760	305	7·9
34·2	845	438	12·9
33·4	920	493	14·7

No. 5.—In this experiment the explosion initiated by the spark-ignition was followed by two shock waves from two detonators d_a and d_b simultaneously fired in nitrogen at points 3·3 and 2·5 metres respectively, behind the point of ignition of the explosive medium. In the resulting photograph these two shock waves are seen (i) passing through the burning medium about 0·45 metre from the firing point with velocities of 1,072 and 920 metres per sec., respectively, (ii) then, after emerging from the flame front, continuing for some distance (see white dotted lines) ahead of the flame with velocities of 482 and 442 metres per sec. respectively, and (iii) finally, being overtaken by the accelerated flame, " detonation " being thereby set up on its overtaking the second of them, after a total run of 1·3 metres, and at each such overtaking a " retonation wave " was sent back through the incandescent medium behind the flame front.

No. 6.—In this experiment, the explosive medium was ignited by a detonator d_a, the conditions being so arranged (see fig. 4) that *precisely at the moment of ignition* the so initiated flame was struck by a powerful shock wave, travelling with a velocity of *circa* 1,000 metres per sec. from another detonator d_d, whereupon " detonation " was instantly set up with a velocity of 1,780 metres per sec. The " banded " appearance of the detonation flame, due to its helical motion of frequency, $f = 49{,}000$ per sec., after a run of 0·4 metre is well shown in the photograph.

Nos. 7 *and* 8.—These two experiments were repetitions of No. 6, *except* it was so arranged that the overtaking "shock wave" from the second detonator d_d arrived at the ignition point in No. 7 a small fraction of a second later, but in No. 8 a small fraction of a second sooner, than the instant of ignition of the explosive medium by the first detonator d_a. From the resulting photographs it will be seen that whereas (i) in No. 7, the setting up of " detonation " at 0·45 metre beyond the firing point was merely delayed a little—the initial flame speed S_1 being 637, but a fraction of a second later being abruptly raised to 1,215 metres per sec. by the impact of the shock wave—(ii) in No. 8, the flame followed hard upon the " shock wave," $S_1' = 1{,}363$ metres per sec., without actually overtaking it, the two almost, but never quite, coalescing, causing a series of " ignitions ahead " without, however, actually setting up " detonation," the conditions established being those of the sensitive " pre-detonation " stage.

No. 9.—This experiment was a repetition of No. 6, so far as the exact synchronisation of impact of the shock wave and the ignition was concerned, the only difference being that electrolytic gas ($2H_2 + O_2$) was employed instead of moist $2CO + O_2$ as the explosive medium so as to show that the almost instant setting up of detonation in such circumstances is independent of the composition of the gaseous medium so long as it is sufficiently explosive. The initial velocity of the "detonation" at the instant of ignition set up in this case was 3,460 falling to 2,780 metres per second after a run of about 0·8 metres, and thereafter remaining constant. It may be mentioned that the normal rate of "detonation" found by the late H. B. Dixon for $2H_2 + O_2$ at 10° C. and 760 mm. in a tube 9 mm. internal diameter was 2,820 metres per sec.

Summary.—Speaking generally, this series of experiments, besides showing how potent are "shock waves" in abruptly accelerating the initial flame movements and ultimately setting up "detonation" in gaseous explosions, have now finally proved that detonation may be set up in a sufficiently explosive gaseous medium *at the instant of its ignition*, provided that the ignition is of sufficient intensity and the flame is simultaneously struck by a sufficiently powerful extraneous "shock wave," a result which recalls an observation published by Dr. W. Payman in 1928 that electrolytic gas may be detonated apparently instantaneously by firing it with a powerful detonator.* Also they show that, in cases where such a medium is ignited by a "detonator," the distance of flame run before "detonation" is set up seems to depend chiefly upon the ratio of the velocity of the initial flame speed to that of the invisible shock wave emitted by the detonator used, which ratio obviously varies with circumstances.

Part V.—*Auto-ignitions in the Compressed Medium ahead of the Flame during the Pre-detonation Phase of Gaseous Explosions.*

[Plates 15, 16.]

In our previous paper two instances were shown of "detonation" in a moist $2CO + O_2$ mixture having been initiated by an ignition of compressed gas well ahead of the advancing flame front, and one more such case has already been illustrated in the present paper. We are now, however, able to prove that during the pre-detonation stage of an explosion not only one but several successive such "ignitions ahead" may occur before detonation is set up.

We find that all such "auto-ignitions ahead of the flame" are conditioned by the close proximity of a flame front, moving with an intrinsic velocity greater than that of sound in the medium, to a shock wave moving ahead of it. They seem also to depend upon the effects of a pressure-gradient just ahead of the flame front *plus* radiant energy superimposed upon the pressure in the shock wave itself. One such auto-ignition does not necessarily set up "detonation," though in some cases it may do so. In other

* *Loc. cit.*, p. 109.

cases, a series of them may occur as the next two photographs (Nos. 10 and 11, Plates 15, 16) show :—

No. 10.—In this case the explosive medium had been ignited by a condenser discharge (0·08 m.f. at 15,000 volts), in a tube arranged similarly to that shown in fig. 4, the flame so initiated being followed by a shock wave from a detonator d_a similarly fired in nitrogen at a point about 5 cm. behind the electrodes. The total run from the igniting spark to the open end of the tube was 2·85 metres, the last metre of which was photographed. The flame front had passed the 1·8 metre mark, with a velocity of 900 metres per sec., preceded by two " shock waves " which had been sent out by the large igniting spark and the " detonator " respectively. From what has been already said in Section IV, it will be understood that these two " shock waves," which originally were following and afterwards overtook the flame front, were now travelling ahead of and were being overtaken by it. Indeed on reaching the 2 metre mark the flame front was just 7·3 cm. behind the rear-most shock wave, whereupon the first auto-ignition ahead of the flame occurred as shown in the photograph. The newly born flame so initiated forthwith spread in both directions, with a velocity of 330 towards the old flame front, and of 885 metres per sec. away from it. There then ensued (i) a " head-on collision " between the old flame front travelling at about 900 and the new one meeting it with a velocity of 330 metres per sec., (ii) a " retonation wave " originating at the point of their collision, and passing backwards through the incandescent medium with a velocity of 855 metres per sec., (iii) a corresponding wave, also originated by the collision, in a forward direction coalescing with and accelerating the old movement, (iv) the last-named wave speedily overtook the new flame front, travelling forward with a velocity of 885, with the result that the latter was rapidly accelerated to 1,460 metres per sec. at which speed it continued to move forward until, shortly after passing the 2·4 metres mark, it was just 3·4 cm. behind the first of the two shock waves referred to. Whereupon a second ignition ahead of the medium ensued, in consequence of which " detonation " was set up at an initial velocity of 1,940, and a second " retonation " wave was sent back through the incandescent medium with a velocity of 890 metres per sec.

No. 11.—Is a similar photograph, obtained on repeating the previous experiment in the same apparatus with, however, the difference that the explosion was initiated by a " fuse head," and the resulting flame followed up by two shock waves from a second fuse head and a detonator d_a, respectively. The flame front is shown passing the 1·0 metre mark on the tube with a velocity of 950 metres per sec., and at this point is being preceded by three shock waves originated by the two " fuse heads " and the " detonator " respectively. Subsequently, as it overtook these in succession, three " auto-ignitions " ahead took place causing successive stepping up of the flame speed to 1,210, 1,320 and 1,960 metres per second, respectively, with corresponding " retonation waves." The final step up of the flame speed produced " detonation."

Abnormally High Initial Flame Speeds in Detonation.—A feature of general interest in connection with this part of our investigation is the cumulative evidence that, whenever detonation is established in a gaseous explosive medium, its initial speed exceeds, at least for something like 0·25 millisec., the normal speed which is afterwards established after a run usually of 0·5 metre or thereabouts. This normal speed, while constant for a particular explosive medium under given experimental conditions, may, and often does, vary somewhat with the internal diameter of the tube, as well as with temperature and pressure. A case in point is that of carbonic-oxide-oxygen detonating mixtures, as shown in one of our recent papers.*

The evidence referred to may be summarised in the following tabulated data comprising (1) the initial abnormally fast and (2) the corresponding normal and constant rates of detonation so far observed in our experiments for a number of different explosive media in a tube 1·3 cm. internal diameter at 18° C. and barometric pressure :—

Explosive Medium.	Observed Rates of Detonation. Metres per sec. (1) Initial and Transitory.	(2) Normal and Constant.
(i) $2CO + O_2$ (moist)	2,090 2,175	1,750 1,760
(ii) $2H_2 + O_2$	3,185 3,100 3,460 3,370	2,820 2,790 2,780 2,790
(iii) $2CO + 4H_2 + 3O_2$	3,880	2,390
(iv) $H_2 + 2N_2O$	2,590	2,200
(v) $2H_2S + 3O_2$	2,120 2,200	1,946 1,930
(vi) $C_2N_2 + O_2$	3,310	2,760
(vii) $C_2H_2 + 2NO$	3,350	2,740

Nos. 12 *and* 13.—These two photographs, relating to the setting up of detonation in $2CO + 4H_2 + 3O_2$ and $C_2N_2 + O_2$ mixtures, respectively, are included as showing how clearly the camera brings out the last-named feature of a gaseous explosion. In each case it will be seen that immediately upon the setting up of "detonation," and for a distance of about 60 cms. thereafter, the flame speed was momentarily higher than the constant value which soon afterwards was established.

Part VI.—*The Phenomenon of "Spin" in Detonation.*

[Plates 16–20.]

In Part III hereof,† attention was directed to the remarkable "banded" appearance of a photograph of a detonation flame moving horizontally through a moist $2CO + O_2$

* 'Proc. Roy. Soc.,' A, vol. 130, pp. 524–551 (1931).

† 'Phil. Trans.,' A, vol. 222, pp. 223–234 (1929).

medium when taken upon a vertically moving film. It was first observed in 1926 by C. Campbell and D. W. Woodhead, working in the late H. B. Dixon's laboratory in Manchester,* and subsequently it was confirmed by ourselves.

In 1927 Campbell and Woodhead published a further paper† in which it was said that the appearance in question is exhibited by the detonation flames, not only of *all* carbonic-oxide-oxygen mixtures, but also of certain mixtures of oxygen with methane, ethane, ethylene, carbon disulphide and cyanogen respectively, although those of carbonic-oxide-hydrogen-oxygen media with H_2-contents exceeding about 6 per cent. do not show it. Also, with moist $2CO + O_2$ detonations, they showed that, although the pitch of the " undulations " causing the banded appearance varied with the internal diameter of the tube, the ratio between them (L/D) for diameters between 8 and 15 mm. was constant and nearly equal to 3·0, the frequency being of the order of 40,000 per second.

In a third paper of the series,‡ C. Campbell and A. C. Finch adduced evidence satisfying them that (i) the said banded appearance is not caused by vibrations in the explosion tube, but by a helical rotation of the flame itself, sometimes " clockwise " and at other times " counter-clockwise " in respect of the forward movement of the flame front, and (ii) such rotation applies not only to a luminous " head " of detonation in the flame front, but also to a long luminous tail lying close to the wall of the tube, and rotating with a frequency almost identical with that of the " head," but diminishing slightly as the distance therefrom increases.

It should be noted that while considering the rotation in question as one of the gaseous medium as a whole—the peripheral velocity of which is approximately constant for one and the same explosive medium at a given temperature and pressure in tubes of different diameters—Campbell and Finch admitted that it is " not yet clear how such rotation is initiated, or whether the absence of striæ (*i.e.*, bands) when certain given mixtures are employed is due to the absence of rotation or the predominance of other factors."

Although our own previous observations upon the phenomenon—as exhibited by moist $2CO + O_2$ detonations in tubes of 12·5 mm. bore in which the flame front was advancing with a velocity of 2,090 metres per sec. and the frequency of the bands was about 54,000 in the flame front, but gradually slowing down to about 49,000 per sec. at a distance of 140 cm. behind it—generally harmonised with the supposition of a highly luminous rotating local " head " of detonation with a similarly rotating " tail " behind it—probably due to intensively ionised gases interacting—it scarcely seemed credible that the whole mass of the gaseous medium, both in the flame front and for at least a metre behind it, could be rotating with a peripheral speed of something like 2,000 metres per second.

Hence it seemed desirable that the matter should be further investigated with the

* ' J. Chem. Soc.,' 1926, p. 3010.

† *Ibid.*, 1927, p. 1572.

‡ ' J. Chem. Soc.,' 1928, p. 2094.

aid of the much greater analysing power of our Fraser High Speed Camera, which (as will be seen later) already enables us to measure frequencies up to 300,000 per second. Accordingly it was decided to undertake a more systematic investigation, and the selection of photographs included herein illustrates the principal results thereof to date.

Some Mathematical Considerations.

In order that the mathematical aspects of the problem should receive due consideration, we sought the help of Professor H. Levy, who very kindly consented, and we desire to acknowledge our great obligation to him in the matter. At some future time, when the experimental work has been still further developed, he will embody his considered views in a separate communication; meanwhile the following brief provisional statement may serve to indicate the possibilities as they appear at this stage of the enquiry.

(i) In the first place, it seemed possible that the spiralling effects observed in the flame, and which give rise to the banded appearance referred to, might be due to vibrations caused by compression waves in the explosion tube itself, especially as the speed at which they would be transmitted along the tube so as to set up spiral lines of constant pressure in the enclosed gaseous media, seemed to be of the right order. Moreover, it was observed in one experiment when the glass tube was shattered on detonation being set up in a $C_2N_2 + O_2$ medium, the fractures had followed a spiral track, as shown in photograph No. 34. This possibility was finally ruled out, however, by the results of an experiment (Photograph No. 27) in which a plasticine junction between two glass sections of the tube along which the detonation of a $2CO + O_2$ medium had passed made no difference to the pitch or intensity of the spiral movement in the flame.

(ii) Secondly, in considering the actual propagation of the flame through the gaseous medium, it would appear necessary to distinguish between the speed at which the flame traverses its particular path—a speed which presumably is largely bound up with the chemical interactions therein—and the actual path selected; it is, of course, possible that the two questions are intimately connected. In the initial stages of an explosion the gaseous medium is undoubtedly moved forward along the direction of the tube axis, probably with considerable rotation about it. This forward impulsive motion would set up rotation about lines which may roughly be described as circles on planes perpendicular to the axis, and with centres approximately on it. And if this were superposed on an axial rotation, a spiral vortex system—*i.e.*, rotations of the gas about lines winding helically down the tube—would be initiated. The determination of whether such a system would develop into a stable vortex system is a mathematical problem of no mean order which, though capable of solution, would involve considerable further investigation. It would seem, however, that the establishment of such a system would require a much longer time than that actually involved in such an explosion; hence it is scarcely likely that such a system could be a predominating factor in determining the observed spiral path of the flame *after* "detonation" has been established, though it may operate before. Moreover, the high temperature in the "nose" of the flame would probably considerably modify any such arrangement.

(iii) Thirdly, the combustion in the flame, being a chemical reaction involving rapid evolution of heat, entails the passage of a rapid agitation of molecules through the gaseous medium, corresponding very closely with the head of a "wave." Such a "wave" will change shape as it passes along the tube; but whether, starting with a disturbance along the axis, it would change to a spiral wave-front is not easily established, though it is quite possible. If, however, such were the case, combustion would travel along a spiral path at a speed corresponding with the wave-speed of the combustion in the flame front; and in such event, the medium would not be moving spirally as a whole, but a wave front would travel spiral-wise down the tube at the flame speed. This view of the matter (if true) would seem capable of accounting for the facts so far observed, the banded appearance of the "tail" being ascribable to periodic waves along itself.

Experimental.

Before describing in order the relative flame photographs, it will be convenient now broadly to summarise the principal experimental results obtained to date, since this will help the reader to understand the meaning of the photographs which invite his study in detail.

Apparatus.—In all essentials the apparatus employed was similar to that already described in Part IV, but from time to time modifications were introduced for special purposes, which need not be detailed. The explosions were all carried out at room temperature (*i.e.*, about 18° C.) and the prevailing barometric pressure.

(1) Although (*a*) a sinuous flame front, associated with a pronounced "banded" appearance of the luminous medium for some distance behind it, has always been observed in all photographs of detonations in $CO - O_2$, $CO + N_2O$, $CH_4 + O_2$, C_5H_{12}-air, $9C_2H_2 + O_2$ and undiluted acetylene media, and the phenomena causing them persists so long as detonation continues (*vide* Photographs Nos. 14 to 16 inclusive), (*b*) in other cases (*vide* Photographs Nos. 17 to 19 inclusive)—such, for example, as detonations in $C_2H_2 + O_2$, $C_2H_2 + 2NO$, $C_2H_2 + N_2O$, $C_2H_4 + O_2$, $C_2N_2 + O_2$, $C_2N_2 + 2O_2$, $C_2N_2 + O_2 + 2Ar$, $2H_2 + O_2$, $H_2 + 2N_2O$, $2CO + H_2 + 1\frac{1}{2}O_2$ and $2CO + 4H_2 + 1\frac{1}{2}O_2$ media—while a "banded" appearance is visible in the flame photograph at or near the initiation of detonation, it does not persist long afterwards, and is not associated with the sinuous flame front. It would thus appear that, while the phenomenon causing the "banded" appearance may, and usually does, come into play at or near the commencement of detonation in *all* media, in some it persists indefinitely, but in others it *either* does not

or the luminosity of the rotating " head " of detonation soon ceases to differ sufficiently in quality and/or intensity from that of the surrounding medium to produce any visible effect on the resulting flame photograph. Or it might also be that in the (*b*) cases the rapidity of the phenomenon concerned soon gets beyond the analysing power of our present camera—although we think it rather unlikely.

(2) Detonations induced by " detonators " in undiluted endothermic media, such as acetylene or nitrous oxide, exhibit " spin " at the start, and for so long afterwards as a certain flame speed is maintained (*vide* Photographs Nos. 16, 28, 29 and 30).

(3) Compression waves produced by firing a " detonator " immediately after a detonation wave has passed through a combustible medium, and while it is still chemically " active," also cause " spin " with the associated " banded " appearance in the resulting photograph (*vide* Photograph No. 32).

(4) " Retonation waves," passing backwards through highly heated and still active or reactive products, also produce " spin " therein ; this is well shown by the case of a retonation wave passing backwards through the still reacting products behind the wave front of a $C_2N_2 + 2O_2$ detonation (Photograph No. 33), because here the reaction $C_2N_2 + 2O_2 = 2CO + O_2 + N_2$ concerned in the wave front was followed by the completion of combustion, $2CO + O_2 + N_2 = 2CO_2 + N_2$, behind it.

(5) The hot gases discharged by the firing of a " detonator " in a tube may also exhibit signs of " spin," as illustrated in Photograph No. 31.

(6) The previous observation of CAMPBELL and WOODHEAD that the pitch of the helical undulation causing the persistent banded appearance of the detonation flame in a moist $2CO + O_2$ medium varies with the internal diameter of the tube, in such wise that the distance traversed per second by the luminous " head " of detonation along its helical path is constant, has been confirmed for tubes of circular cross section up to about 2·5 cms. internal diameter. In such circumstances, in both their experiments and ours, there is only a single rotating " head " of detonation, and the ratio of pitch/diameter (p/D) is very nearly 3·0, suggestive of π operating (*vide* Photographs Nos. 14 and 20). When, however, the internal diameter of the tube much exceeds 2·5 cms., two or more rotating " heads " of detonation may occur in the $2CO + O_2$ medium, in which case the aforesaid p/D ratio no longer holds (*vide* Photograph No. 21).

In this connection it should perhaps be mentioned that in all cases so far examined, where the " spin " is persistent and the sinuous flame front has a single rotating luminous " head " of detonation, it has been found that the helical velocity of the latter is approximately of the same order, irrespective either of the composition of the medium or of the tube diameter. Thus, for example, in a moist $2CO + O_2$ medium it has been found to be approximately 2,550, in a $3CO + O_2$ medium 2,600, in a $CO + N_2O$ medium 2,500, and in a pure acetylene medium between 2,600 and 2,700 metres per sec.

This suggests that possibly in such cases the really significant thing about the speed of detonation in a tube is the helical velocity of the " head " of detonation rather than the forward velocity of the flame front. It would, however, be premature to draw such a conclusion from the cases so far examined, and therefore the matter is reserved for further investigation.

(7) In detonations of a $CH_4 + O_2$ medium in a tube of circular section of 1·3 cms. internal diameter, three different rotation-frequencies of 68,000, 110,000 and 221,000 per second, respectively, have been observed at different times (*vide* Photographs Nos. 22, 15 and 23); and in one experiment all three frequencies were observed alternating, as though there were two or three "heads" of detonation of approximately equal helical frequencies moving simultaneously forward in the flame front but rotationally in and out of phase (*vide* Photograph No. 24). Something similar apparently happened also in $2CO + O_2$ detonations in a fairly wide tube, *e.g.*, 4·1 cms. internal diameter (Photograph No. 21), as well as in a $CO + N_2O$ detonation (*vide* Photograph No. 25).

(8) Although in explosions of most media a helically rotating "head" of combustion is not visible in the resulting photographs before detonation has set in, it has been seen in $CH_4 + O_2$, $C_2N_2 + 2O_2$, and $2H_2 + 2N_2O$ explosions just before its occurrence (*vide* Photographs Nos. 22 and 33).

(9) The present experimental evidence as a whole leads to the conclusion that "spin" in gaseous detonation does not depend primarily upon such factors as the density of the gaseous medium, the speed of detonation in it, or its chemical composition. These, however, are points which are being further examined by us.

(10) In one series of experiments with a moist $2CO + O_2$ medium, in which the glass explosion tube of 1·2 cm. internal diameter had been drawn with a longitudinal glass "ridge" along its whole length, and projecting 1 mm. into it, neither the speed nor the frequency of the helical motion of the luminous "head" and "tail" of detonation were at all affected thereby, the phenomena occurring precisely the same as in an ordinary tube of same internal diameter without such "ridge" (compare Photographs Nos. 20 and 26). Hence it is highly improbable that the "spin" causing the sinuous character of the flame front, and the banded appearance of the detonation flame behind it, can be due to a helical rotation of the gaseous medium as a whole.

(11) Any supposition that the "spin" is primarily due to some stationary wave system set up in the gaseous medium as the result of vibrations (due to distortions) along the explosion tube itself seemed disposed of when it was found that the insertion of a 2·5 cms. plasticine junction between two successive glass sections of the explosion tube had no effect whatsoever upon either the frequency or intensity of the phenomenon observed in a moist $2CO + O_2$ detonation (*vide* Photograph No. 27).

Taking the foregoing facts and circumstances as a whole, as constituting substantially the principal experimental evidence so far available, they seem to be consistent with Professor LEVY's third suggestion (*c*), namely, that the observed "spin" in detonation is due, not to the medium rotating as a whole, but to the "head" of detonation travelling spiral-wise as a wave-front through the medium in the tube at the observed flame speed, the banded appearance of the "tail" being ascribable to periodic waves along itself.

The Flame Photographs. (Plates 16–20.)

In describing individually the relevant flame photographs, the following additional symbols will be used :—

f = frequency per second of the phenomena causing the banded appearance of the flame ; p = pitch of its helical path in cms.

No. 14.—*Detonation in a moist* $2CO + O_2$ *Medium in a Tube of* 2·55 *cms. internal diameter.*

V_d = 1,795 metres per sec., p = 7·5 cms., f = 24,000. Forward speed of gaseous medium following the wave front = 1,175 metres per sec. This is an excellent example of the "spin" and its persistent uniformity in the medium in question. The observed extension of the banded appearance and luminosity behind the flame front was limited by the fracturing of the glass tube by the force of the explosion.

No. 15.—*Detonation in a* $CH_4 + O_2$ *Medium, in a Tube of* 1·3 *cms. internal diameter.*

V_d = 2,510 metres per sec., p = 2·26 cms., f = 110,000. This photograph also shows another "wave" following that of detonation with a velocity of 1,960 metres per sec. The initiation of detonation in this same explosion is shown in No. 22 (*q.v.*).

No. 16.—*Detonation in a pure undiluted Acetylene Medium in a Tube of* 2·55 *cms. internal diameter and* 2 *metres long.*

Detonation was initiated by firing a d_d detonator in the medium, and the photograph shows the flame travelling the first $1\frac{1}{2}$ metres from the firing-point. The initial forward speed of the flame was 2,135 metres per second which was maintained for a distance of about 0·5 metre, but it afterwards gradually diminished to 1,390 metres per sec. after a 1·2 metres run. The helical path of the "head" of detonation is well marked, and with the original V_d = 2,135 metres per sec., p = 10 cms. It should be observed that the pitch of the helical path increased as the forward velocity of the flame diminished; thus, when the forward flame speed had fallen to 1,390 metres per sec., p = approximately 20 cms., after which the "spin" disappeared. Carbon was deposited from the medium, owing to the endothermic decomposition $C_2H_2 = 2C + H_2$ resulting from the wave passing through it; and it was observed that such carbon-deposition was most dense along the helical path of the "head" of the wave.

No. 17.—*Initiation of Detonation in a* $2H_2 + O_2$ *Medium in a Tube of* 1·2 *cms. internal diameter.*

The initial V_d = 3,185, which speedily fell to a constant of 2,810 metres per sec. It should be noticed that although there is no sign in the photograph of a spinning "head of detonation," *i.e.*, of a sinuous wave front, a well-marked banded appearance, $f = 70{,}000$, is seen in the medium behind it; this, however, did not long persist after the initiation of detonation.

No. 18.—*Initiation of Detonation in a* $C_2H_2 + O_2$ *Medium in a Tube of* 1·5 *cms. internal diameter and* $1\frac{1}{2}$ *metres long.*

Here again, although $V_d = 2{,}850$ metres per second, and there is no sign of a spinning "head" of detonation, there is a well-marked "spin," $f = 53{,}000$, in the medium behind the wave front immediately after the initiation of detonation; the "spin," however, did not long persist.

No. 19.—*Initiation of Detonation in a* $2H_2S + 3O_2$ *Medium in a Tube of* 1·3 *cms. internal diameter and* $1\frac{1}{2}$ *metres long.*

This shows much the same features as Nos. 17 and 18; here, however, $V_d = 1{,}930$ metres per second, or not much faster than that observed in the moist $2CO + O_2$ medium (No. 1), while $f = 44{,}000$, or the same as observed persisting in a moist $2CO + O_2$ medium in a tube of same bore as that used in No. 20.

No. 20.—*Detonation in a moist* $2CO + O_2$ *Medium, in a Tube of* 1·3 *cms. internal diameter.*

Here $V_d = 1{,}750$ meters per sec., $p = 3 \cdot 95$, and $f = 44{,}400$. This photograph should be compared with Nos. 14 and 21 respectively, because whereas in Nos. 14 and 20, in each of which there was only a single spiralling "head" of detonation, the distance travelled by it per sec. along its helical path was nearly independent of the tube diameter, thus:—

Internal Diameter of Tube. D. cms.	V_d Metres per sec.	p cms.	p/D	f per sec.	Velocity along helical path. Metres per sec.
2·55	1,795	7·5	3·04	24,000	2,600
1·3	1,750	3·95	2·95	44,000	2,520

in No. 21, where the same medium was detonated in a tube of 4·1 cms. internal diameter, there were at least two spiralling "heads" of detonation, so that the foregoing relationship no longer held.

No. 21.—*Detonation in a Moist* $2CO + O_2$ *Medium in a Tube of* 4·1 *cms. internal diameter.*

Here $V_d = 1{,}825$ metres per sec., p apparently varying between 4·5 and 9·35 cms. (instead of the calculated 12·1 cms. for a single "head of detonation") owing to there being two or more spiralling "heads" of detonation (compare with Nos. 14 and 20).

No. 22.—Initiation of Detonation in a $CH_4 + O_2$ *Medium in a Tube of* 1·3 *cms. internal diameter.*

In this case the medium was ignited by a detonator d_b, and detonation was developed after the flame had travelled 1·4 metres. The flame in its "pre-detonation" stage is seen entering the field of view at the right-hand top corner of the photograph with a velocity of about 400 metres per second, and detonation was developed, after an ignition ahead, just before the flame passed out of the field of view. The chief interest of the photograph is that it shows most clearly the development of "spin" during the pre-detonation stage, when the flame had attained a speed of about 1,200 metres per second, which (from the evidence so far available) seems to be a lower critical speed for the occurrence of "spin" in the explosion of any medium. In this case $f = 68{,}000$ and $p = 2{\cdot}5$, which should be compared with the $f = 110{,}000$ and $p = 2{\cdot}26$ cms. in Photograph No. 15, relating to the further development of detonation in the same explosion as is shown at its initiation in No. 22 (*q.v.*).

Nos. 23 *and* 24.—*Detonations in a* $CH_4 + O_2$ *Medium in a Tube of* 1·3 *cms. internal diameter.*

Showing (*a*) in No. 23, the detonation flame after a 10 metres run, with a very rapid "spin," $f = 227{,}000$ and $p = 1{\cdot}13$ cms.; and, in No. 24, a similar detonation flame after 60 metres run, in which two different and alternating "spin" frequencies are clearly shown, presumably due to two spiralling heads of detonation moving in and out of phase. $V_d = 2{,}540$ metres per second.

No. 25.—*Detonation in a* $CO + N_2O$ *Medium in a Tube of* 1·28 *cms. internal diameter.*

Showing the detonation flame after a run of 5 metres. Here are also signs of two spiralling "heads" of detonation moving in and out of phase; when "in phase," $f = 44{,}000$, and $p = 3{\cdot}8$ cms. $V_d = 1{,}715$ metres per sec. Attention is also directed to the close approximation of these data to those for the corresponding $2CO + O_2$ detonation shown in No. 20 (*q.v.*).

No. 26.—*Detonation in a Moist* $2CO + O_2$ *Medium in a "Ribbed" Glass Tube of internal diameter* 1·3 *cms. having along its whole length a longitudinal "ridge" projecting* 1 *mm. into the medium.*

The point here to be noticed is that, as compared with No. 20 showing detonation in the same medium and tube diameter but without any "ridge," the presence of the latter made no difference as regards either the established frequency or the pitch of the single spiralling " head of detonation " ; thus :—

	f per sec.	p cm.	d_v metres per sec.
No. 20 *without ridge*	44,400	3·95	1,750
No. 26 *with ridge*	44,000	3·95	1,780

No. 27.—Detonation in a " moist " $2CO + O_2$ *Medium in a Tube* 1·21 *cms. internal diameter having a Plasticine Junction* 2·5 *cms. long, inserted between two successive glass sections, as shown by the wide black band in the photograph.*

The importance of this photograph lies in its showing that the insertion of such a junction had no measurable effect upon the single spiralling " head " of detonation, the values of $f = 46{,}000$ and $p = 3 \cdot 64$ cms. being the same before and after the flame had passed the junction.

Nos. 28 and 29.—Explosions induced by a " detonator " in an undiluted pure Acetylene Medium in a Tube of 1·4 *cms. internal diameter.*

These two photographs, which are shown joined together, relate to the first $4\frac{1}{2}$ metres run of a " detonation " induced by the explosion of a d_a " detonator " in a pure undiluted acetylene medium. It will be seen that " spin " ($p = 5 \cdot 69$ cms.) was well developed in the flame front after a 40 cms. run, the V_d at this point being 2,160 metres per second. And it continued until the forward flame-speed had fallen to about 1,470 metres per second. A very curious feature of this explosion, which is well shown in the photographs, is the subsequent occurrence of a non-luminous region between the highly luminous flame-front and the luminous carbon in its rear ; and it is now being further investigated by us.

No. 30.—Explosions initiated by a " detonator " in (*a*) *a* $4C_2N_2 + O_2$ *and* (*b*) *a* N_2O *Medium, respectively, in a Tube* 1·3 *cms. internal diameter.*

The interest of these two photographs lies in the fact of their both showing signs of a "spinning head" in the flame-front just before the latter ceased to be visible at forward flame-speeds of approximately 1,400 metres per second.

No. 31.—Bursting of a Detonator (d_c) *in Air in a Tube of* 1·3 *cms. internal diameter.*

Showing a " banded structure " presumably due to " spin " in the incandescent gaseous products following the " shock wave " from the detonator.

No. 32.—*Bursting of a Detonator* (d_b) *in the Hot Products of a* $2CO + O_2$ *Explosion, in a Tube of* 1·3 *cms. internal diameter.*

In this experiment a d_b-detonator was fired 4·1 millisecs. after the ignition of a moist $2CO + O_2$ medium by an electric spark; the photograph shows (*a*) in the upper portion, the natural development of "detonation" in the gaseous medium after its ignition, and (*b*) in the lower portion, the subsequent effects upon the hot explosion products of the compression wave produced by the bursting of the detonator, showing distinct signs of "spin" therein. It should be noted that the actual ignition of the medium is not shown in the photograph, which began when the flame had already traversed a distance of 0·6 metre from the point of its origin.

No. 33.—*Initiation of Detonation in a* $C_2N_2 + 2O_2$ *Medium in a Tube of* 1·3 *cms. internal diameter.*

The special interest of this photograph lies in its showing the occurrence of "spin," not only before and at the initiation of "detonation," but also in the "retonation" wave which is thrown back through the medium from the point when detonation started. It should be noted that, as in some previous cases, the "spin" was not visible after "detonation" was well established.

No. 34.—*Spiral Fragments of a Glass Tube, of* 1·3 *cms. internal diameter.*

This shows the spiral fragments of a glass tube which had been shattered by the detonation of a $C_2N_2 + O_2$ medium in it, as though a spiralling compression wave had passed through the glass and sheared it. The pitch of the spiral fragment was approximately 8 cm., or about twice that usually observed for a spiralling "head" of detonation in tubes of this diameter.

Having thus described the principal results of our investigation to date, we must defer the discussion of the many important problems involved until further experiments, which are now in hand, have been completed. In particular, we propose in the immediate future (*a*) investigating *inter alia* the effects of strong electric and magnetic fields upon the phenomenon of "spin," and (*b*) making further experiments with a view to establishing an experimental foundation for the further mathematical elucidation of the problem, for it is evident that the present theory of detonation in gaseous media needs revision.

In conclusion, we desire to express our great indebtedness (1) to Professor H. LEVY for his help in the mathematical aspects of the problem; (2) to Mr. W. H. WHEELER for assistance in some of the later experiments included herein; (3) to Messrs. Nobels Explosives Company and Imperial Chemical Industries, Limited, for generous financial aids towards the heavy expenses of the work, including not only a personal grant to one of us (R. P. F.), but also the recent installation at great expense of a new large photographic machine, embodying a mirror rotating in a vacuum chamber containing a fixed film, whereby our present analysing power will be increased at least three-fold; and finally (4) to Mr. WILLIAM RINTOUL for the frequent helpful discussions we have had with him during the progress of the work and the interest he has shown in it.

DESCRIPTION OF PLATES 13–20.

PART IV. (PLATES 13–15.)

No. 1.—*Control Experiment.* Explosion in $2CO + O_2$ after ignition by condenser discharge near closed end of tube.

No. 2.—Explosion in $2CO + O_2$. Initiated by "fuse head" near closed end of tube.

No. 3.—Explosion in $2CO + O_2$. Initiated by "detonator" d_b near closed end of tube.

No. 4.—Explosion of $2CO + O_2$. Initiated by high tension spark, 2·5 metres from closed end of tube, and afterwards accelerated by an overtaking "shock wave."

No. 5.—Explosion in $2CO + O_2$. Initiated by spark, and accelerated by two successive shock waves.

Nos. 6, 7 AND 8.—Explosion in $2CO + O_2$. Initiated by detonator *plus* simultaneous powerful "shock waves."

No. 9.—Explosion in $2H_2 + O_2$. Initiated by detonator *plus* simultaneous powerful "shock waves."

PART V. (PLATES 15, 16.)

Nos. 10 AND 11.—Explosion flame in $2CO + O_2$ overtaking a series of intense "shock waves" during the pre-detonation stage.

Nos. 12 AND 13.—Initiation of detonation in $2CO + 4H_2 + 3O_2$ (12) and $C_2N_2 + O_2$ (13) media.

PART VI. (PLATES 16–20.)

No. 14.—Detonation in $2CO + O_2$, in tube of 2·55 cms. internal diameter.

No. 15.—Detonation in $CH_4 + O_2$, in tube of 1·3 cms. internal diameter.

No. 16.—Detonation in C_2H_2, in tube of 2·55 cms. internal diameter.

No. 17.—Initiation of detonation in $2H_2 + O_2$, in tube of 1·2 cms. internal diameter.

No. 18.—Initiation of detonation in $C_2H_2 + O_2$, in tube of 1·5 cms. internal diameter.

No. 19.—Initiation of detonation in $2H_2S + 3O_2$, in tube of 1·3 cms. internal diameter.

No. 20.—Detonation in $2CO + O_2$ in tube of 1·3 cms. internal diameter.

No. 21.—Detonation in $2CO + O_2$ in tube of 4·1 cms. internal diameter.

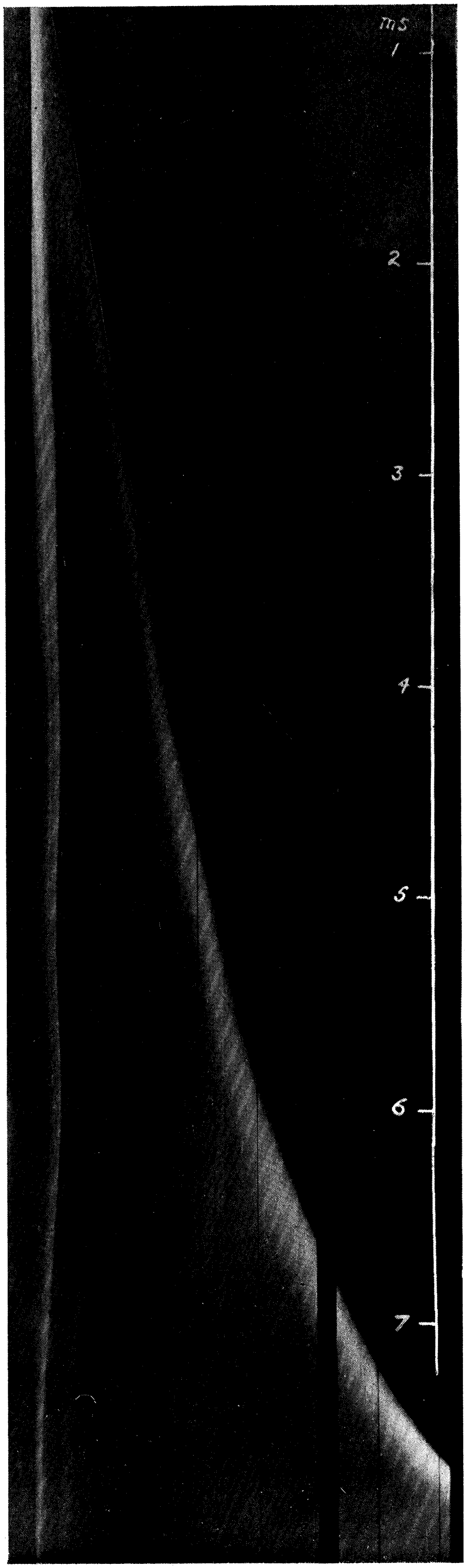
No. 22.—Initiation of detonation in $CH_4 + O_2$, in tube of 1·3 cms. internal diameter.

Nos. 23 AND 24.—Detonations in $CH_4 + O_2$, in tube of 1·3 cms. internal diameter.

No. 25.—Detonation in $CO + N_2O$, in tube of 1·28 cms. internal diameter.

No. 26.—Detonation in $2CO + O_2$, in ribbed glass tube of 1·3 cms. internal diameter.

No. 27.—Detonation in $2CO + O_2$, in tube of 1·21 cms. internal diameter with plasticine junction between successive glass sections.



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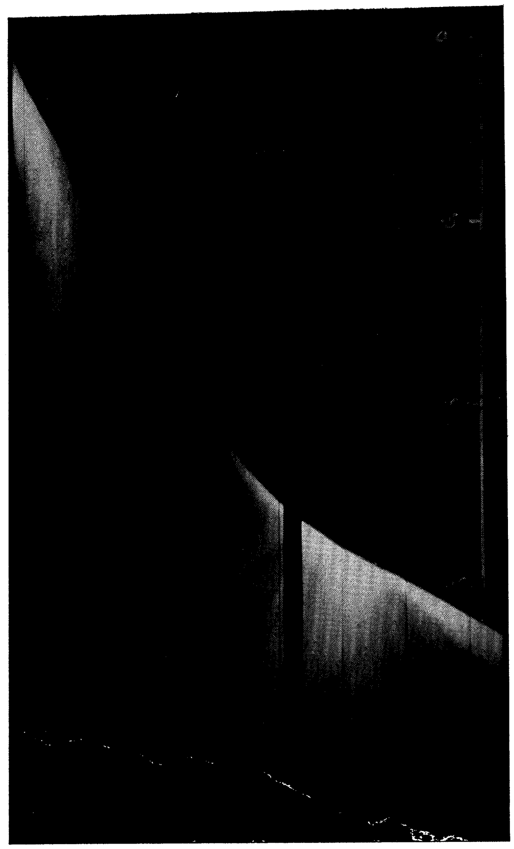

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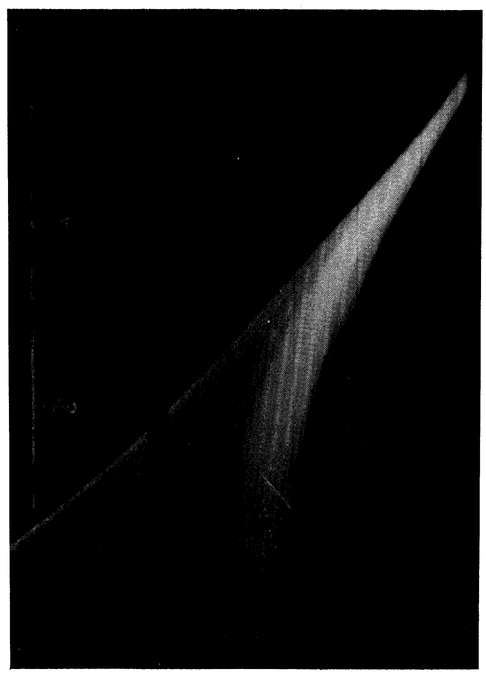
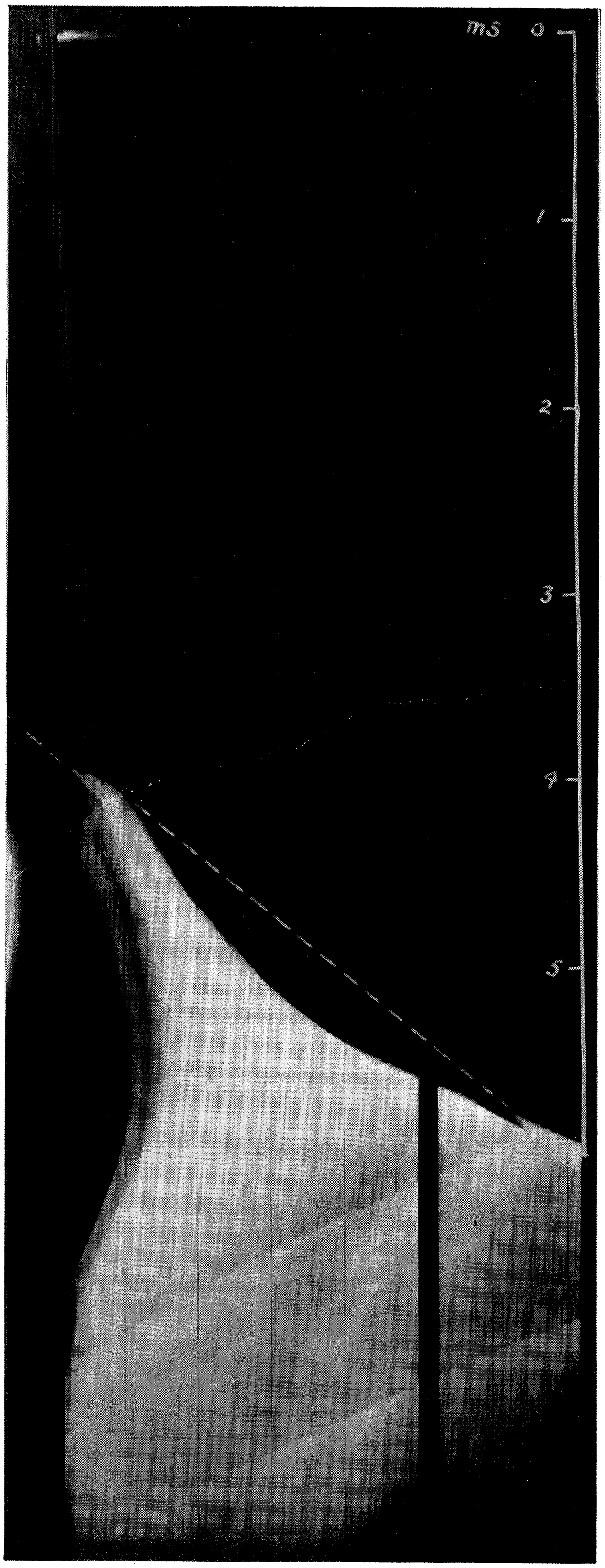


No. 3.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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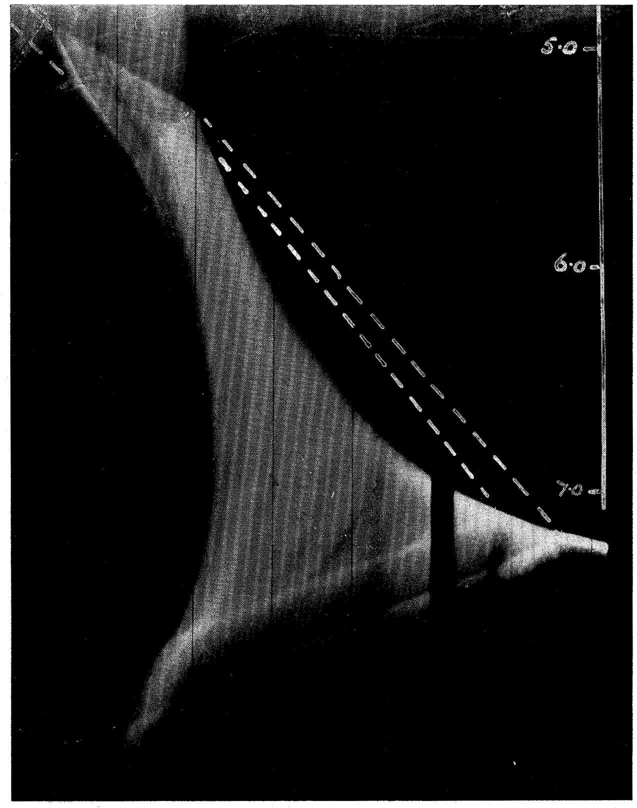

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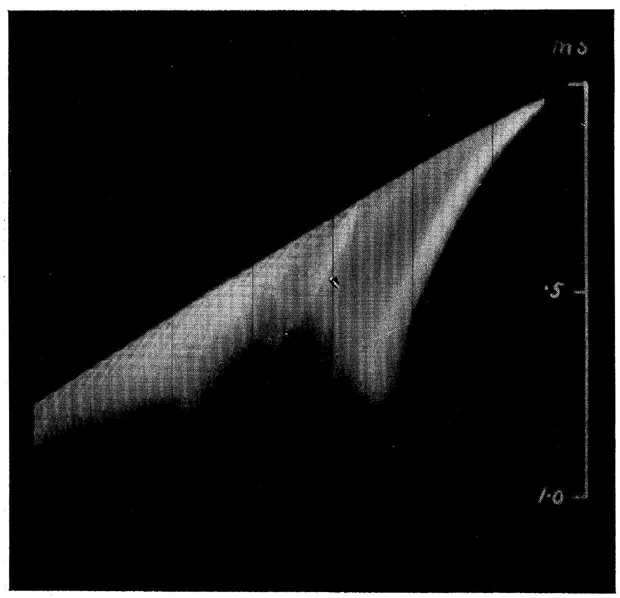
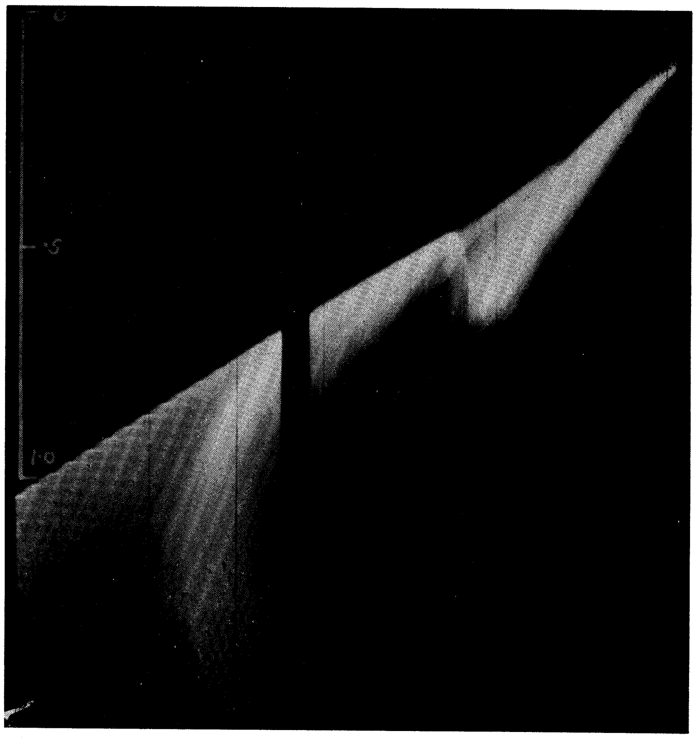


No. 6.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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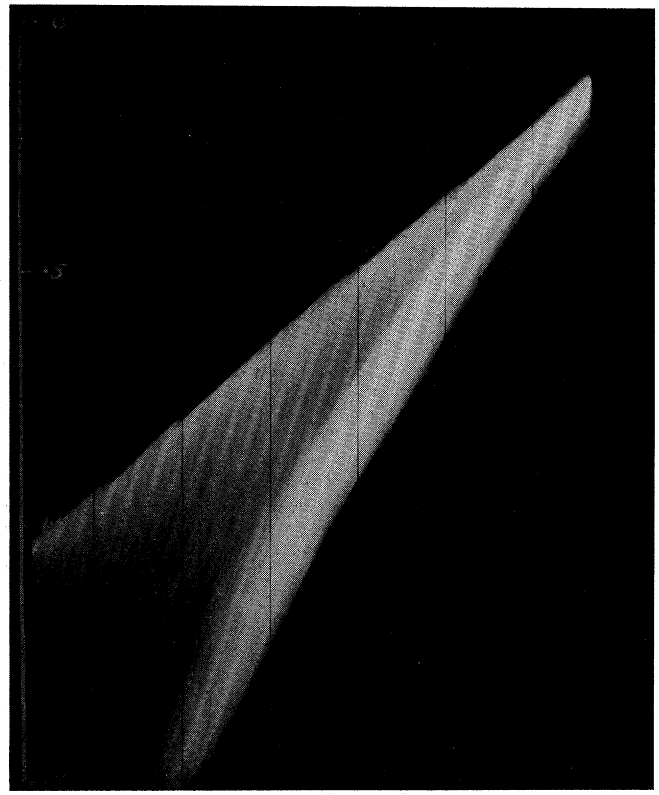

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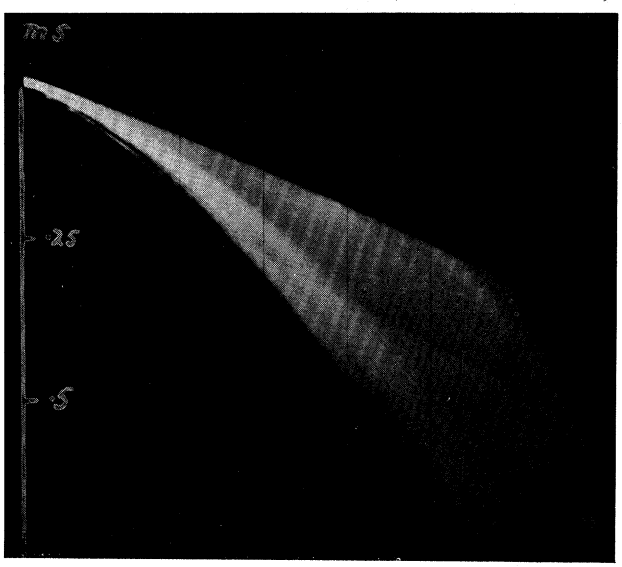
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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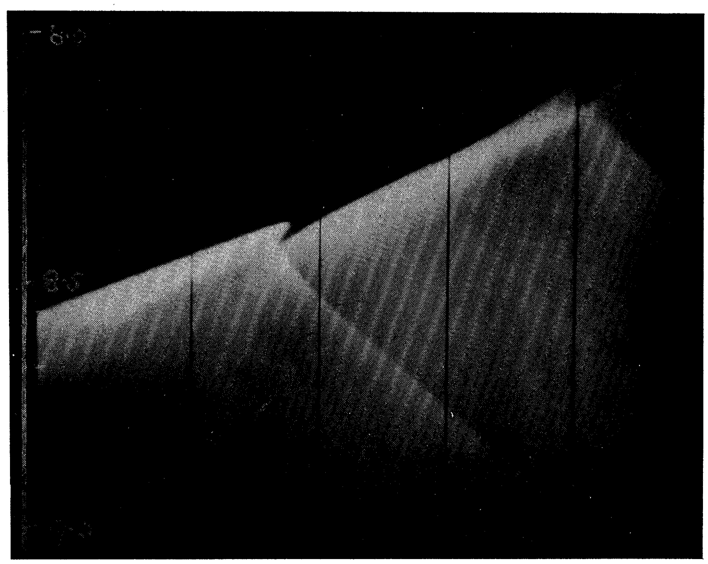

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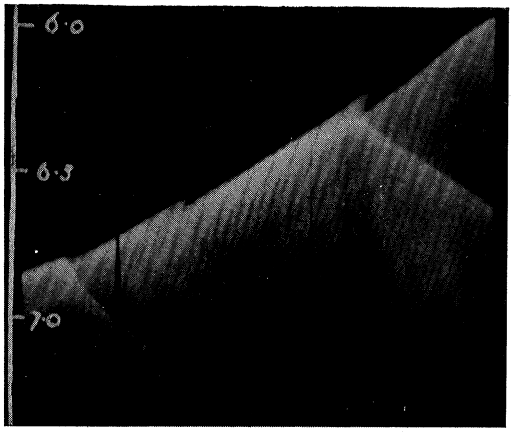

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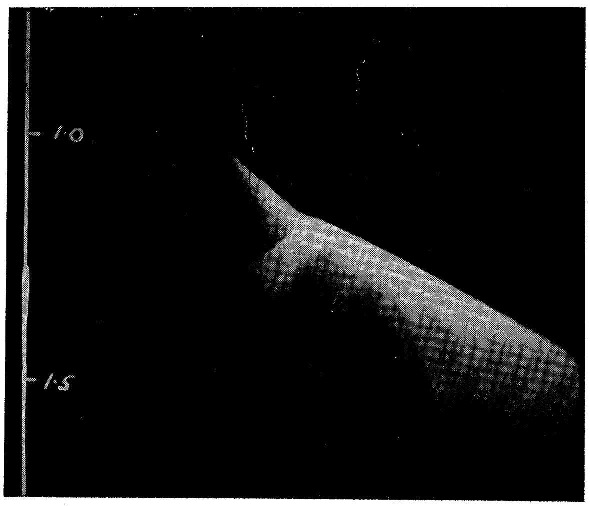

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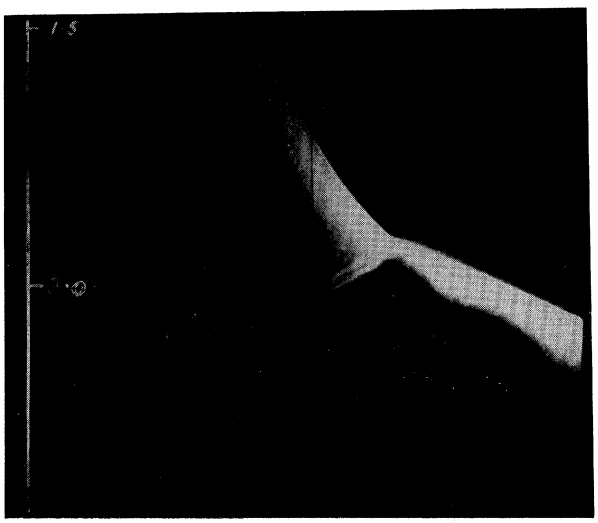

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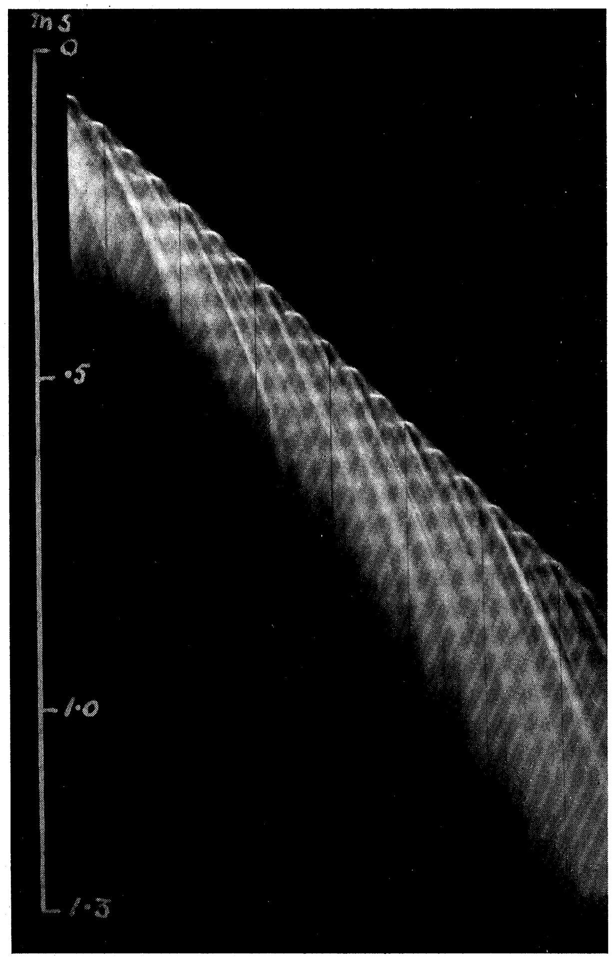

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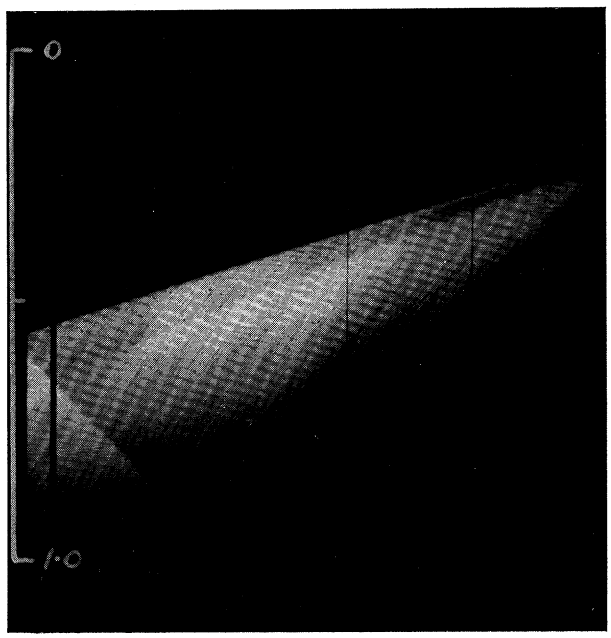

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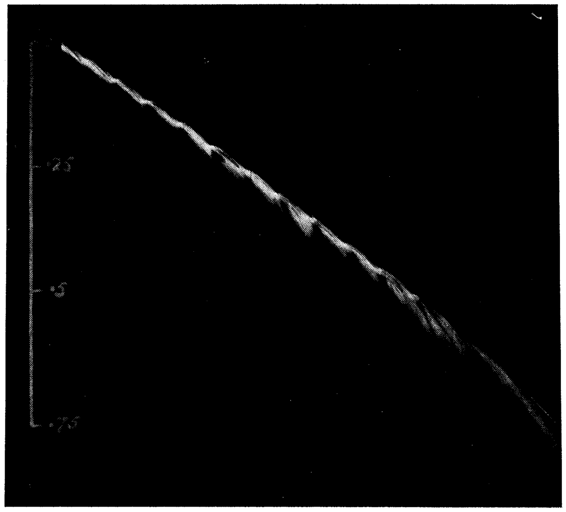

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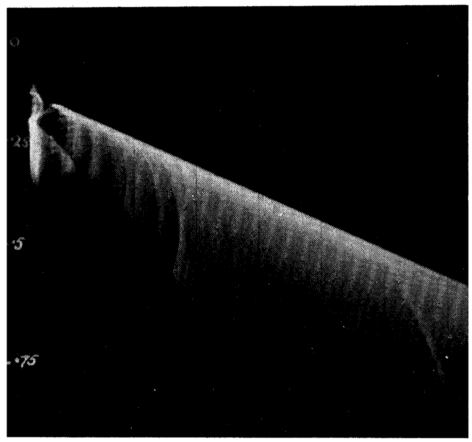

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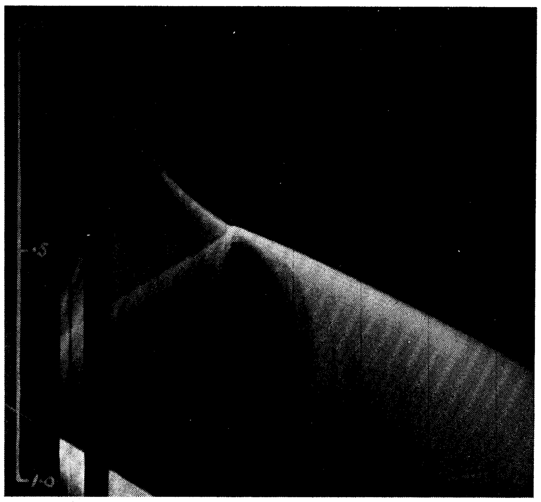

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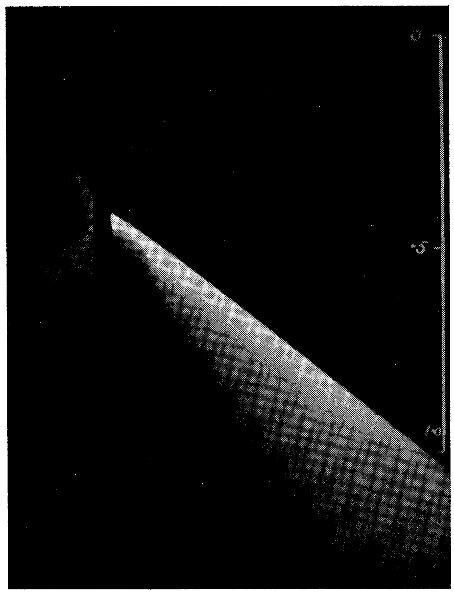

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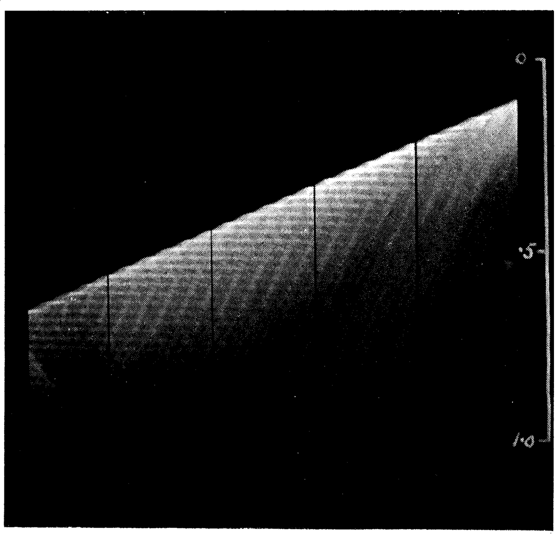

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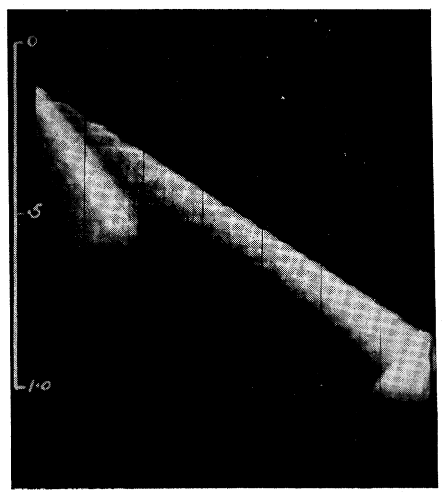

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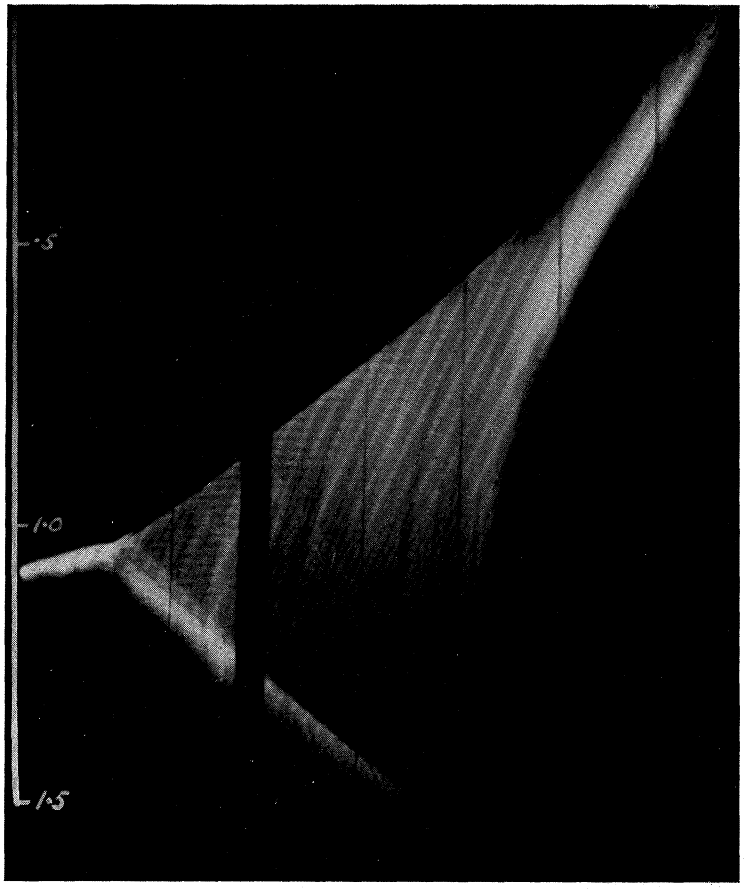
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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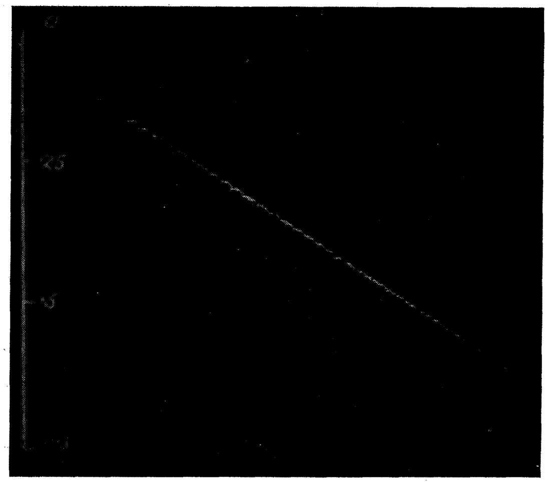

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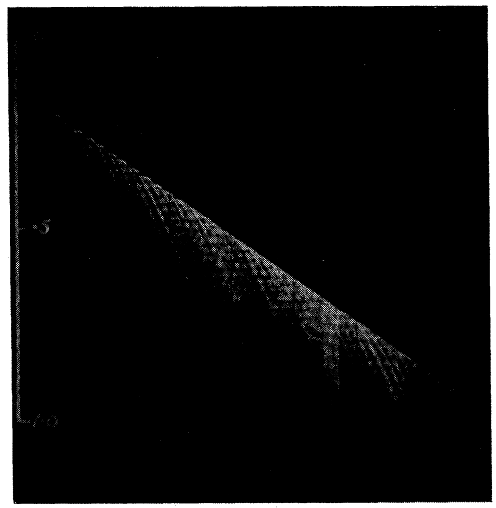

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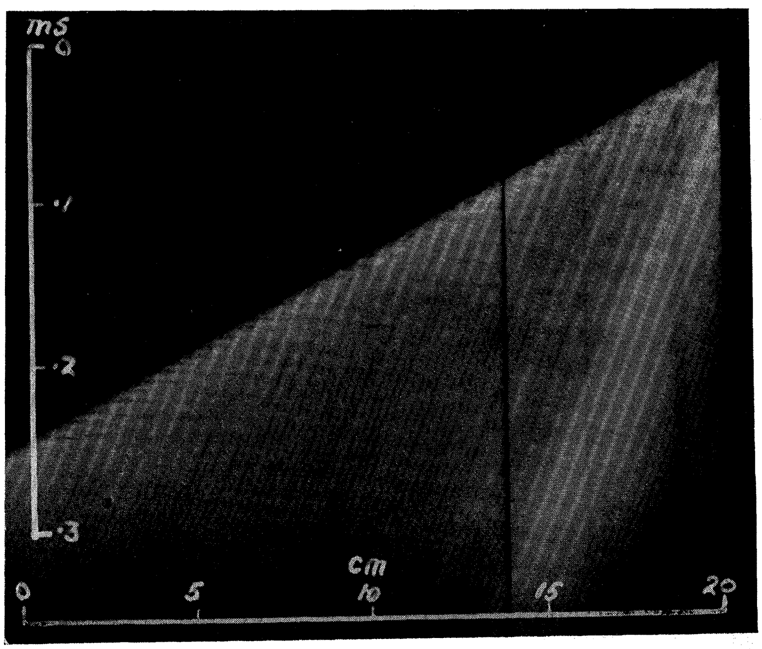

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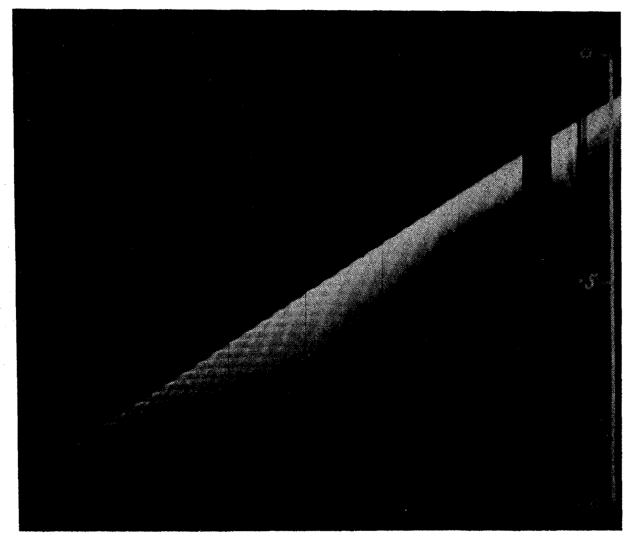

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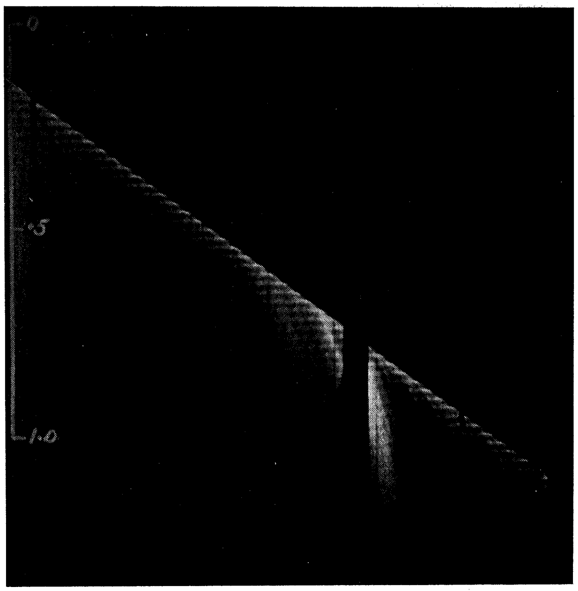

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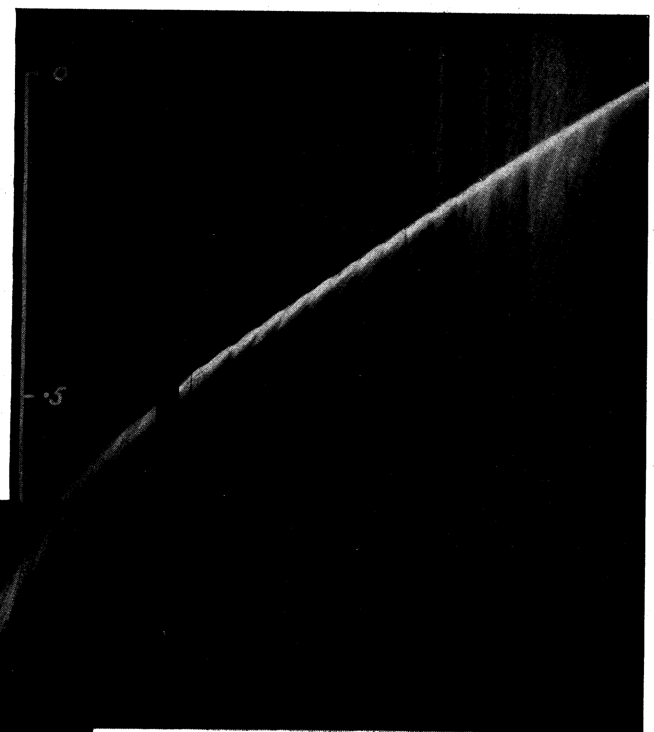

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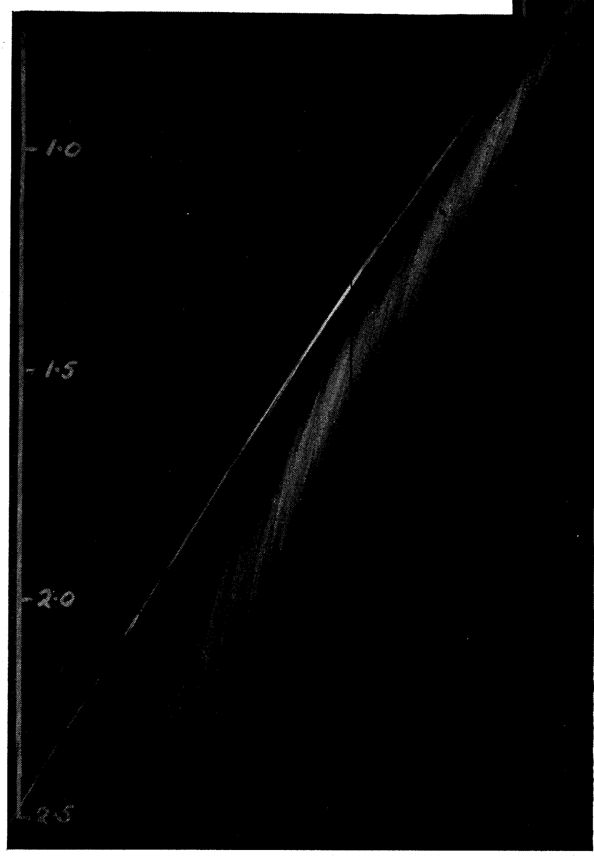

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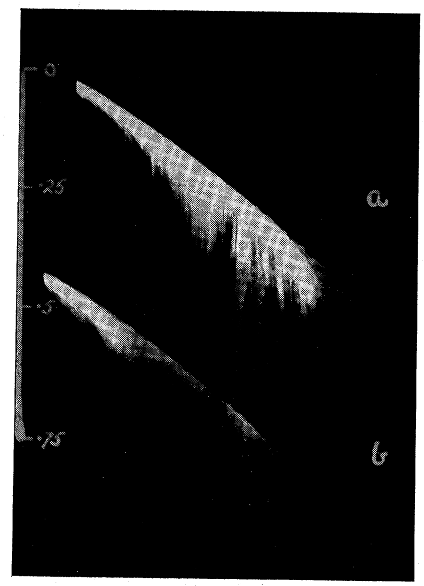

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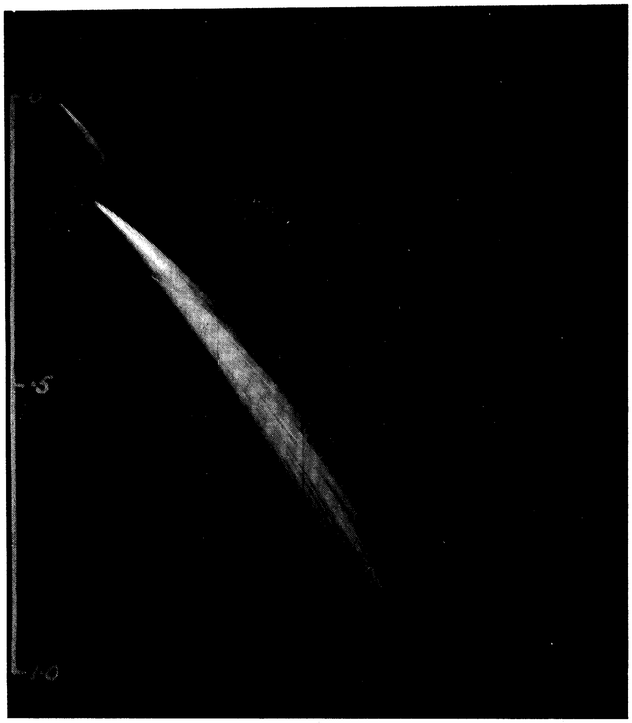
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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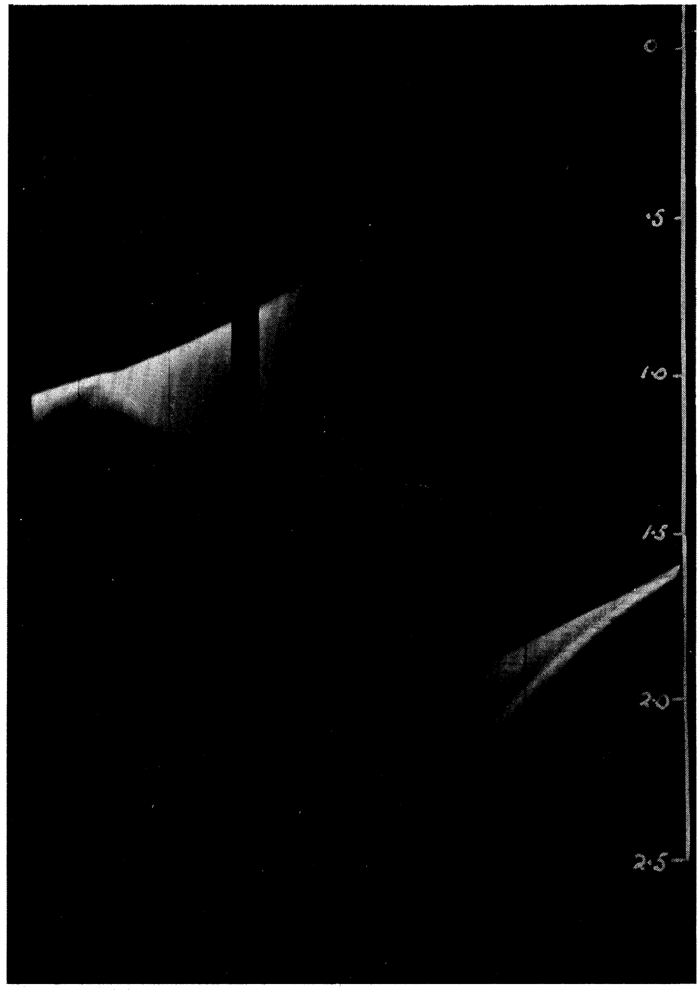

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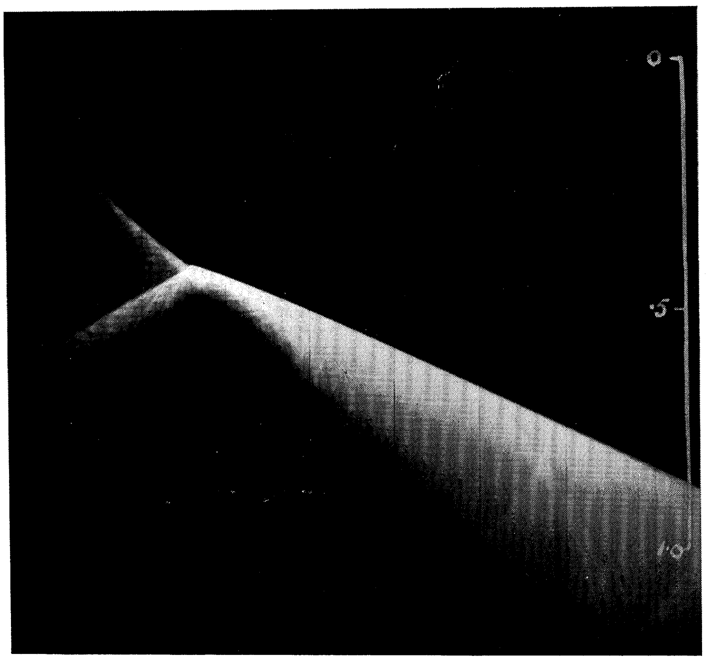


No. 33.

No. 34.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Nos. 28 AND 29.—Detonations induced by "detonators" in a pure C_2H_2 medium, in tube of 1·4 cms. internal diameter.

No. 30.—Explosions initiated by detonators in (*a*) $4C_2N_2 + O_2$ and (*b*) in N_2O medium, in tubes of 1·3 cms. internal diameter.

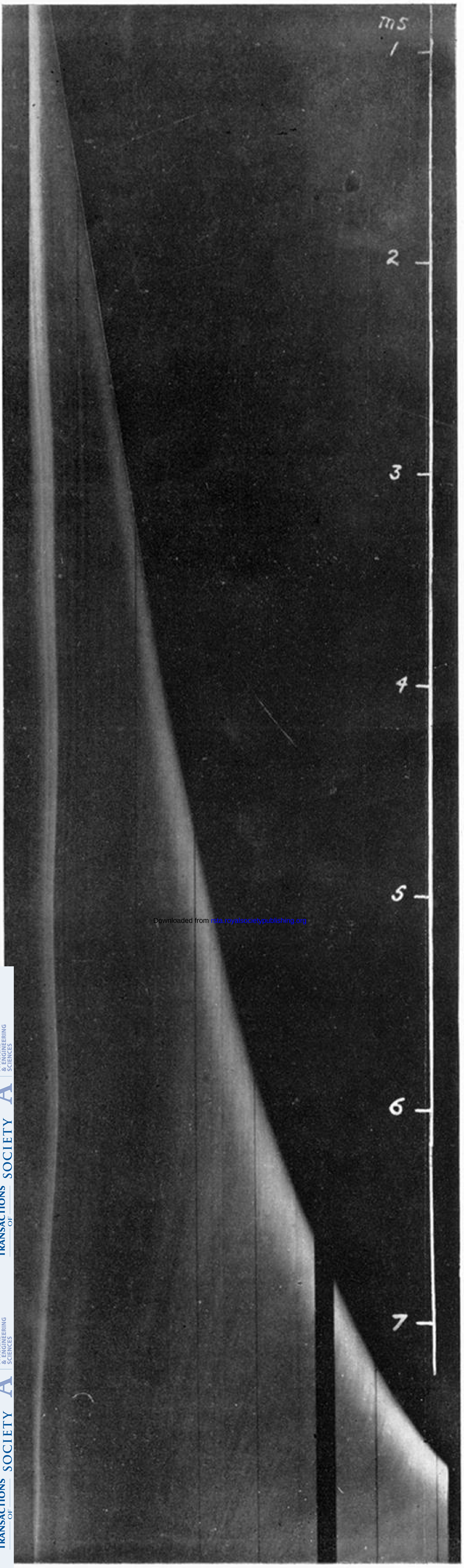
No. 31.—Bursting of "Detonator" d_a in air, in tube of 1·3 cms. internal diameter.

No. 32.—Bursting of "Detonator" d_b in hot products of a $2CO + O_2$ explosion, in tube of 1·3 cms. internal diameter.

No. 33.—Initiation of detonation in $C_2N_2 + 2O_2$, in tube of 1·3 cms. internal diameter.

No. 34.—Spiral fragments of glass tube after being shattered by the detonation of a $C_2N_2 + O_2$ medium.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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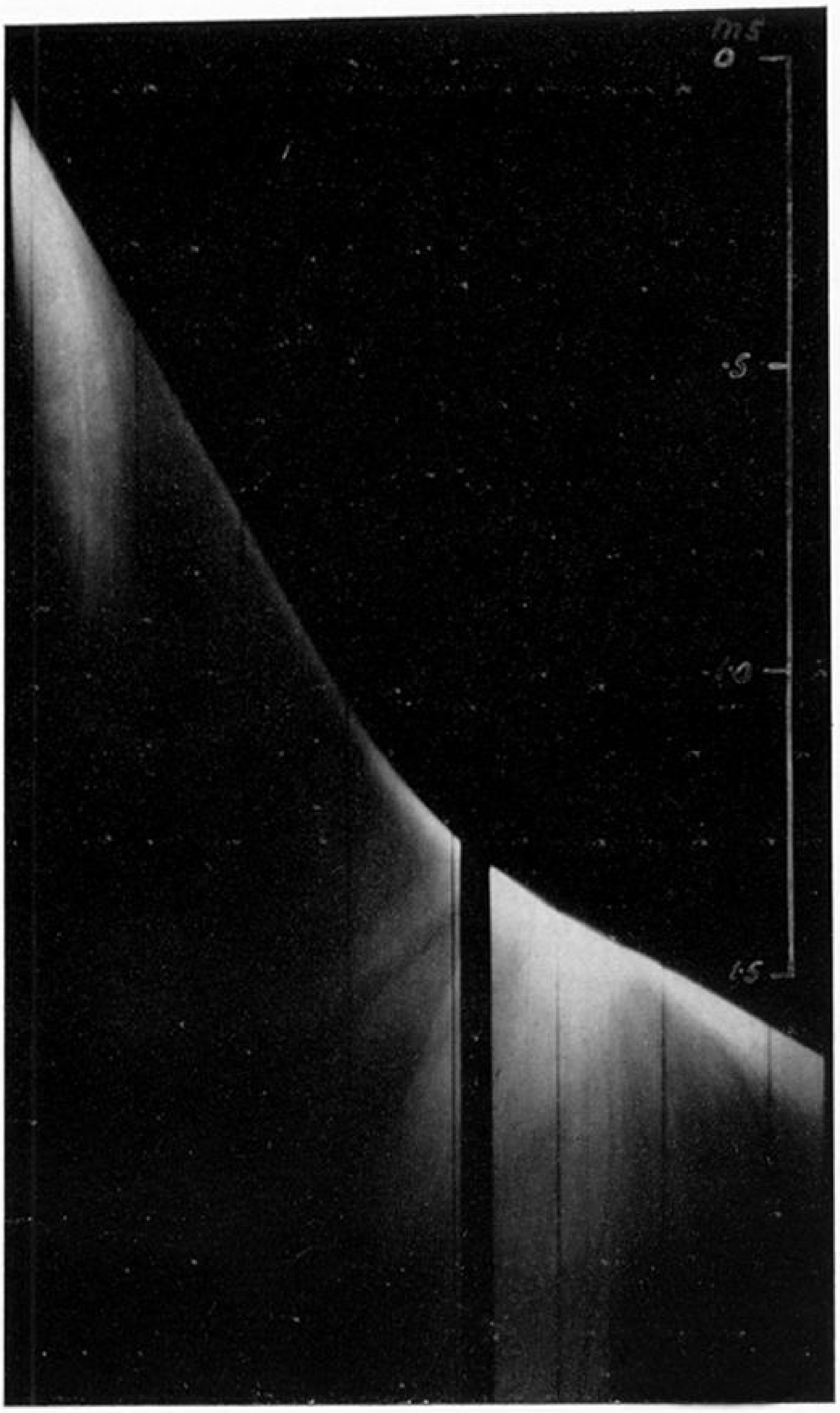

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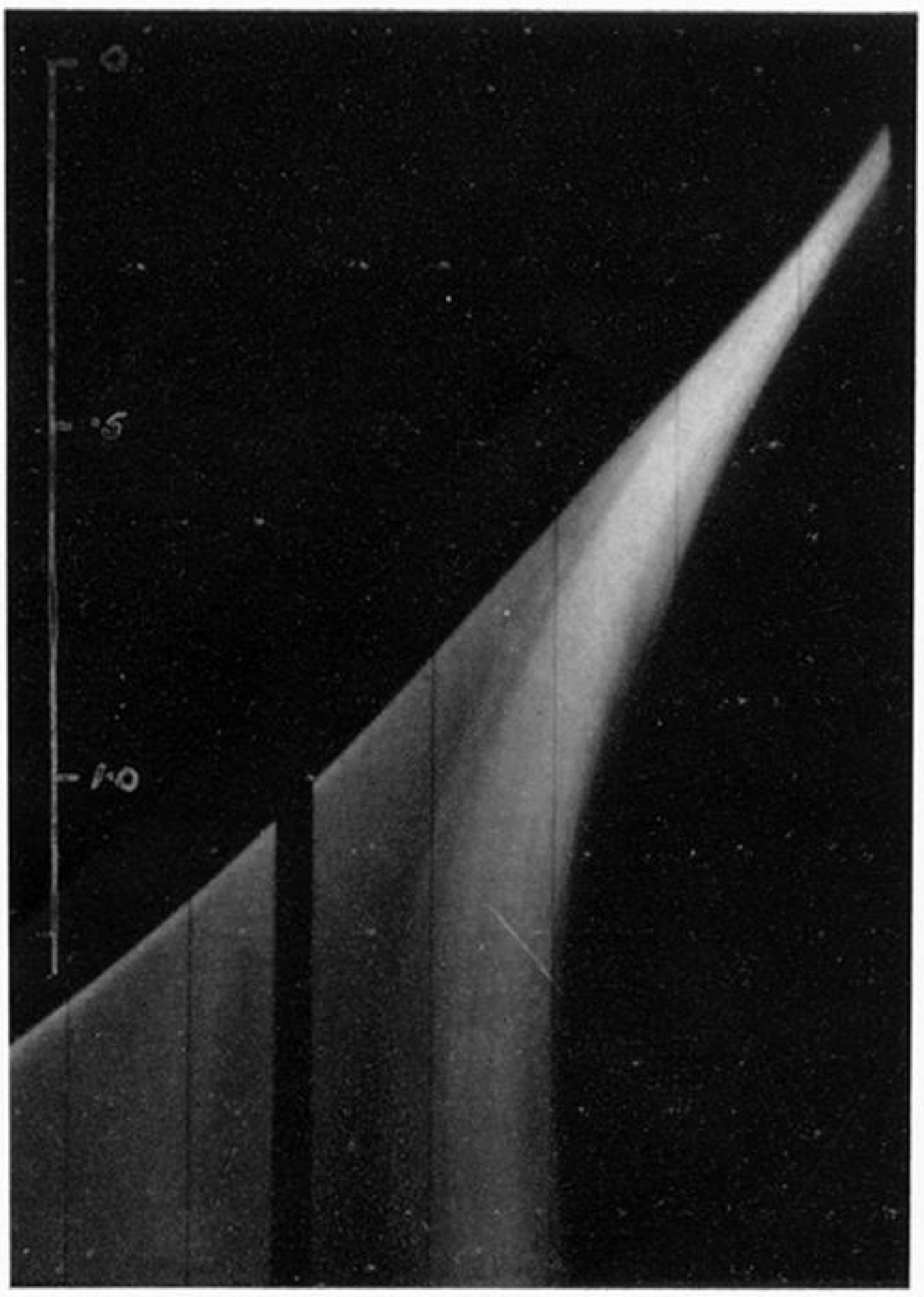

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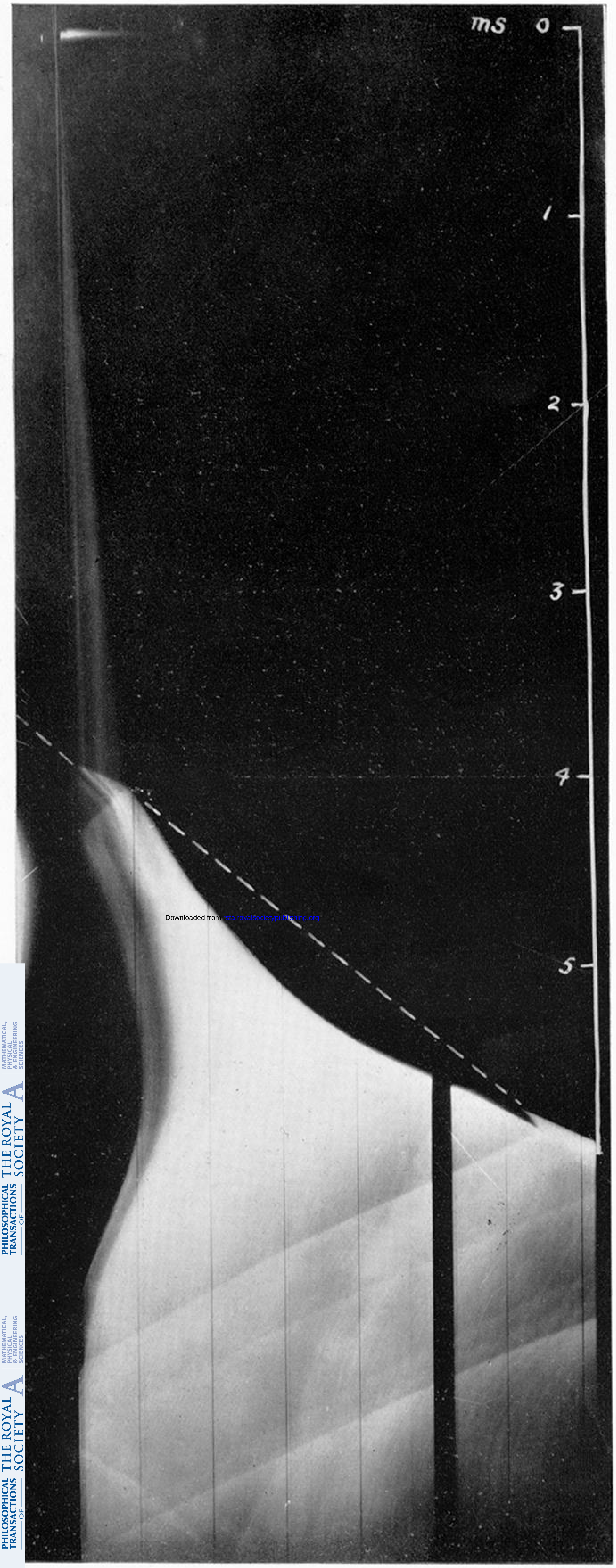
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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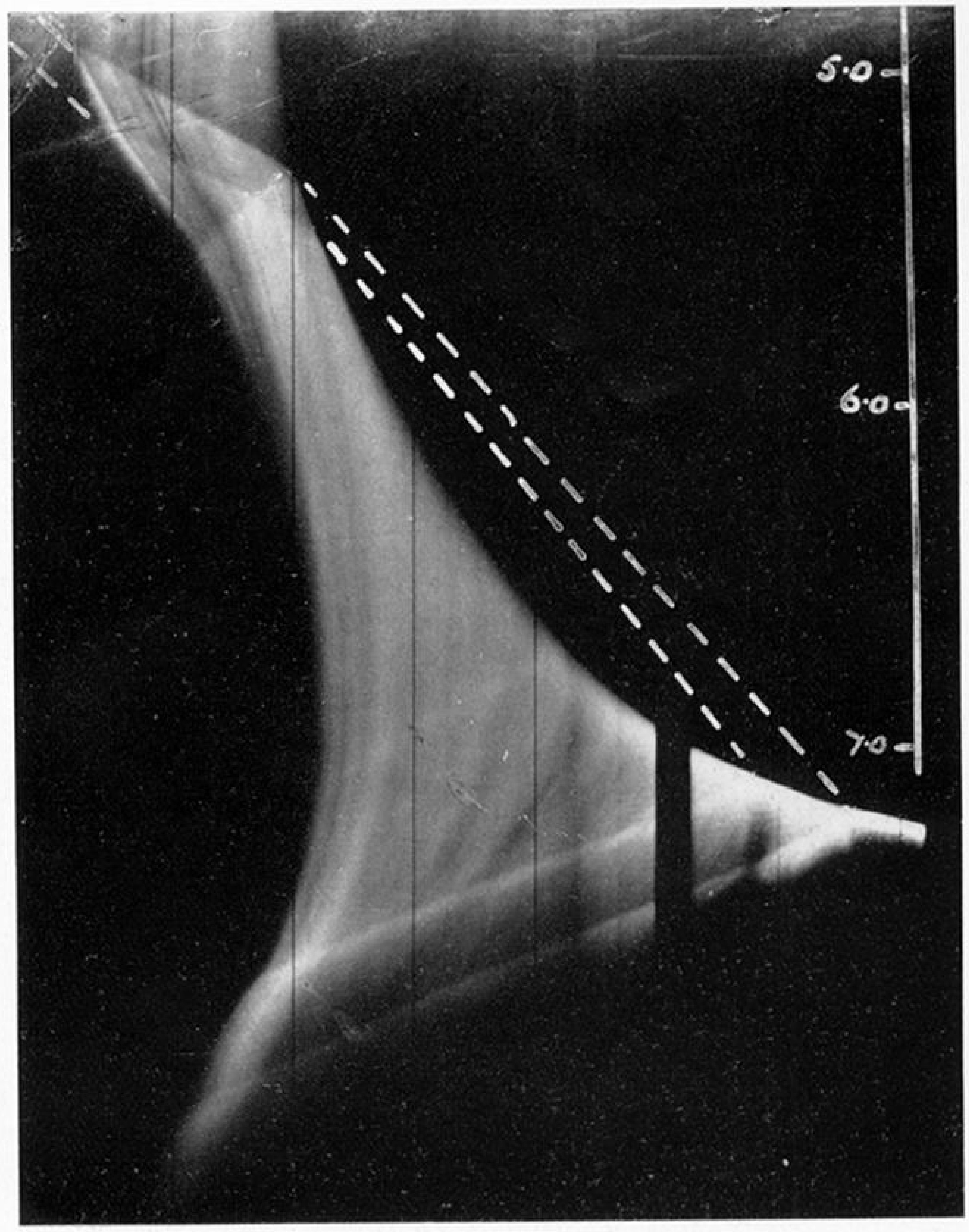

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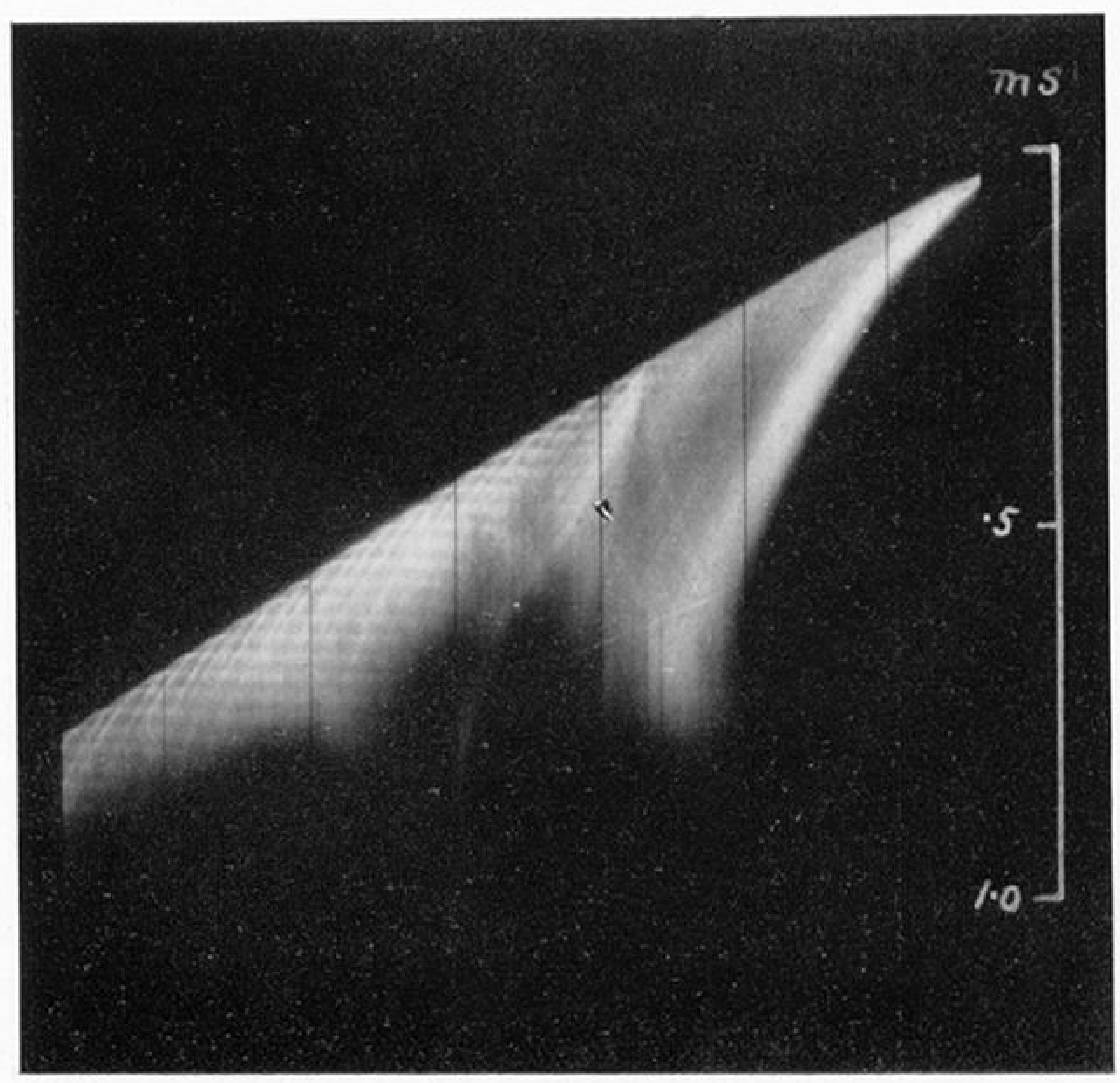

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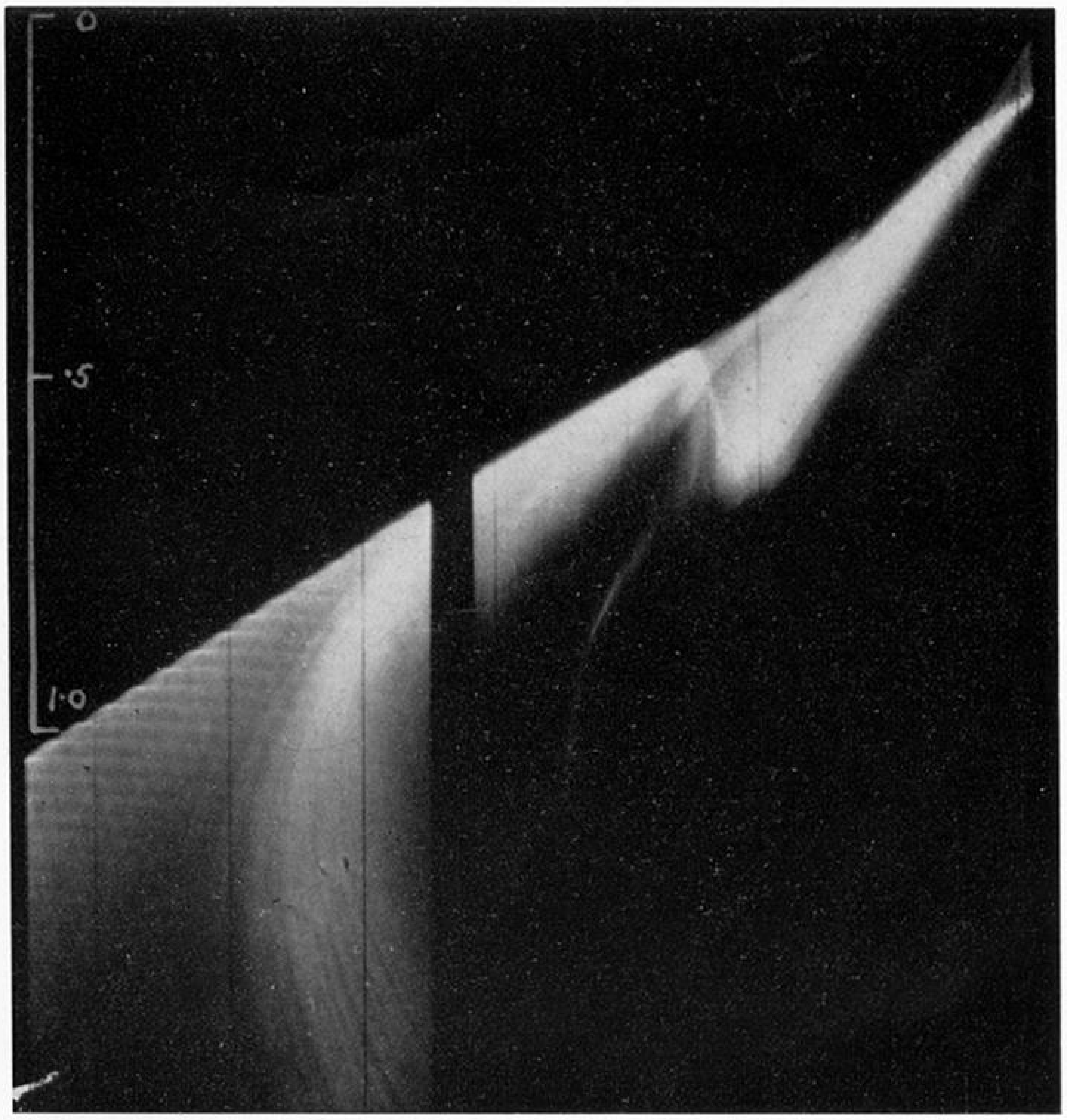

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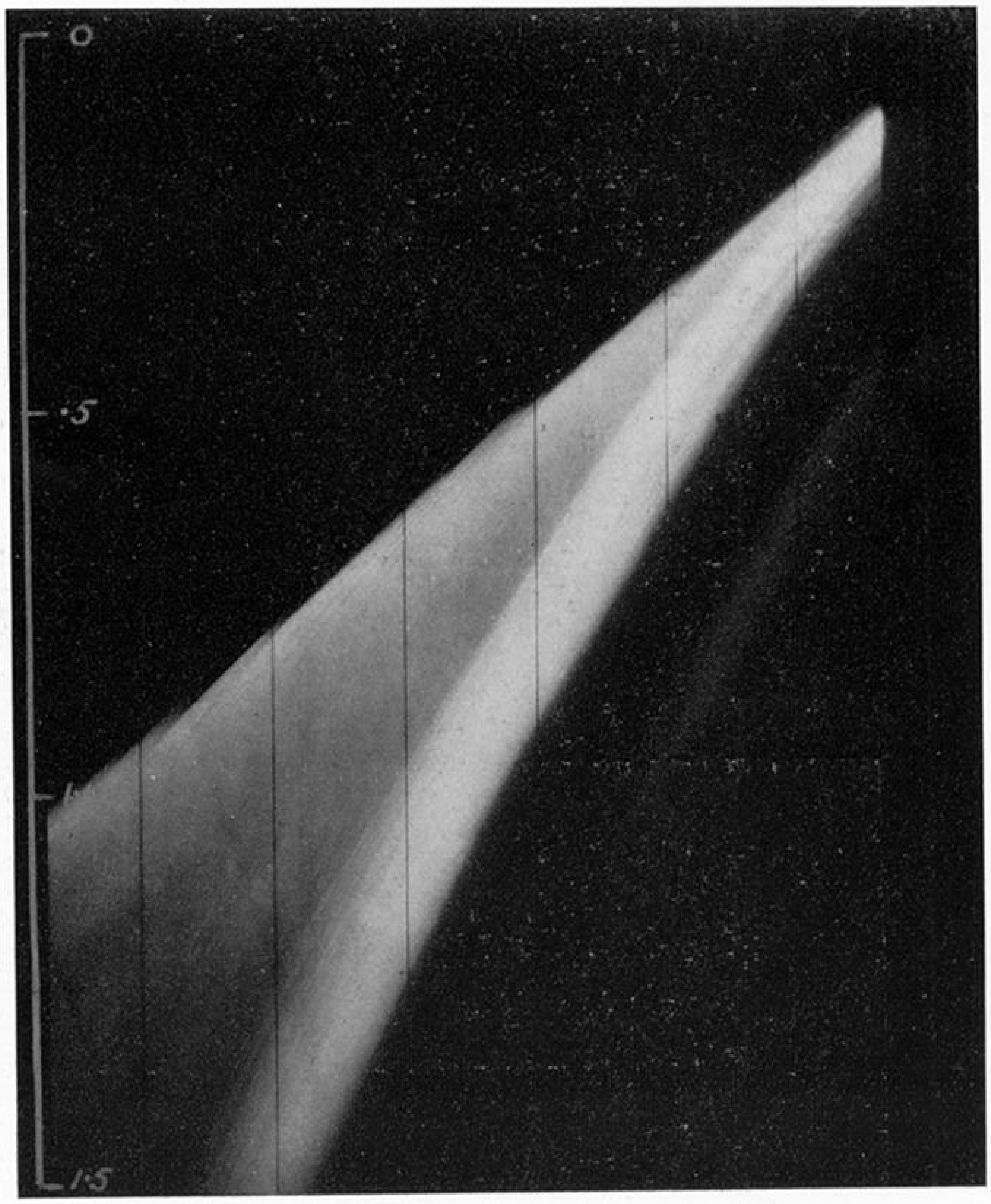

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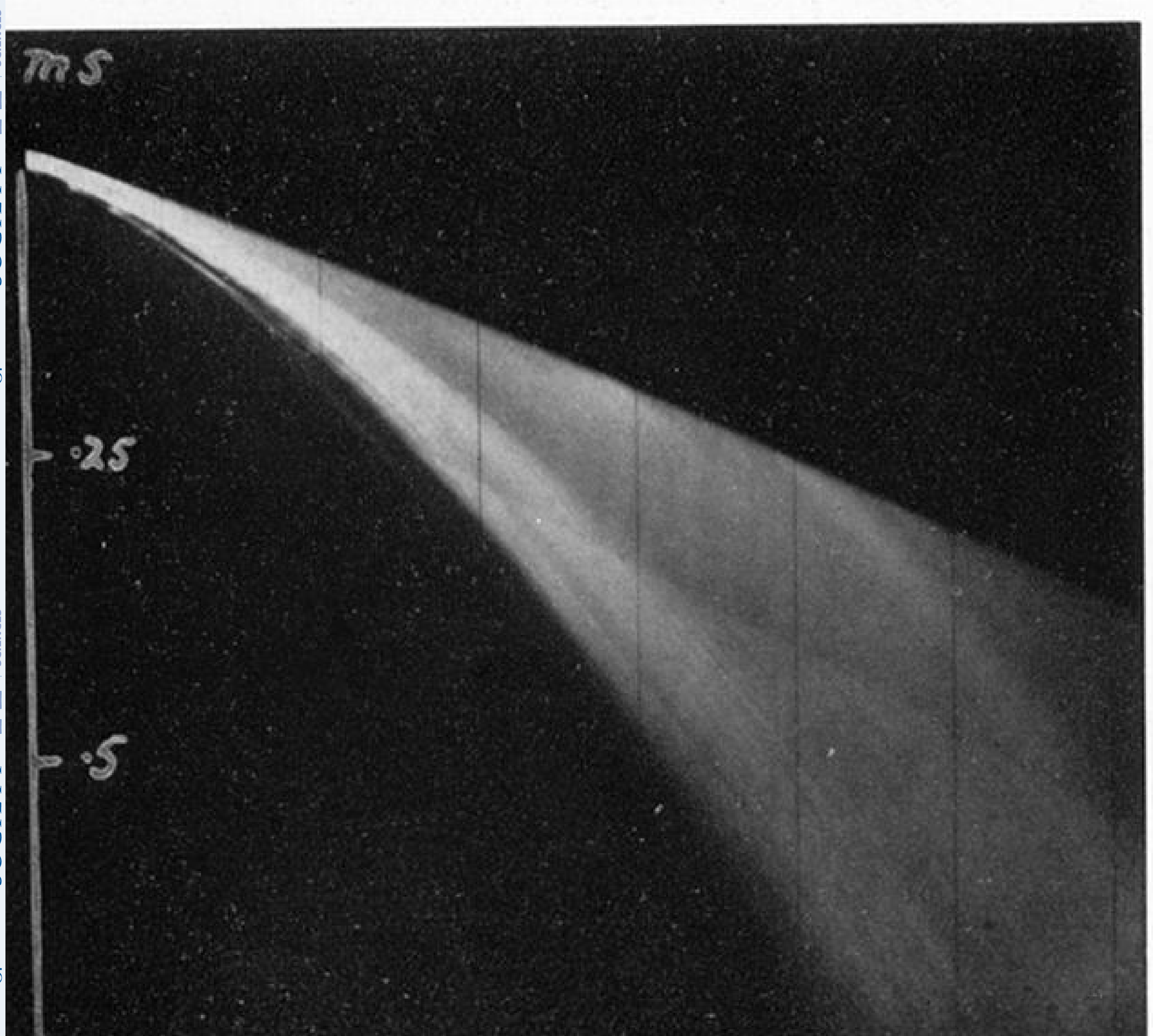

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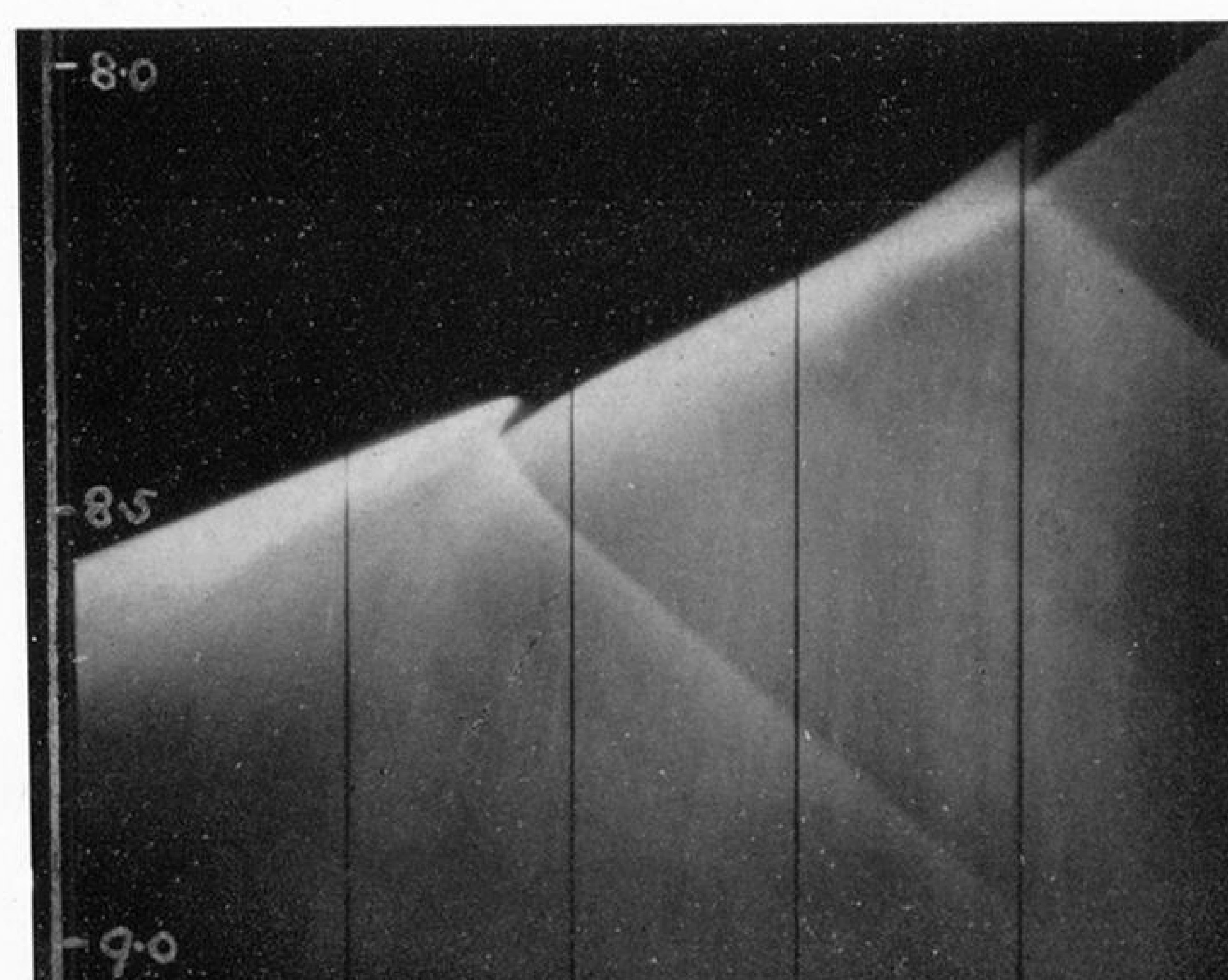

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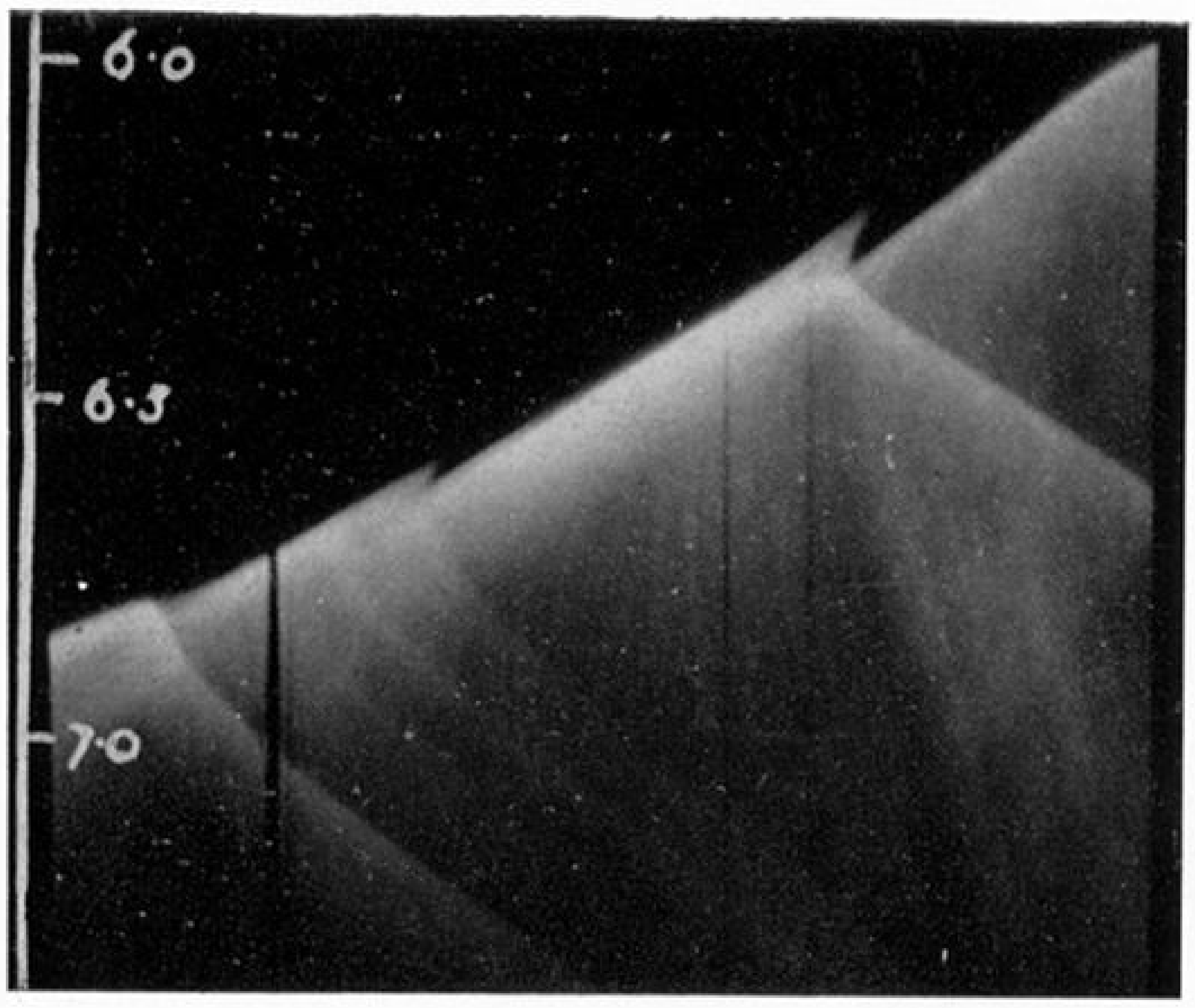

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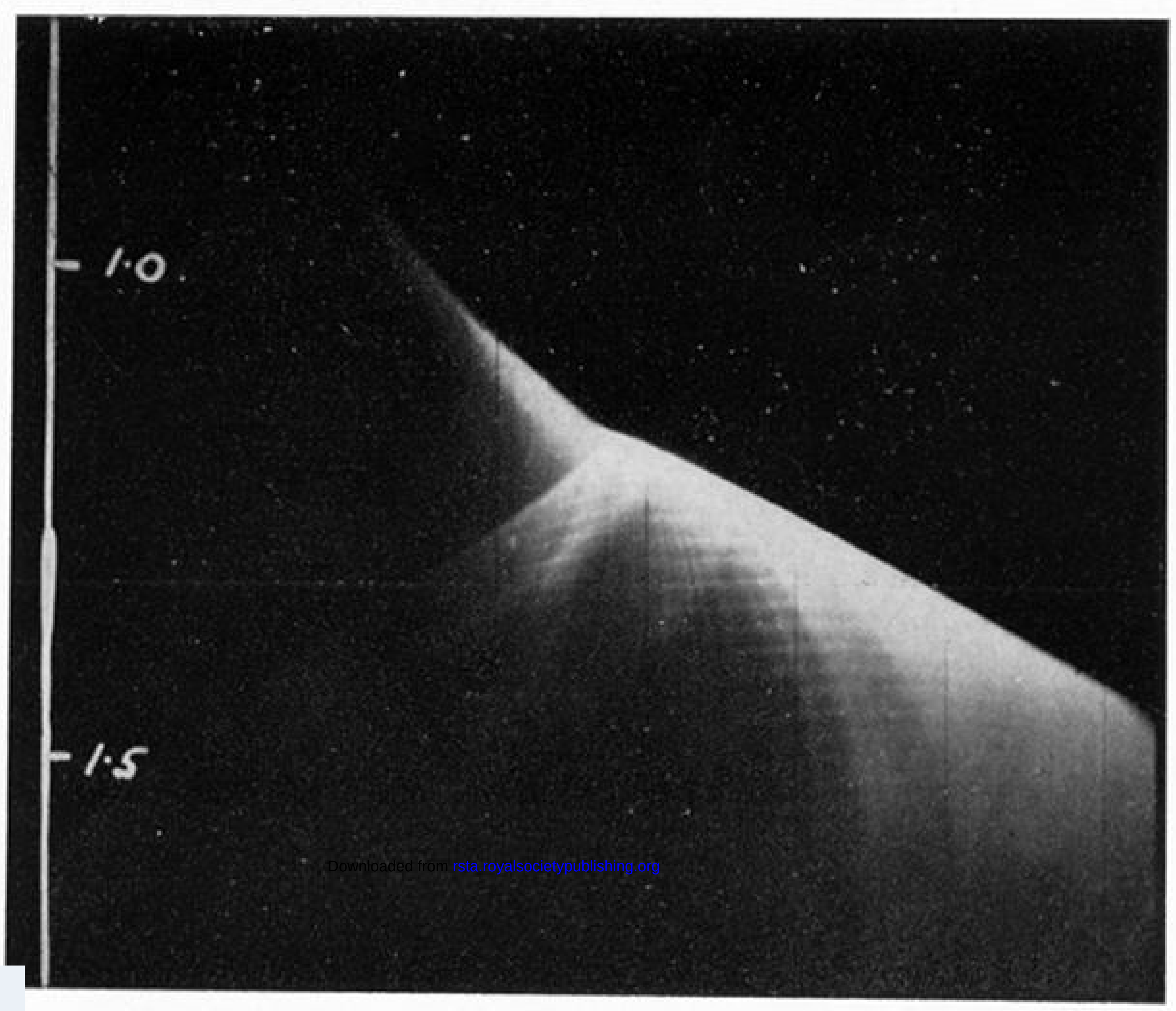

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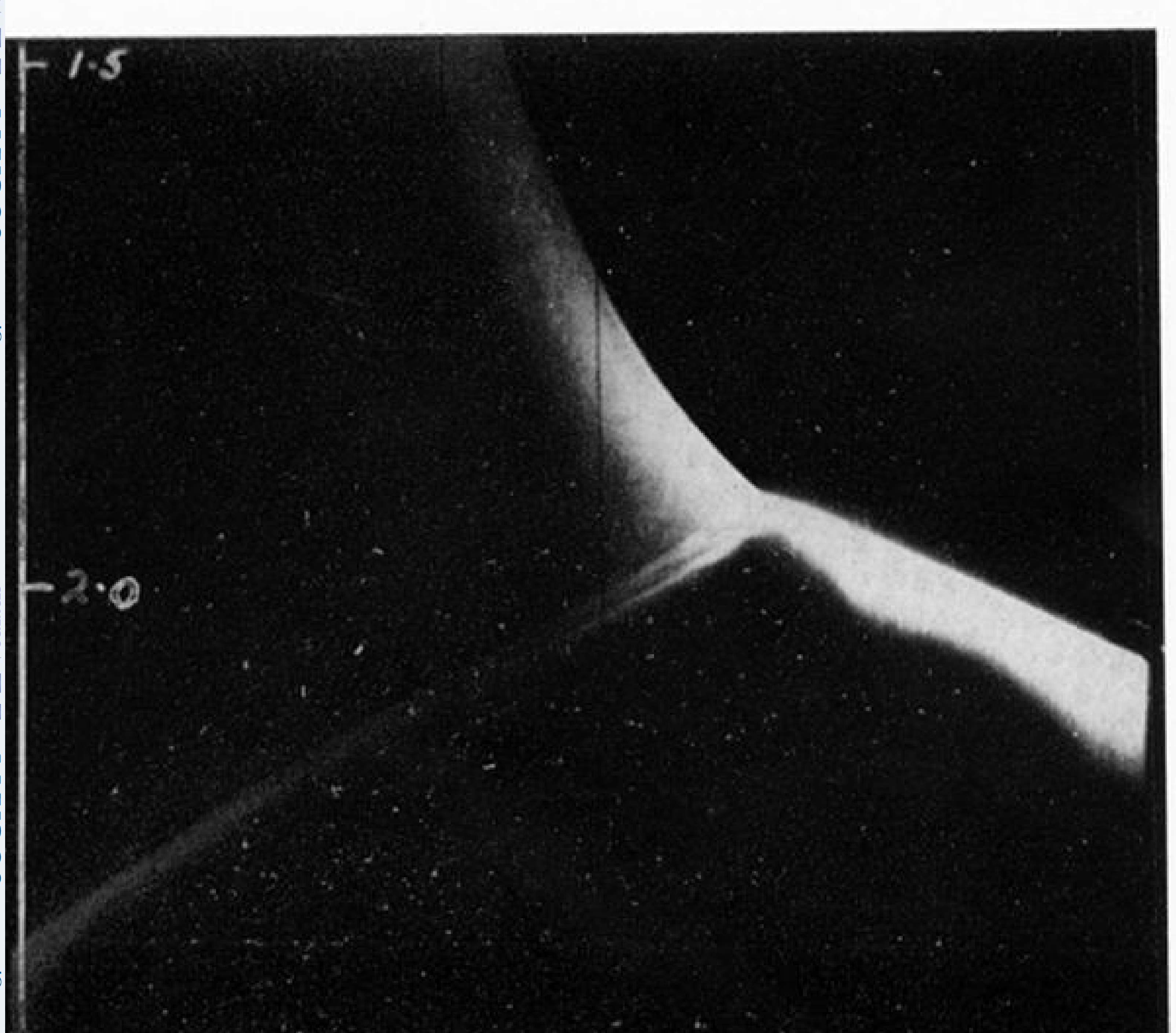

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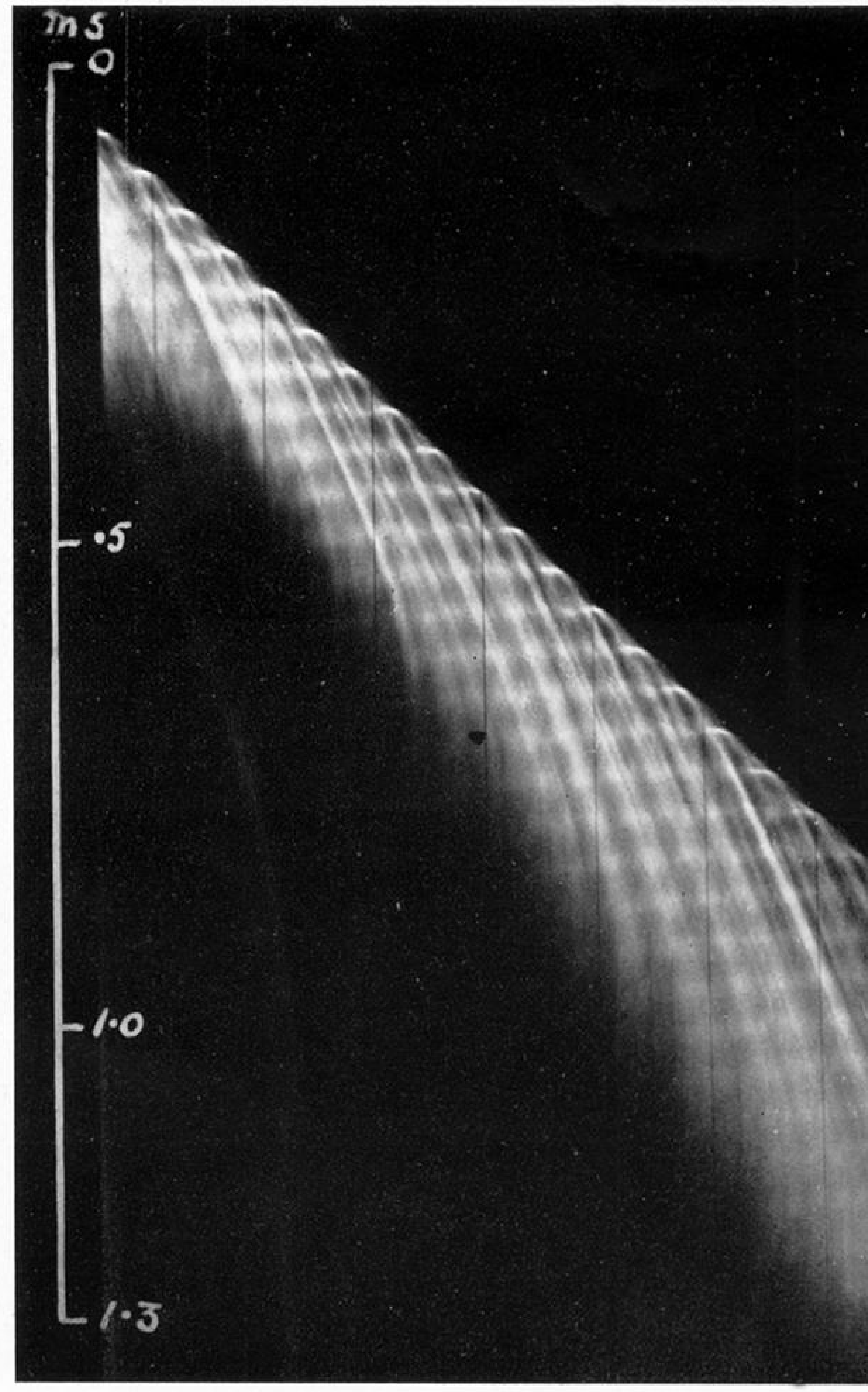

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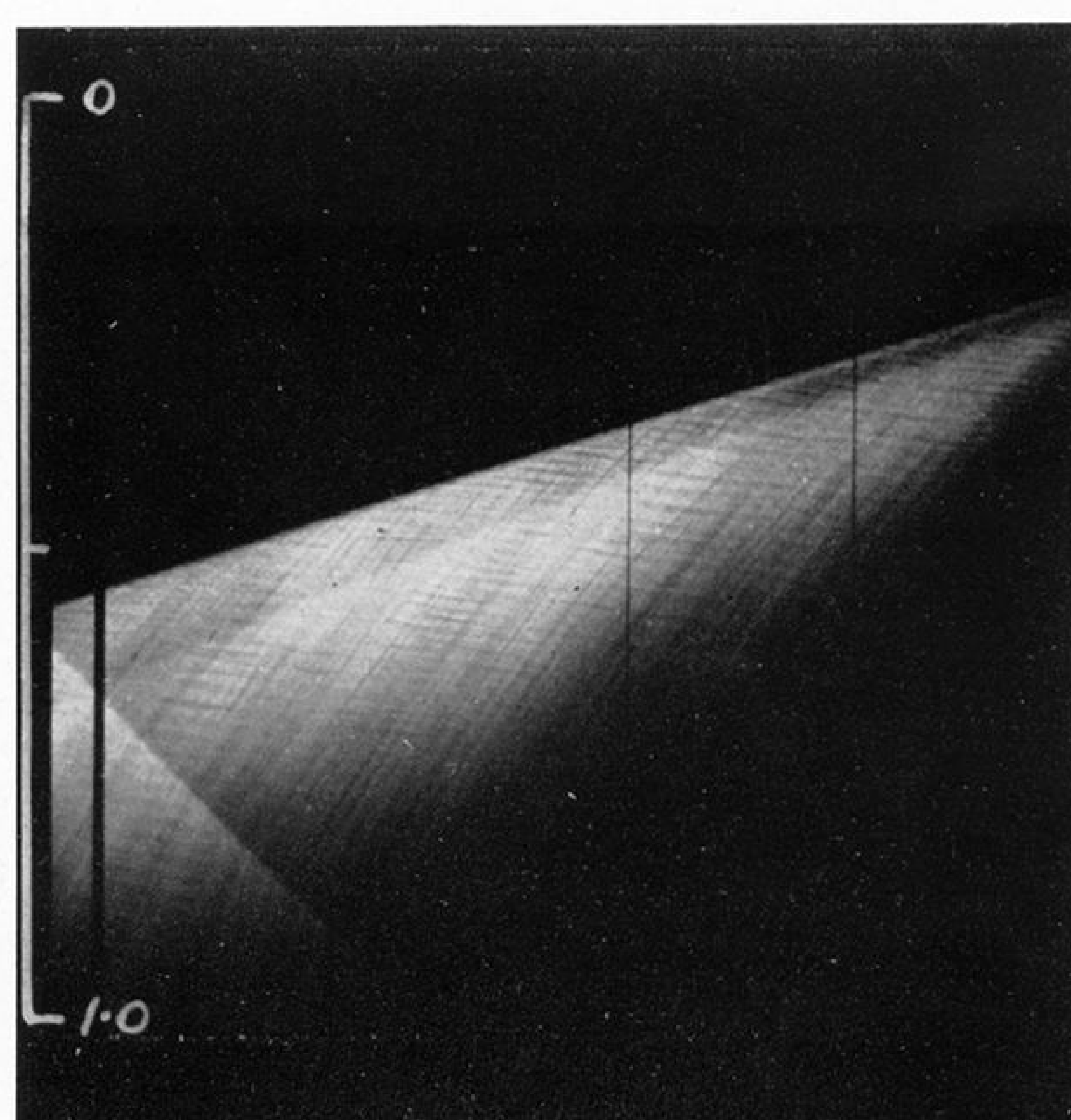

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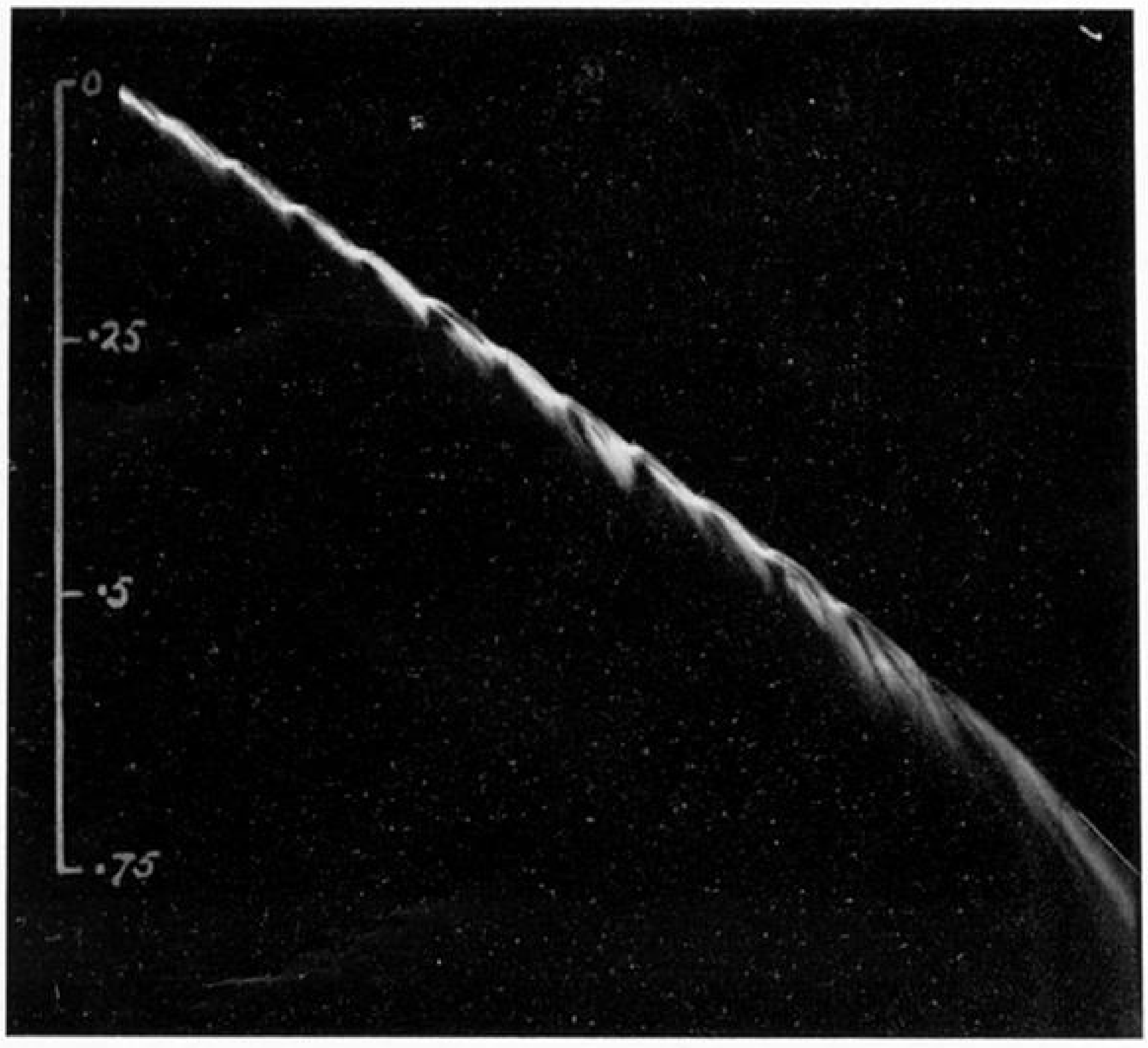
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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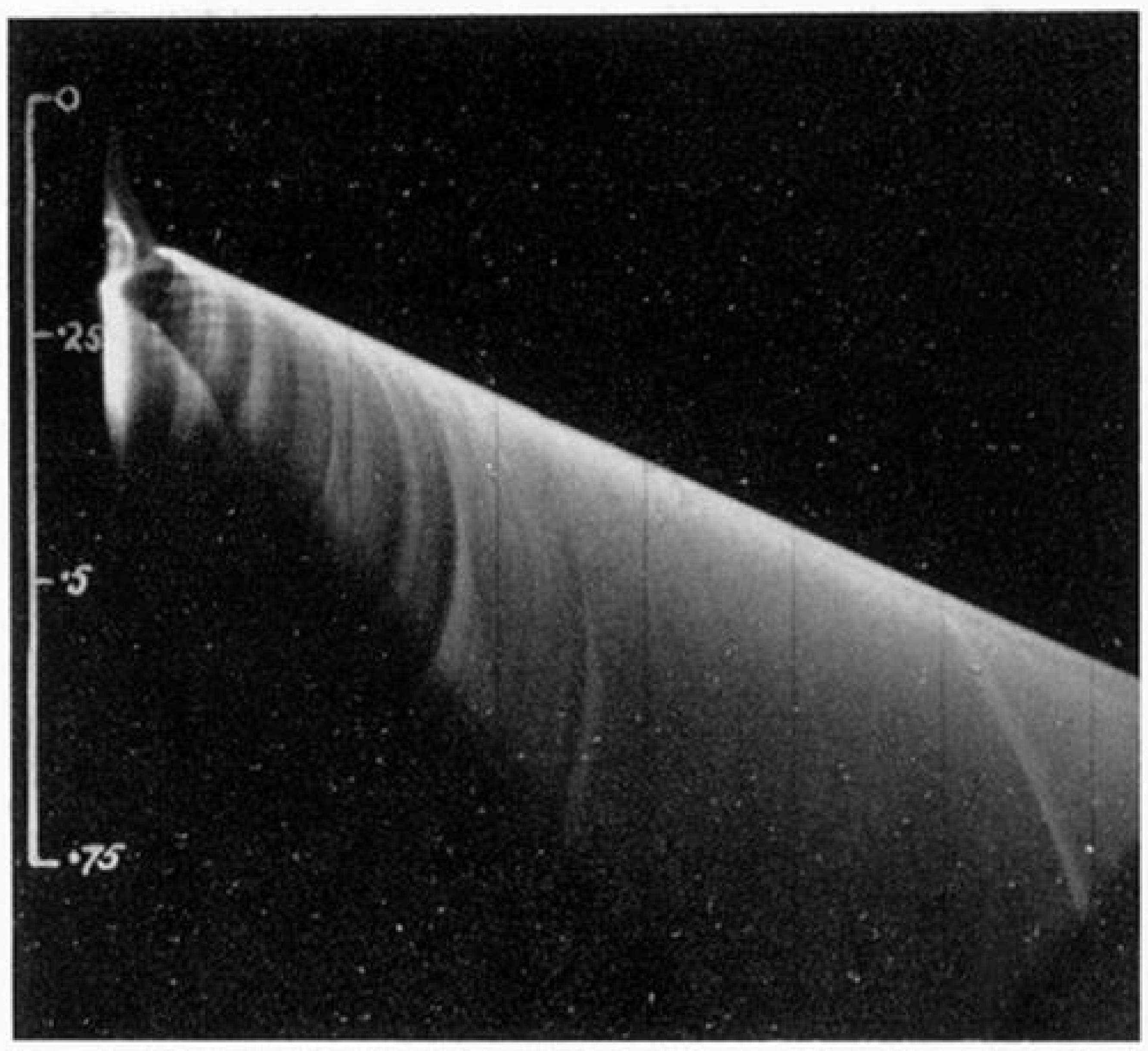

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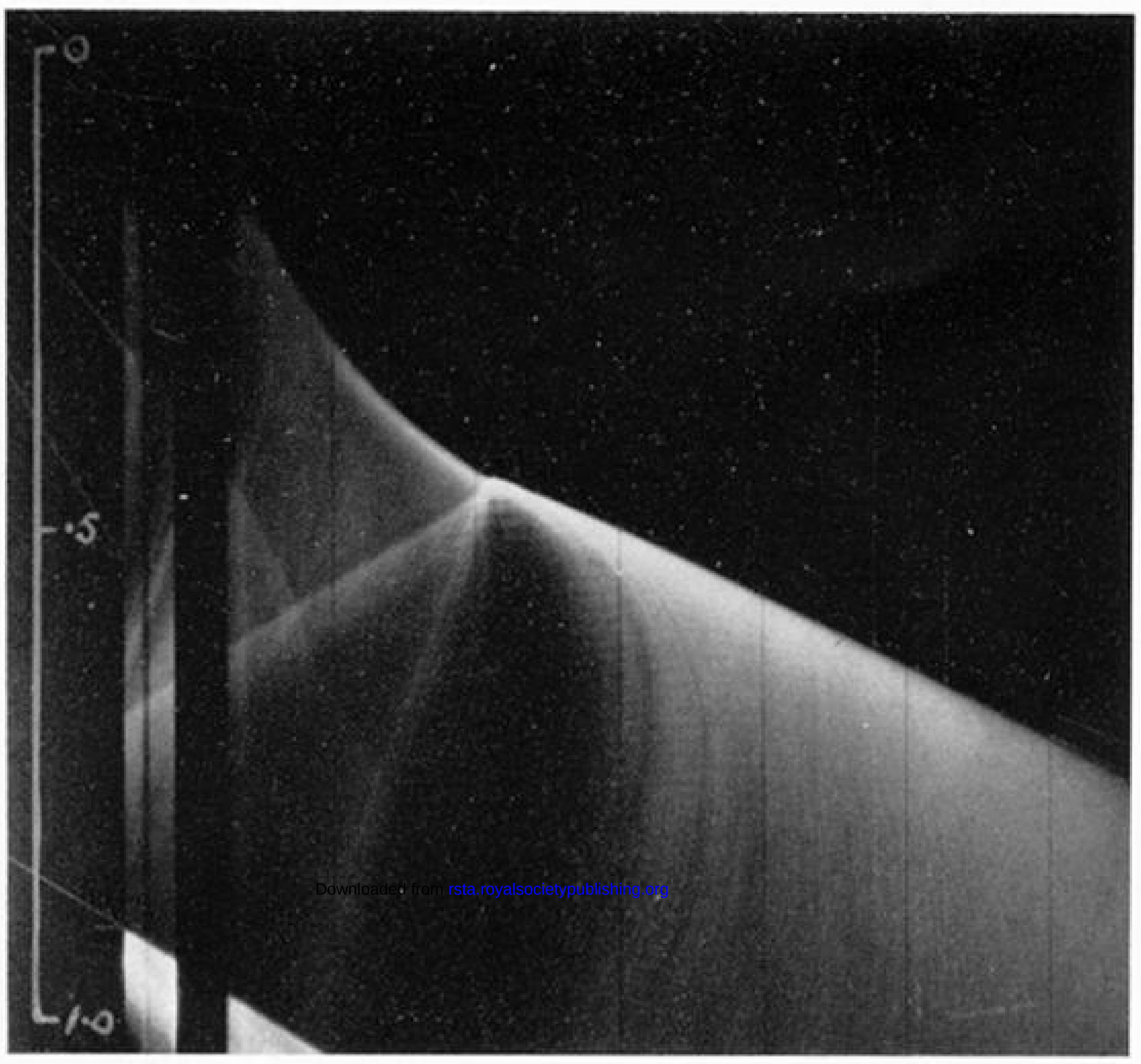

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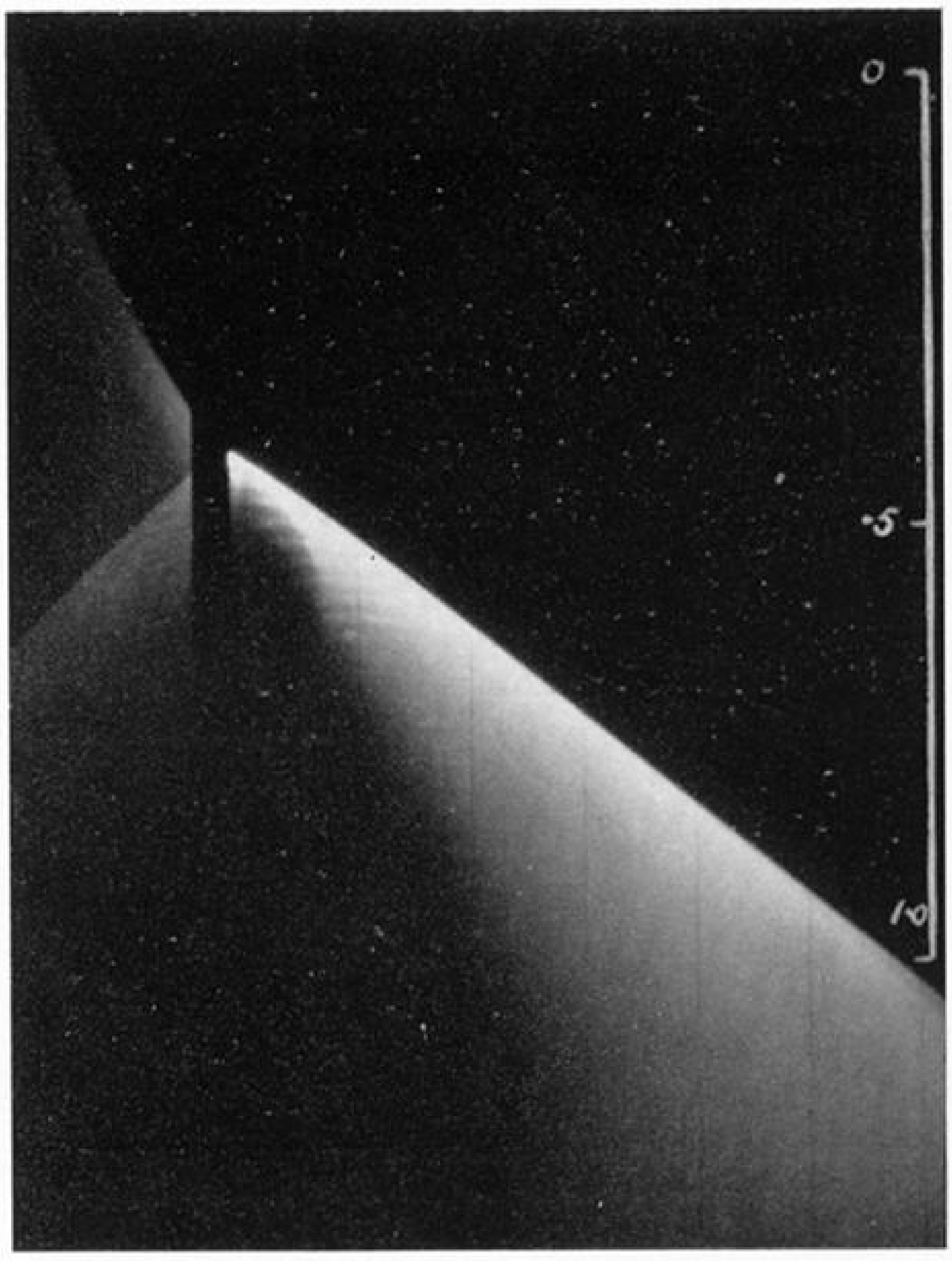

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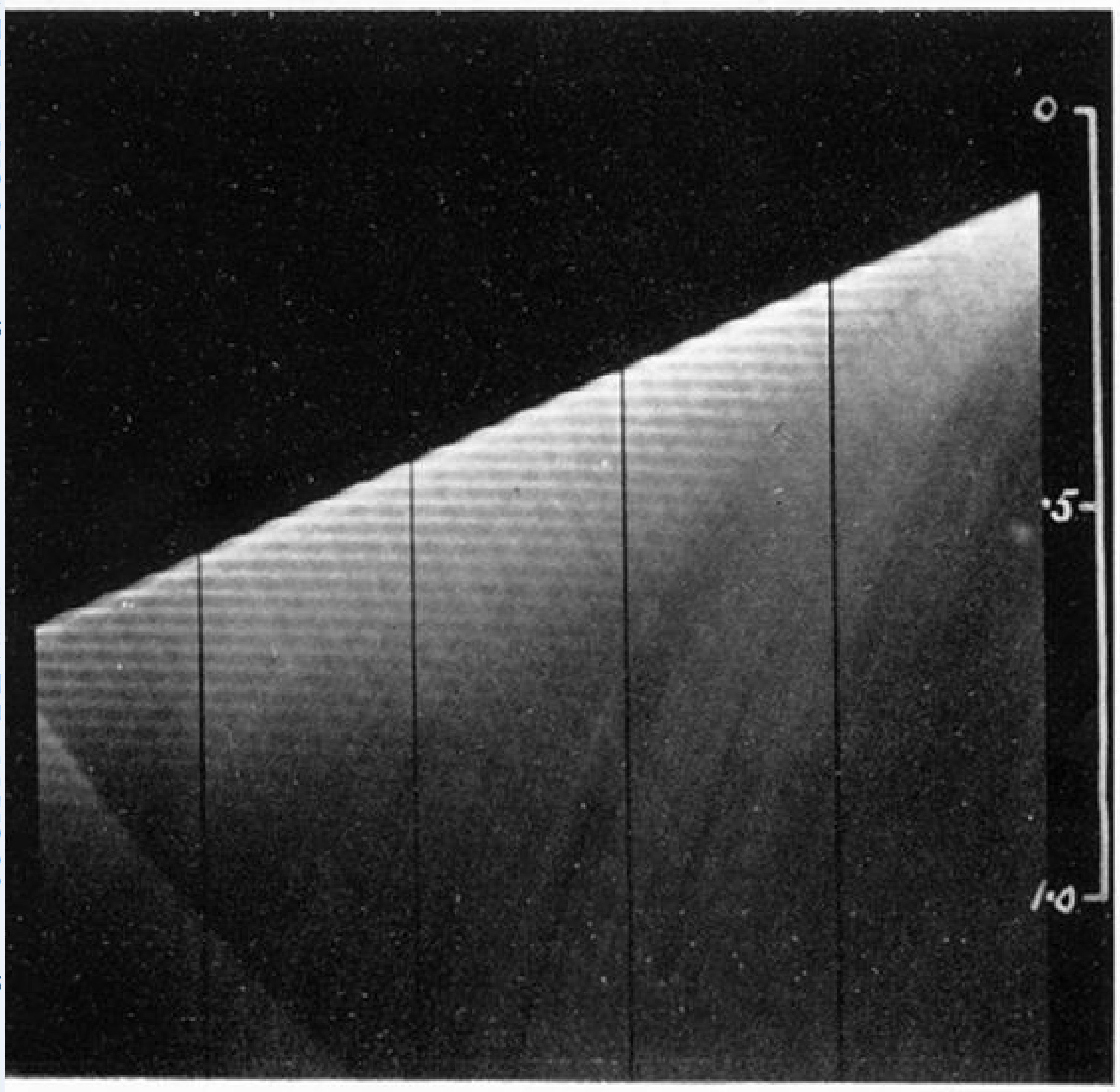

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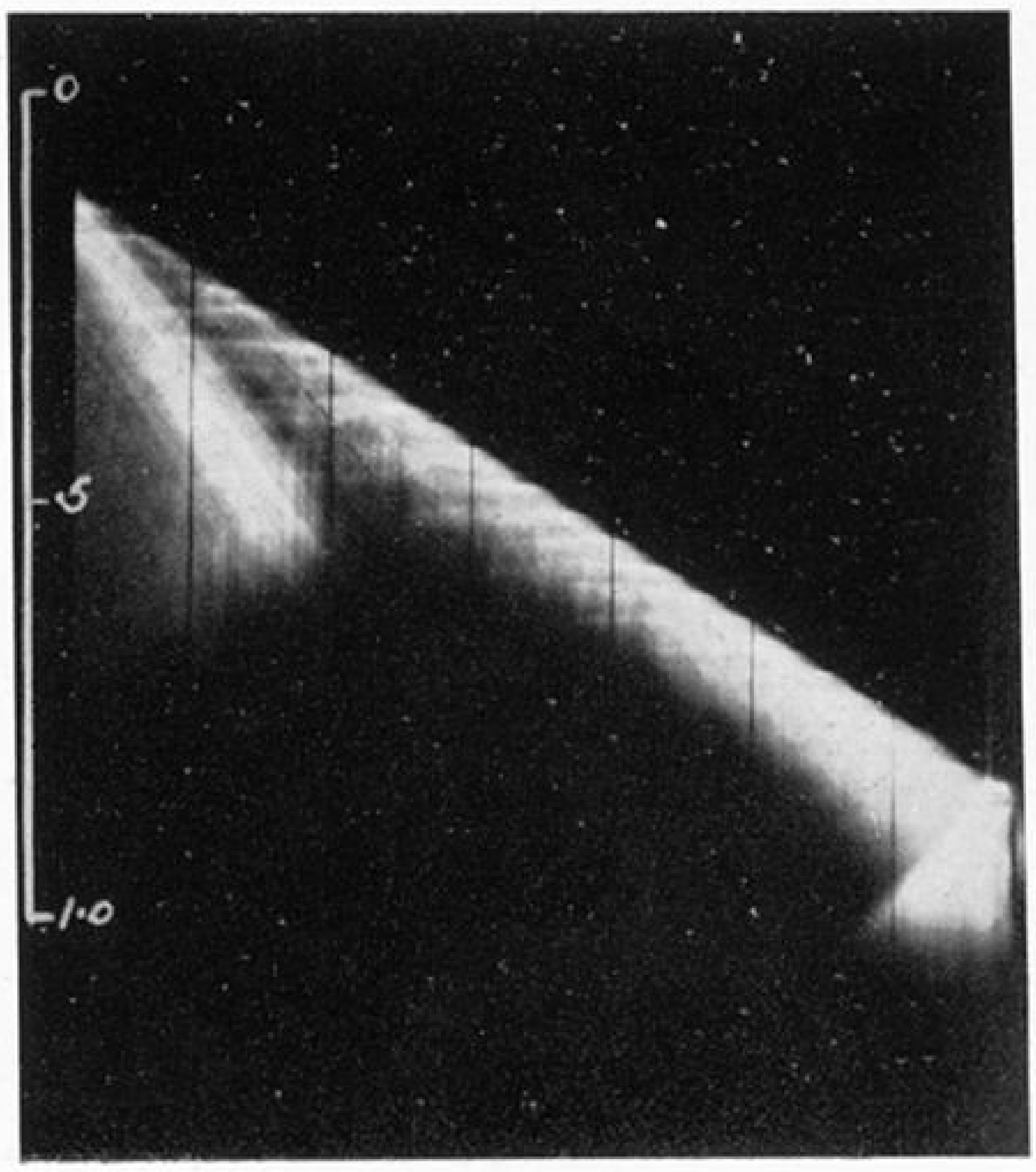

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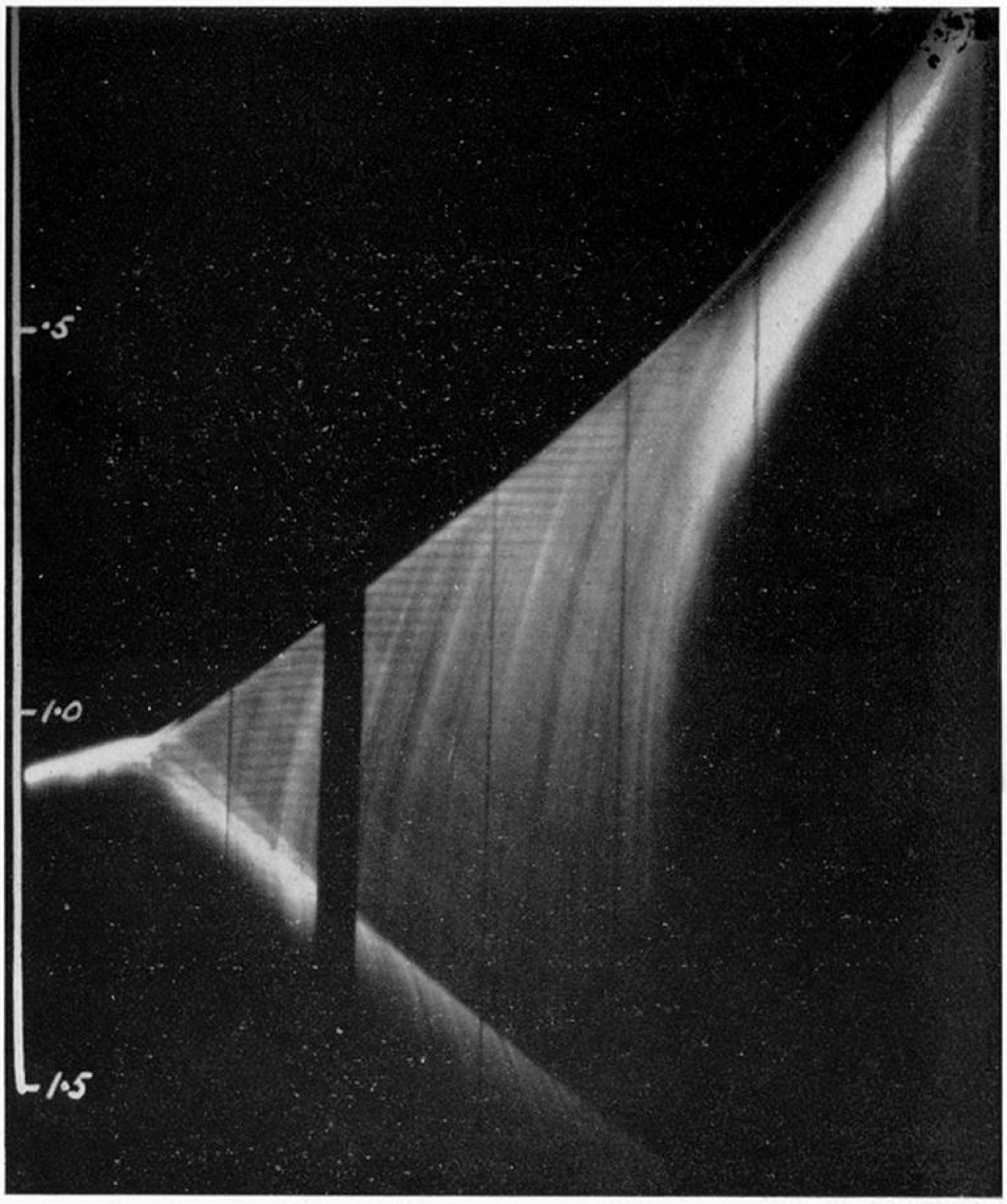

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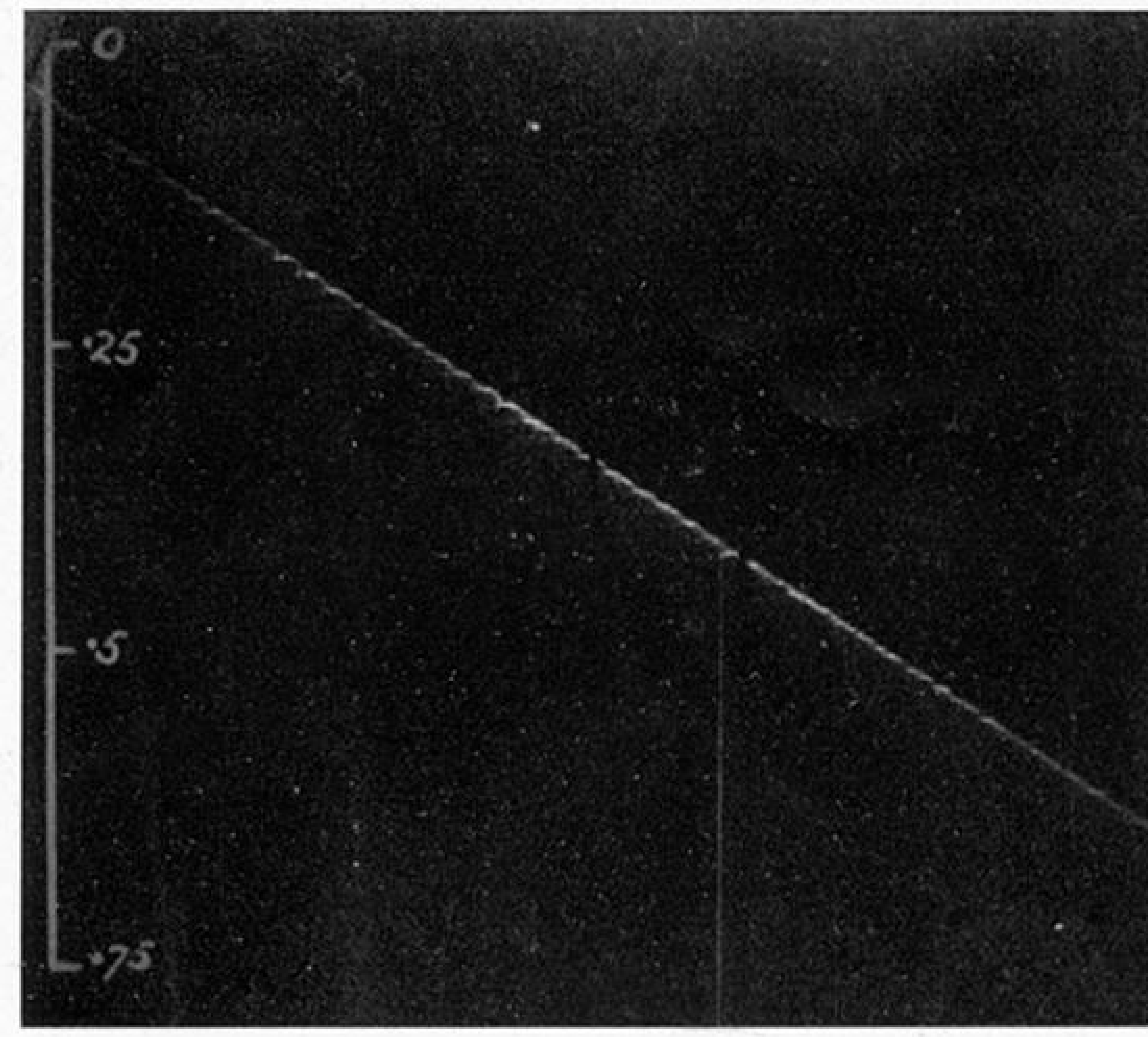

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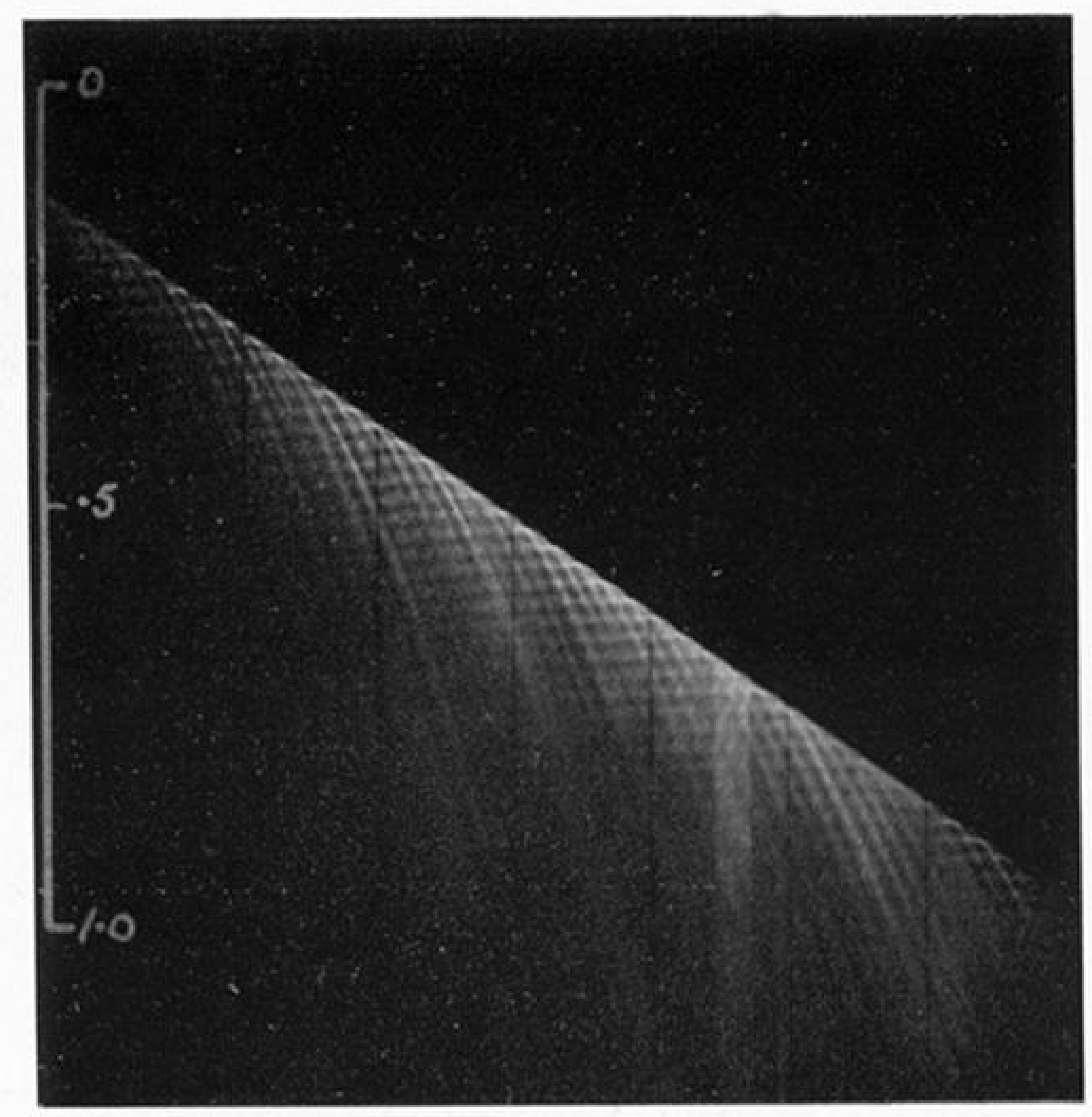

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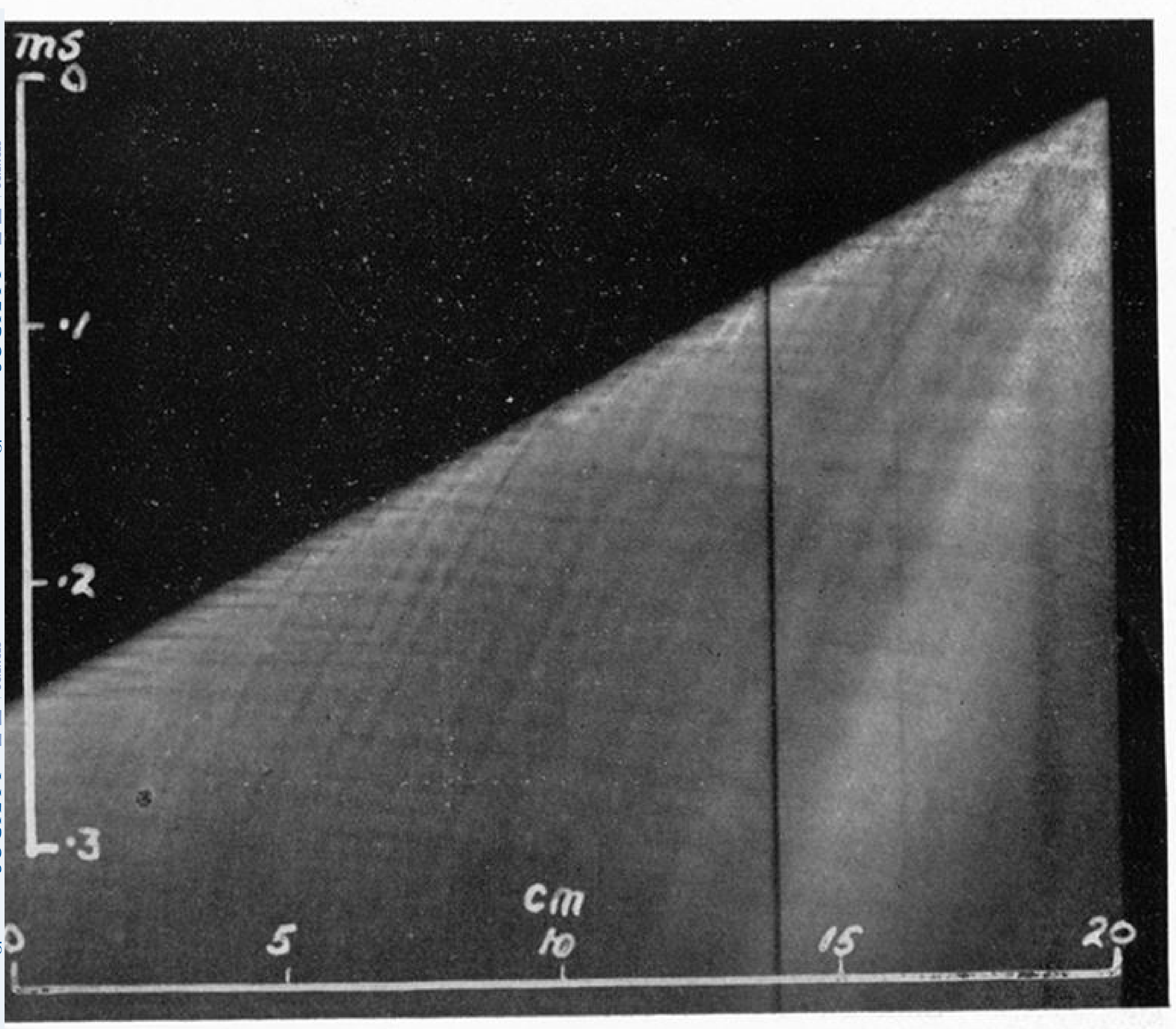
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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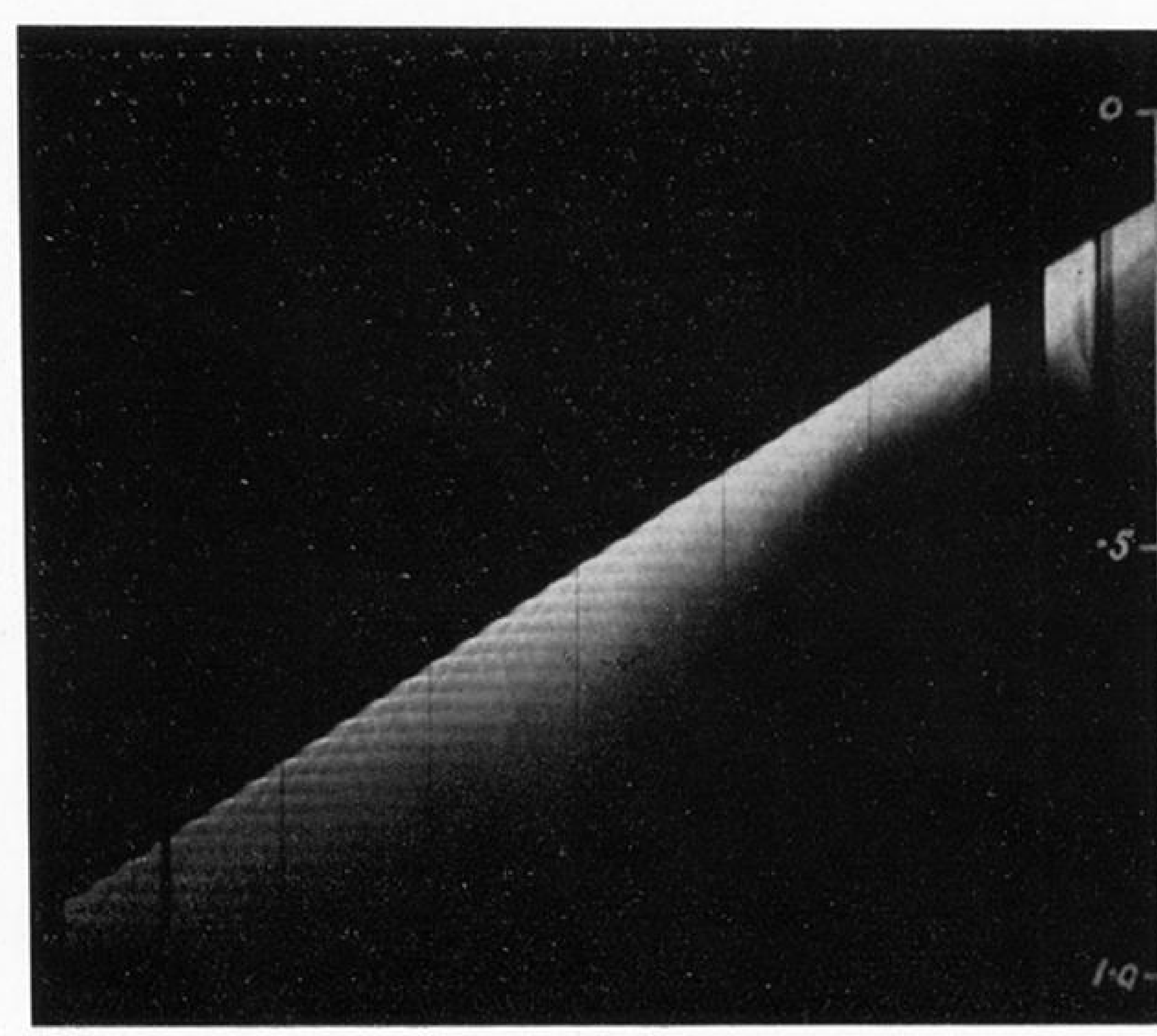

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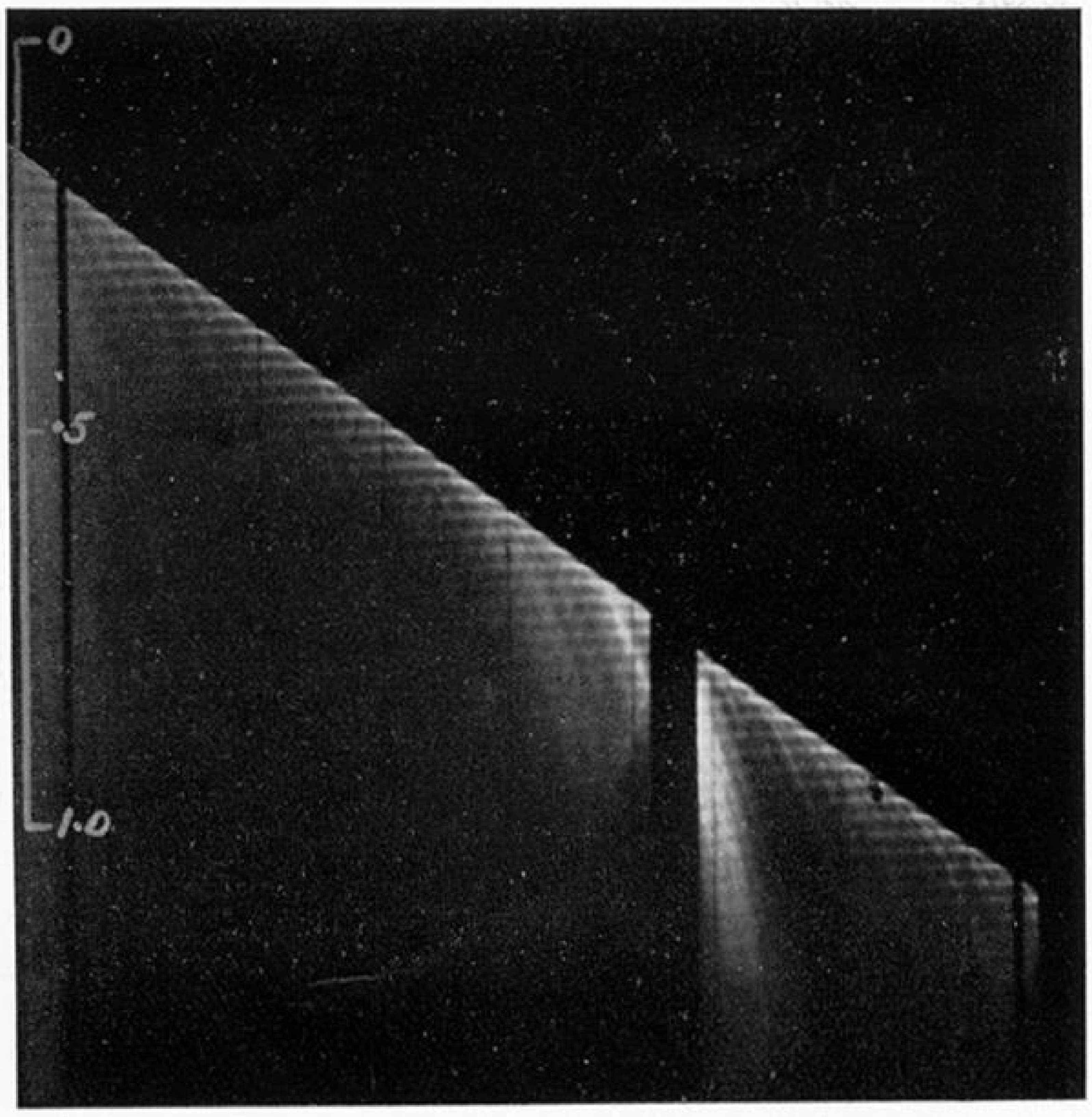

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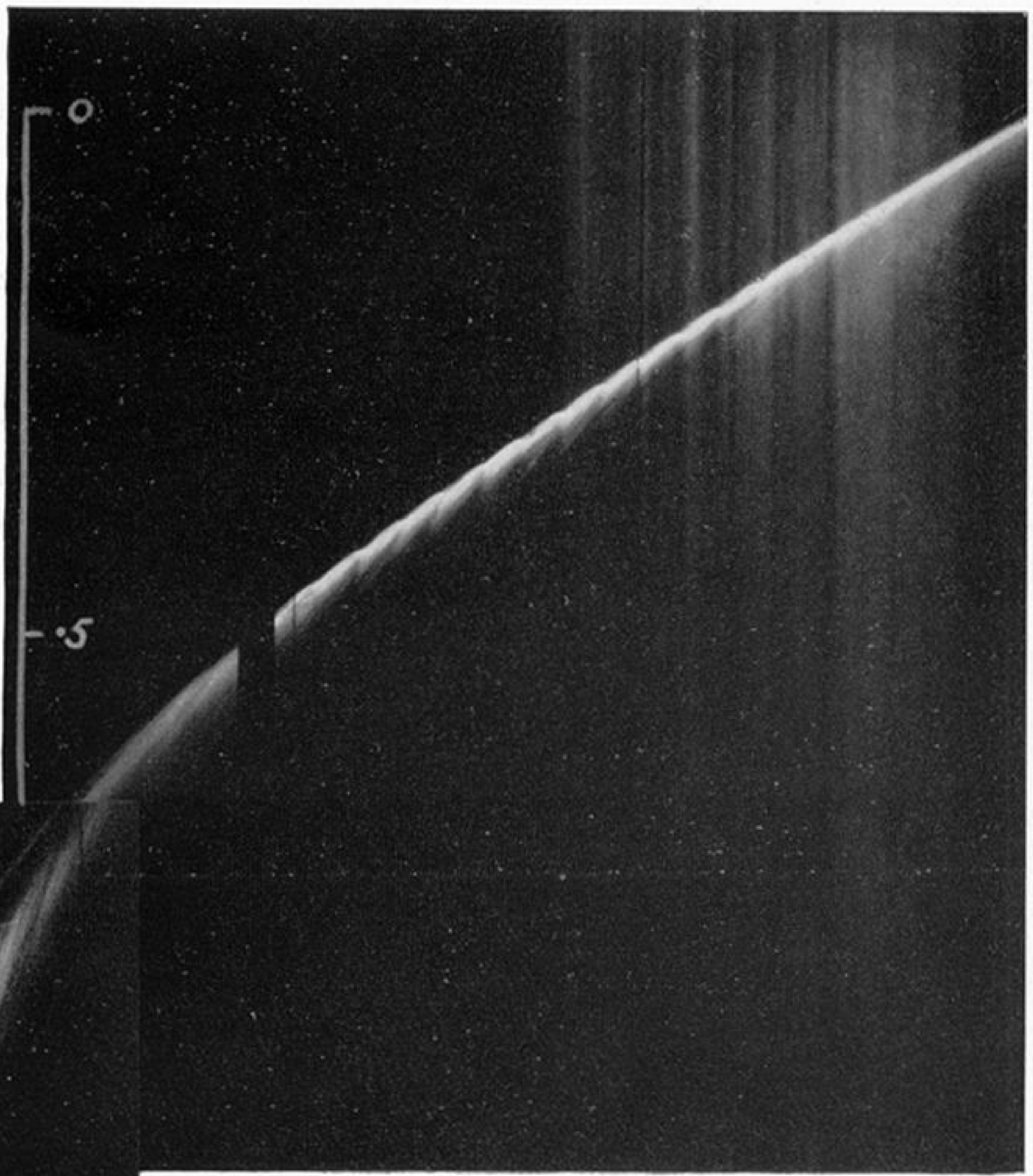

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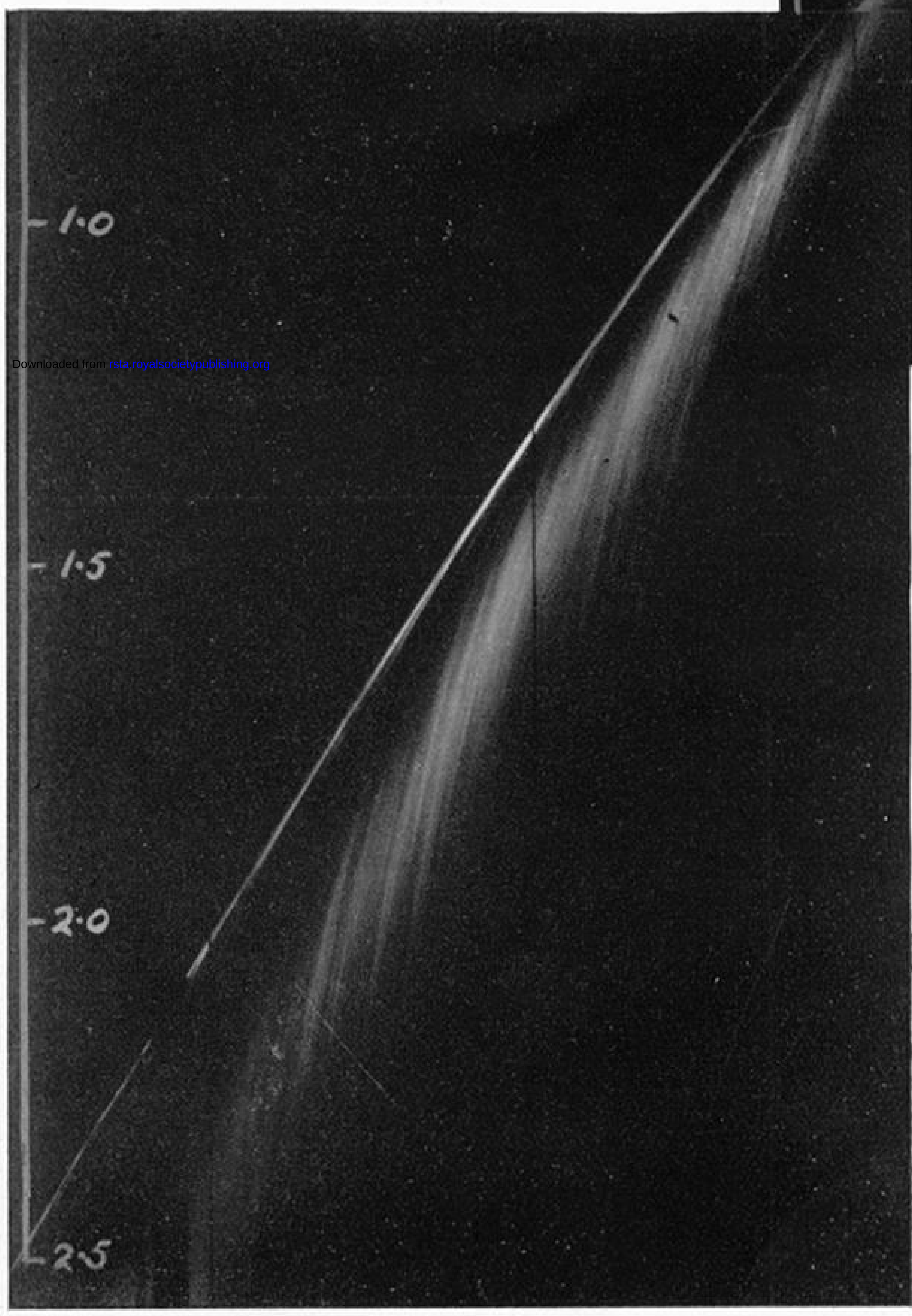

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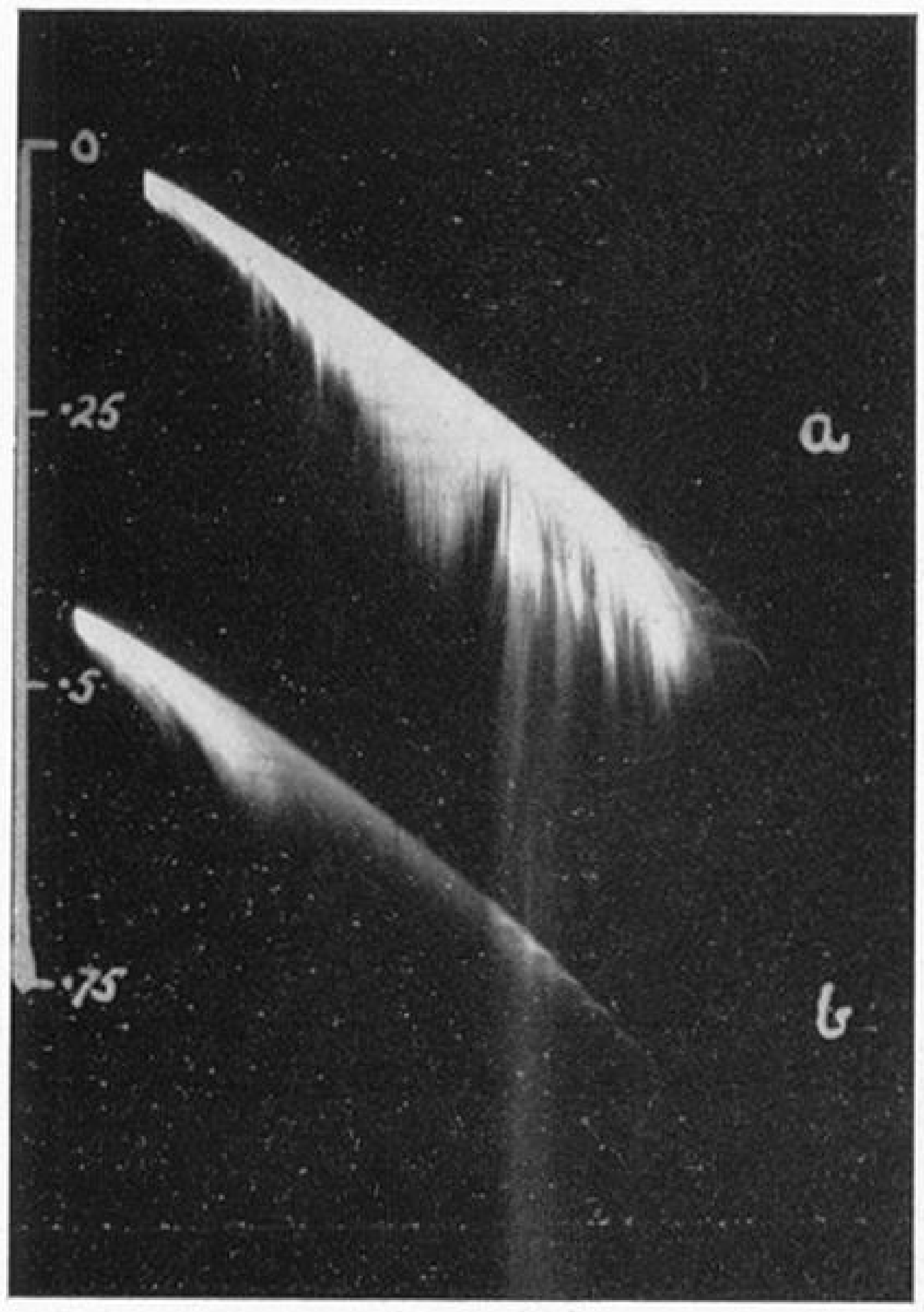

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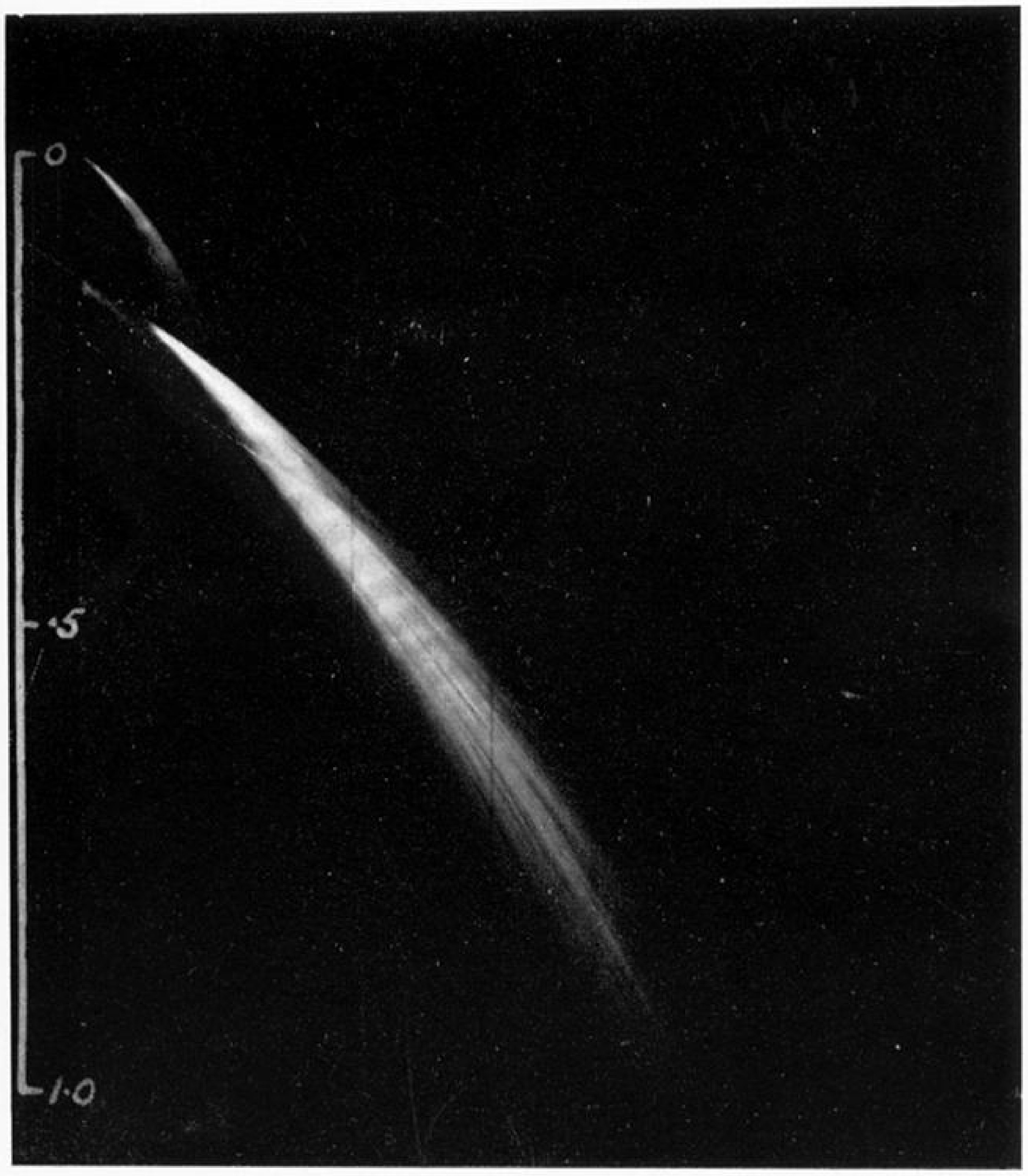

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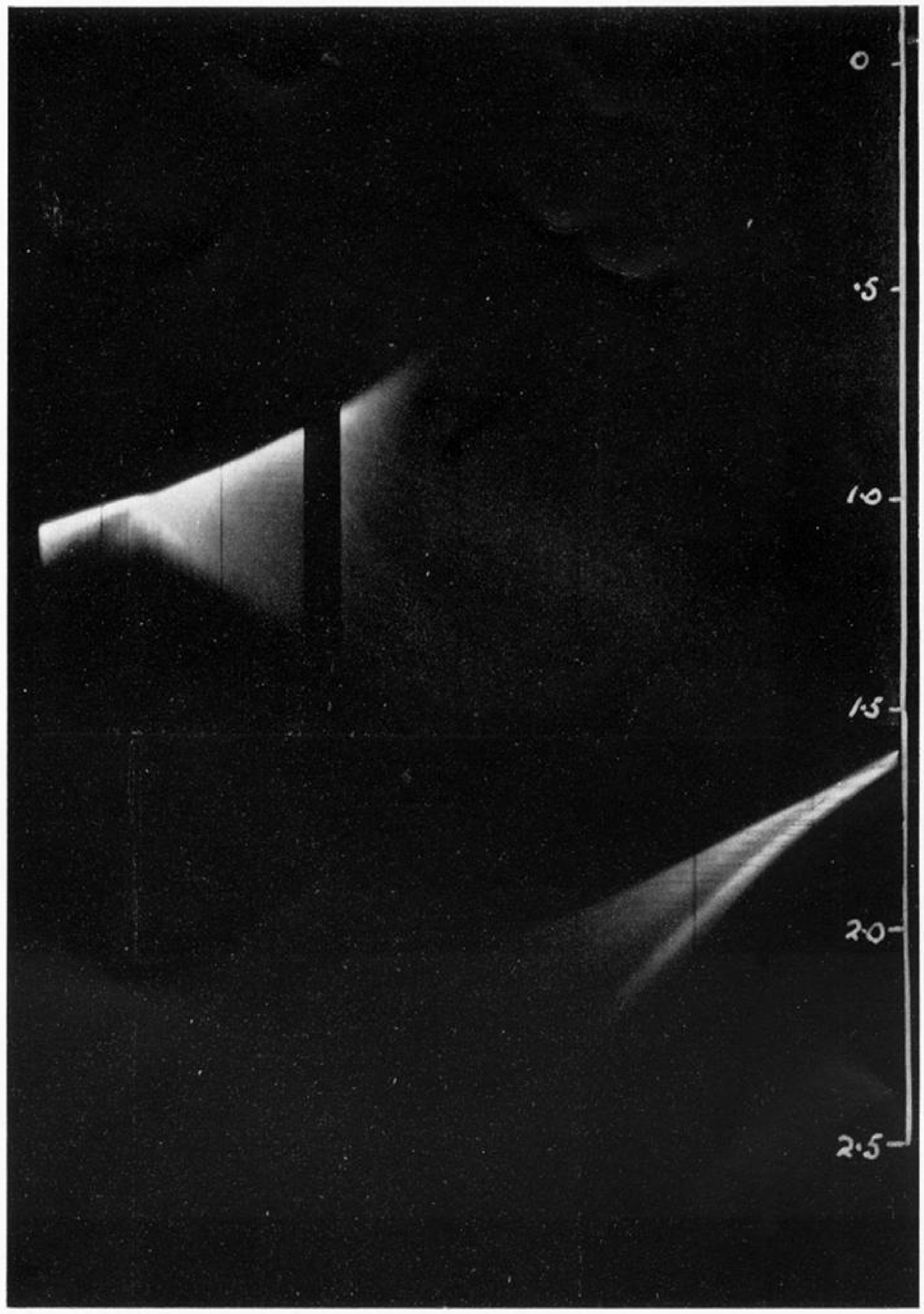

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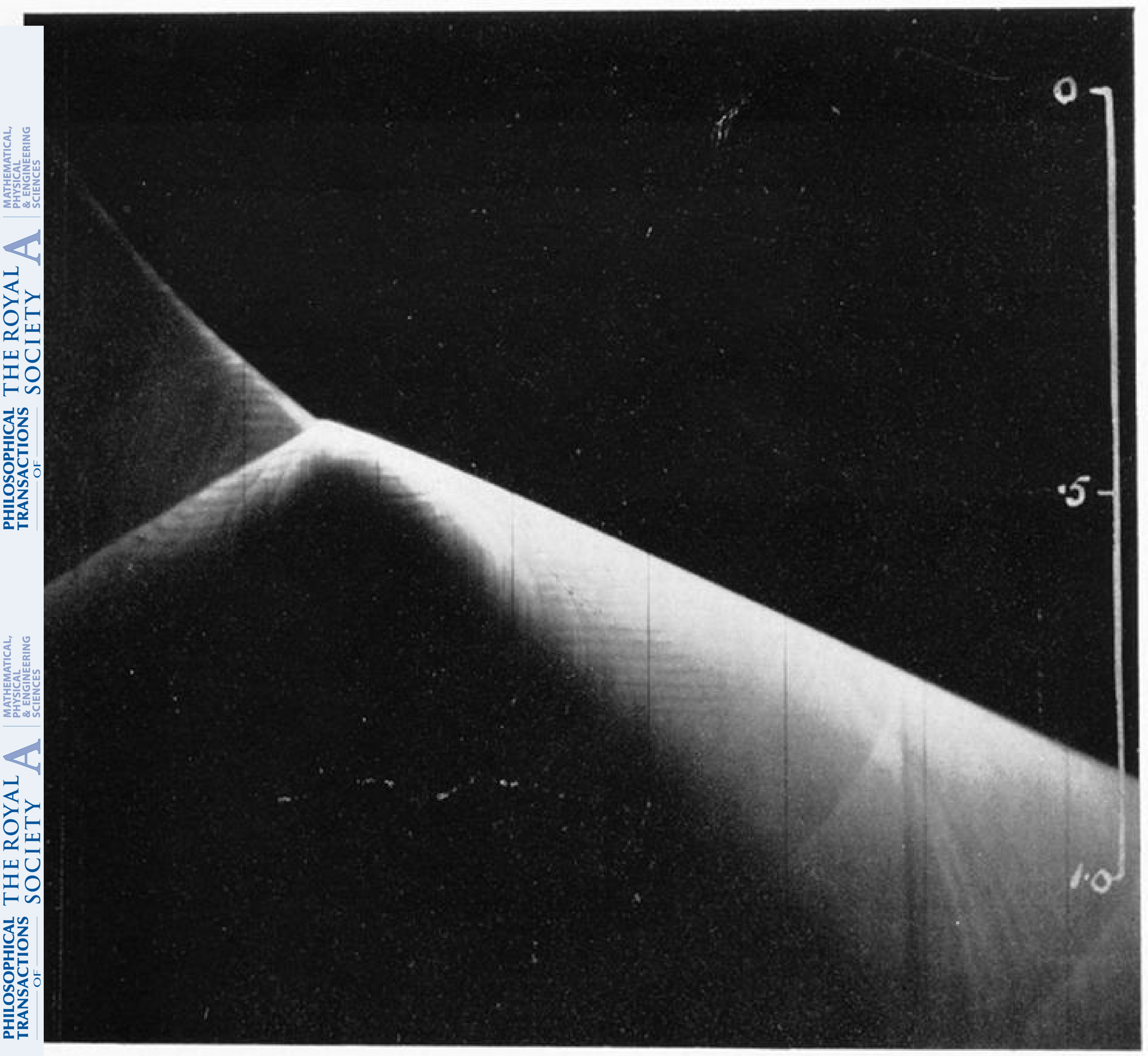

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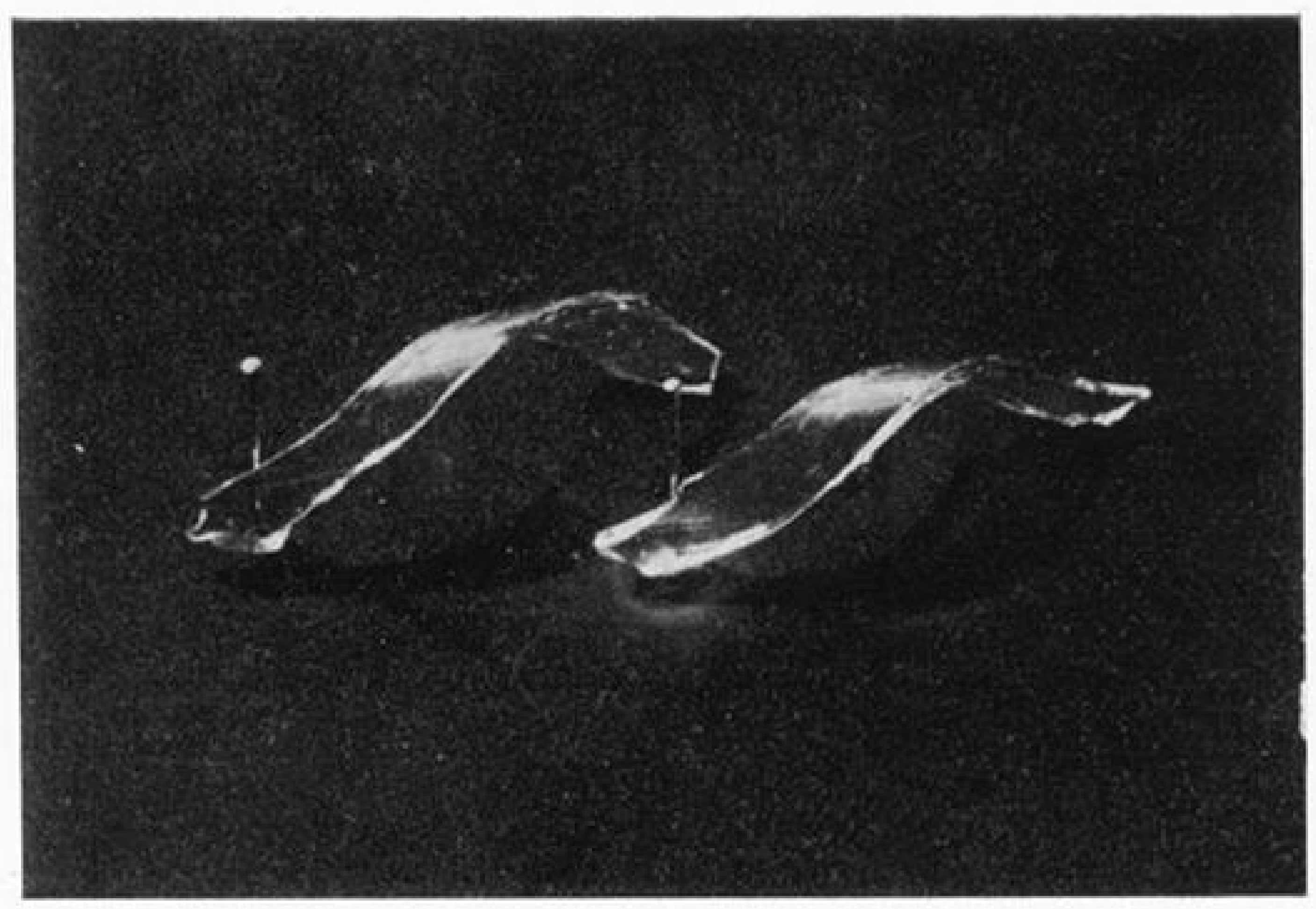

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES