VIII. *On the Movements of the Flame in the Explosion of Gases.*

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PART I.

HISTORICAL INTRODUCTION.

(1.) *On the Rate of Movement of the Flames, and the Pressures produced in the Explosion of Gases.*

HUMPHRY DAVY* was the first to observe the rate at which an explosion of gases was propagated in a tube, and he also made the first rough experiment on the temperature reached in an explosion. When gas from the distillation of coal (which he found more inflammable than fire-damp) was mixed with eight times its volume of air, and was fired in a glass tube 1 foot long and $\frac{1}{4}$ inch in diameter, the flame took more than a second to traverse the tube. When cyanogen mixed with twice its volume of oxygen was fired in a bent tube over water, the quantity of water displaced showed that the gases had expanded fifteen times their original bulk.†

BUNSEN,‡ in 1867, made the first careful measurement of the rate at which an explosion is propagated in gases, and he also made the first systematic researches on the pressure and temperature produced by the explosion of gases in closed vessels. His results led him to the remarkable conclusion that there was a discontinuous combustion in explosions. When electrolytic gas, or when carbonic oxide with half its volume of oxygen, is fired, only one-third of the mixture is burnt, according to BUNSEN, raising the temperature of the whole to about 3000° C. No further chemical action then occurs until the gaseous mixture falls, by cooling, below 2500° C. Then

* 'Phil. Trans.,' 1816; 'Collected Works,' vol. 6, p. 26.

† 'Phil. Trans.,' 1817; 'Collected Works,' vol. 6, p. 73.

‡ 'Ann. Phys. Chem.,' vol. 131, p. 161; 'Phil. Mag.,' vol. 34, p. 489 (1867).

a further combustion begins, and so on *per saltum*. These deductions were criticised by BERTHELOT, who pointed out that they assumed the constancy of the specific heats of steam and of carbonic acid at high temperatures.

BUNSEN also in the same paper makes the important statement that the rapidity with which a flame spreads is synchronous with the attainment of the maximum temperature and with complete combustion. Having determined the rate at which the flame is propagated in pure electrolytic gas as 34 metres per second, BUNSEN finds that the time required to ignite the gas in his pressure-tube from a central spark through a radius of 8·5 millims. is 8·5/34,000 = 1/4000 second. *We may conclude*, he says, *that the time which the whole of the gas takes to burn completely, and therefore also to reach the maximum temperature, is not more than* 1/4000 *part of a second.* BUNSEN thus identifies the rate of ignition with that of complete combustion. I do not know on what grounds BUNSEN based this statement, which I have found to be nearly true of the detonation-wave itself (*l'onde explosive* of BERTHELOT), but not of the initial periods of the explosion.

In 1881 BERTHELOT* and LE CHATELIER† independently discovered the great velocity with which the flame travels in gaseous explosions. BERTHELOT showed that this velocity was a constant for each gaseous mixture, and compared the rate of the detonation-wave (l'onde explosive) with the mean velocity of the molecules produced by the combustion before they had lost any heat. In the Bakerian Lecture for 1893 the author showed that BERTHELOT'S theory did not account for many observed rates of explosion, and put forward the view that the "explosion-wave" (now called the detonation-wave) travelled with the velocity of sound in the burning gases. Using the rates determined by the author, D. L. CHAPMAN‡ has argued that, if the detonation-wave is of a permanent type, an equation can be deduced from RIEMANN'S formula by which the rates of explosion can be calculated if the specific heats are known, and *vice versâ*. The rate of the detonation-wave may therefore be utilised, according to CHAPMAN, to determine the specific heats of gases at very high temperatures.

In 1883 MALLARD and LE CHATELIER§ published their researches on the combustion of gaseous explosive mixtures. They were the first to study the movements of the flame by a photographic method, of which I will speak more fully later on. In order to measure the pressures produced in the explosion, MALLARD and LE CHATELIER at first employed a very delicate Deprez indicator connected with the explosion bomb. A spring could be screwed up against the piston so that a certain pressure was required to move it. A thin metal tongue attached to a cord and weight was held in its place by the piston-rod; if the pressure on the piston equalled

* 'Comptes Rendus,' vol. 93, p. 18.

† 'Comptes Rendus,' vol. 93, p. 145.

‡ 'Phil. Mag.,' Jan., 1899, p. 90.

§ 'Annales des Mines' (8th series), vol. 4, 1883.

the pressure of the spring the metal tongue moved; if not, it remained stationary. By successive trials the pressures produced in the bomb could thus be obtained. With this apparatus MALLARD and LE CHATELIER found that, with all rapidly exploding mixtures, very high pressures were often produced during very small intervals of time. These pressures were not always the same for the same mixture. These fugitive pressures are due, according to MALLARD and LE CHATELIER, to the compression-wave which is propagated as the inflammation spreads from layer to layer, and may become of enormous intensity in the detonation-wave itself. As their object was to measure the mean pressure in the whole mass of gas, they abandoned the delicate Deprez indicator and used a Bourdon gauge. From the curves of pressure so registered they obtained expressions for the rate of cooling of the products of combustion, and so calculated the maximum pressures and temperatures of the explosions. Their results may be summarised in the statement that the maximum temperature of explosion of moist electrolytic gas is 3350° and the mean specific heat of steam between this temperature and 0° is 16·6, dissociation being very slight, if any, between these limits; on the other hand, the mean specific heat of carbonic acid rises to 13·6 at 2000°, and above this temperature dissociation begins. The diatomic gases (O_2, N_2, CO, &c.) also show a rise of specific heat, though far less marked than steam or carbonic acid exhibits.

In 1885 BERTHELOT and VIEILLE* published their researches on the pressures produced in the explosion of gases. They measured the pressures by determining the maximum acceleration of a piston of known weight moved against gravity, making a correction for the cooling effect of the walls when a small explosion vessel was employed. From the maximum pressures they calculated the maximum temperatures, arriving at results for hydrogen and carbonic oxide mixtures similar to those obtained by BUNSEN and by MALLARD and LE CHATELIER. But whereas BUNSEN attributed the defect of pressure observed to the inability of two-thirds of the gases to combine at the temperature reached, the French chemists attribute this defect of pressure to the great increase of the specific heats of the gaseous products of combustion. By determining the pressure produced in the explosion of cyanogen with its own volume of oxygen—

$$C_2N_2 + O_2 = 2CO + N_2$$

—they calculate the maximum temperature as 4394° C., and the mean specific heat of CO and N_2 at constant volume between 0° and 4400° C. is found to be 9·6, which is just double the value found at ordinary temperatures. Similar determinations were made with cyanogen and the oxides of nitrogen. It is to be observed that BERTHELOT and VIEILLE assume that at the moment of maximum pressure the combustion is complete. In the same way BERTHELOT and VIEILLE, by determining the pressures produced in the explosion of hydrogen and carbonic oxide, obtain

* 'Annales de Chim. et Phys.' [VI.], vol. 4, p. 13 (1885).

values for the specific heats of steam and carbonic acid at high temperatures. For the purpose of comparison, the results obtained by MALLARD and LE CHATELIER, by BERTHELOT and VIEILLE, and those calculated by CHAPMAN are printed in parallel columns in the following table :—

TABLE I.—Mean Specific Heat of Diatomic Gases (N_2, &c.) at Constant Volume.

Temperature.	MALLARD and LE CHATELIER.	BERTHELOT and VIEILLE.	D. L. CHAPMAN.
0° C.	4·8	4·75	—
0°—1000°	5·4	4·75	—
0°—2000°	6·0	5·4	7·45
0°—3000°	6·6	7·0	7·56
0°—4000°	7·2	8·6	7·67
0°—5000°	7·8*	10·2	7·78
	Mean Specific Heat of Steam.		
0°	5·6	—	—
0°—1000°	8·9	—	—
0°—2000°	12·2	16·2	8·7
0°—3000°	15·5	18·1	11·9
0°—4000°	18·7	20·0	14·3
	Mean Specific Heat of CO_2.		
0°	6·3	6·4	—
0°—1000°	11·1	—	—
0°—2000°	13·6	19·1	—
0°—3000°	Dissociation	20·6	—

On the other hand, D. CLERK† contends that in an explosion of gases, combustion is not completed instantaneously, the products of combustion are cooling while the unburnt particles are still combining, and therefore the maximum temperature reached never coincides with the theoretical temperature calculated for instantaneous combustion. The spreading of the flame throughout the vessel, *i.e.*, the inflammation of the whole mass of gas, is not coincident with the moment of maximum temperature and pressure. On exploding mixtures of coal-gas and air, and of hydrogen and air, in a closed vessel, and registering the pressure with a RICHARDS' indicator, CLERK comes to the conclusion that neither dissociation of the products of combustion, nor a rise in the specific heats, can account for the fall of the observed pressures below those calculated. This fall must be accounted for by the gradual progress of the combustion.

Concerning the rise in the specific heat of carbonic acid there can, I think, be

* Direct experiments made by MALLARD and LE CHATELIER on the explosion of $C_2N_2 + O_2$ give the mean specific heat of CO and of N_2 at 4200° as 10, and at 2500° as 7·5. 'Recherches,' p. 276.

† 'Proc. Inst. Civil Engineers,' vol. 85 (1886).

little doubt that it really exists. REGNAULT and WIEDEMANN both found a distinct increase at constant pressure between 100° C. and 200° C. I have lately, in conjunction with Mr. F. W. RIXON, determined the specific heat of carbonic acid at constant volume at 100° C., 200° C., 300° C., and 400° C., and find a steady rise in the constant.* On the other hand, the facility with which carbonic acid breaks up under the influence of electric discharges indicates that, as its temperature is raised, work is done in loosening the chemical bonds—work which BERTHELOT calls "le travail de désagrégation moléculaire qui précède la décomposition." Of the fact of the partial dissociation of carbonic acid and steam at the temperature of the detonation-wave, Mr. H. W. SMITH and I have found direct proof in the unburnt gases left on cooling.†

LIVEING and DEWAR‡ showed in 1884 that the flame of an explosion of gases in a glass vessel exhibited with marked brightness the lines of sodium and of calcium. When the explosion of electrolytic gas was made to pass along an iron tube about 3 feet long, closed at one end by a plate of quartz, a spectroscope placed in a line with the axis of the tube revealed the fact that the light was largely due to iron lines. When metallic salts in the form of powder were introduced into the explosion tube, the corresponding lines were visible in the spectroscope. These experiments showed how quickly the ignited gases could detach and volatilise solid matter from the side of the tube. But as regards the nature of the detonation-wave itself, the most interesting observation made by LIVEING and DEWAR was the reversal of the red lithium line when the explosion was made to travel *towards* the spectroscope. The natural interpretation of this reversal was that "there are gradations of temperature in the flame, and that the front of the advancing wave of explosion is somewhat cooler than the following part." I would observe on this conclusion that in the many hundreds of photographs taken by me, the front of the detonation-wave is always shown as exceedingly sharp, and that probably the reversal observed was due to the wave reflected back from the quartz plate.

The light produced by the explosions of electrolytic gas is mainly due to particles knocked from the glass. In the faint continuous spectrum shown by the flame, the calcium lines stand out prominently. When the explosion travels first through a metal tube joined to a glass one in which the flame is photographed, the light is more intense near the junction. One can see the stream of luminous matter carried out of the metal tube, as in figs. 23 and 42 (lead) and 39 (copper).

The luminous particles, whatever their nature, follow very closely the movements of the gas in which they float.

The cyanogen explosions gave a continuous spectrum crossed by metallic lines and by the characteristic "cyanogen lines."

* 'Brit. Assoc. Report,' 1900, p. 697.

† 'Manchester Memoirs,' 1889, p. 2.

‡ 'Roy. Soc. Proc.,' vol. 36, p. 471.

By the kindness of Dr. SCHUSTER I was enabled to use his apparatus to photograph the spectrum of the flame of cyanogen and oxygen as it exploded in a tube. With a single prism, a continuous spectrum was obtained showing a few bright lines. In order to get a detailed spectrum, the gases were fired in a gun-metal tube *end-on* to the spectroscope, the end of the tube next the spectroscope being open just before firing. By this means sufficient light was secured to employ considerable dispersion. A cadmium spark spectrum was taken on the same plate for comparison. No reversal of any line was shown on the photograph as in LIVEING and DEWAR'S experiment where the explosion tube was closed by a quartz plate.

(2.) *Photographic Records of the Moving Flame.*

The discovery of the detonation-wave in gaseous mixtures by BERTHELOT and VIEILLE was followed shortly by the researches of MALLARD and LE CHATELIER on the initial phases of the explosion. The method they found most suitable for tracing the progress of the flame was a photographic one; the movement of the flame along a horizontal tube being recorded on a sensitised paper moving vertically. Failing to obtain any photographic image of the flame with mixtures such as carbonic oxide with oxygen, MALLARD and LE CHATELIER employed carbon disulphide with oxygen or nitric oxide, these mixtures yielding highly actinic flames.

When the gases were ignited by a flame at the open end of a long tube, the flame was propagated along the tube for some distance with a uniform slow velocity which MALLARD and LE CHATELIER regard as the true rate of propagation by conduction. In the case of mixtures of carbon disulphide with nitric oxide, this period of uniform movement is succeeded by oscillations of the flame, which sometimes become of larger and larger amplitude and then die down, and sometimes give rise to the detonation-wave. When carbon disulphide is mixed with oxygen the preliminary period of uniform movement is shorter and is immediately succeeded by the detonation-wave. These two mixtures appear to be typical of other gaseous mixtures, carbon disulphide with oxygen resembling oxygen mixtures generally, carbon disulphide with nitric oxide resembling air mixtures generally.

MALLARD and LE CHATELIER draw attention to the fact that in the explosions starting at the open end of the tube the development of the detonation-wave is not progressive, but always instantaneous. The detonation-wave is characterised not only by its great velocity of movement, but by its intense luminosity and the very high pressures instantaneously set up in it.

On the other hand, MALLARD and LE CHATELIER found that, when the mixture of carbon disulphide and nitric oxide was fired near the *closed* end of the tube the movement of the flame was uniformly accelerated, until the detonation-wave was set up. Their apparatus, in which the photographic paper could not be moved faster than 1 metre per second, failed to analyse the more rapid movements of the flame.

To make clear the movements studied by MALLARD and LE CHATELIER I reproduce on Plate 10 four of their photographs.

In fig. 1 the mixture of carbon disulphide with six times its volume of nitric oxide is ignited at the open end of a tube 3 metres long and 20 millims. in diameter. The tube is made up of three pieces, of 1 metre each, fastened together by rubber rings, which, eclipsing the flame as it passes, show as blank bands on the photographs. The flame advances with a uniform velocity of 1·25 metres per second to the point *b*, where the rate increases and vibrations begin. From this point the rest of the combustion takes place with strong vibrations of the flame.

In a tube of 10 millims. diameter the period of uniform velocity is shorter (fig. 2). The vibrations die down and recommence, but after the flame has traversed a little over 1 metre the flame is extinguished.

Fig. 4 is the photograph of the explosion of carbon disulphide and oxygen fired at the open end of the tube. A short period of uniform progression is followed abruptly by a flame which appears to be propagated instantaneously.

Fig. 3 shows the effect of igniting the mixture of carbon disulphide and nitric oxide near the closed end of a tube 2 metres in length. The velocity of the flame continually increases from the point of inflammation, *a*. This photograph* clearly shows a "rebound" wave, *c d*, from the end of the tube, which was not broken like the one described in the text ('Recherches,' p. 71).

Experiments of A. VON OETTINGEN *and* A. VON GERNET.

OETTINGEN and GERNET† set out to prove the truth of BUNSEN'S principle of successive partial explosions. This discontinuous step-like combustion ("welches wir mit neuen Methoden experimentell zu prüfen unternahmen") should yield evidence of its real existence if the flame of the explosion were analysed by a rotating mirror. By an ingenious arrangement they contrived to pass a spark through a eudiometer tube at the moment when the image of the tube was thrown by the rotating mirror into a camera, so that the light of the flame might be drawn out and its movements recorded on a photographic plate. But although the flame of electrolytic gas appeared intensely bright, its spectrum only gave the sodium and calcium lines, and the most sensitive photographic plates showed "hardly a trace of the process." Failing to photograph the flame itself, they added finely divided salts to the tube, and found that the most brilliant pictures were given by cuprous chloride.

The pictures show the passage of waves sharply reflected backwards and forwards from the ends of the tube, and gradually diminishing in intensity and velocity.

* This photograph is not described in the text of MALLARD and LE CHATELIER'S book. M. LE CHATELIER writes to me that my interpretation of the photograph is correct. I did not notice this "rebound" wave in the photograph until after my experiments of 1896.

† "Ueber Knallgasexplosion," 'Annalen der Phys. und Chemie,' 33, 586 (1888).

These visible waves, according to OETTINGEN and GERNET, are not a picture of the process of combustion itself, but are compression-waves moving through the products of combustion after the explosion is completed. The explosion itself, they say, *is quite invisible.*

Fig. 5, Plate 10, is a reproduction of their picture, showing the waves produced when the electrolytic gas is fired in the middle of a eudiometer 400 millims. long.

The image of the spark is lengthened into a vertical line by reflexion from the sides of the eudiometer. Nothing else is visible on the plate for some time except a thin wavy line, which, according to OETTINGEN and GERNET, is due to the particles of salt raised to incandescence by the spark. Then after the lapse of $\frac{1}{1000}$ second the material in the tube becomes luminous and a wave is seen starting from the upper end of the tube at d and traversing the gases to the lower end where it is reflected at e, and so on backwards and forwards, making nearly four complete vibrations before it becomes non-luminous. The photograph shows very beautifully the passage of these compression-waves through the heated gases, and the way in which the mass of gas (carrying with it the luminous particles from the salt) follows the compression-waves backwards and forwards. But I can see no evidence in this photograph for the conclusion drawn by OETTINGEN and GERNET, viz., that a true detonation-wave has proceeded from the spark, and its compression-wave has traversed the tube several times before it becomes visible by raising the salts to incandescence. The fig. 5A (reproduced from their Memoir) shows in outline the course of one of these hypothetical waves starting downwards from the spark and being reflected at a, b, c, and d before it becomes visible. According to this view, the wave has traversed the tube $3\frac{1}{2}$ times before it is photographed, and the true chemical combustion gives no light.

In the next photograph reproduced (fig. 6) the gases were fired at a point a quarter of its length from the bottom of the tube. In this case there is a displacement of the wavy line joining the spark to the luminous portion, but hardly sufficient to justify the conclusion that the visible wave proceeding downwards from d is the residue of a detonation-wave starting upwards from the spark and being reflected at b, and again at c. But this is the interpretation put upon the photograph by OETTINGEN and GERNET, as is shown in fig. 6A. By constructing these invisible waves backwards from the visible ones, it is possible, according to OETTINGEN and GERNET, to arrive at the velocity of the true detonation-wave at starting. In this way they calculate that the explosion travels from the spark at a velocity of about 2550 metres per second, and criticise BERTHELOT'S statement that the flame increases regularly in velocity from the point of ignition. I will show in the sequel that the interpretation put upon these photographs by their authors is erroneous. The flame really starts slowly, but its rate of progress is remarkably affected when it is reflected from the end of a tube. It is quite true that the flame of electrolytic gas when first ignited has very slight luminosity, but this only holds during the period of slow motion. The

temperature and luminosity increase with the velocity; the flames are probably most luminous where they are hottest.

But besides these primary waves there are others to which OETTINGEN and GERNET call special attention; these are "secondary waves" running nearly parallel to the primary waves. The photograph given in fig. 5 is referred to as showing very clearly four of these waves near together running parallel to the chief wave, which starts downwards from *d*. Other photographs show somewhat similar appearances, *i.e.*, of weaker waves running nearly parallel with and sometimes coalescing with primary waves. OETTINGEN and GERNET say that they can find no other reason for these waves following one another at a short interval, but that successive explosions have taken place from the electrodes exactly as BUNSEN imagined. The evidence relied on for these successive explosions, even if we accept the general interpretation of the photographs given by the authors, appears to me exceedingly slender. My own photographs will show how complicated the reflexions are when gases are exploded in a short tube, and how readily "nearly parallel waves" are produced with a single ignition of the gases. In the many photographs of the initial period of the explosion taken by me and my fellow-workers there is no indication of any *second* flame starting from the region of the spark.

PART II.

PHOTOGRAPHIC ANALYSIS OF DETONATION-WAVES AND THEIR REFLEXIONS.

(*In conjunction with* E. H. STRANGE, *B.Sc.*, *and* E. GRAHAM, *B.Sc.*)

In 1895 we were engaged on an investigation* into the nature of the flame produced by the explosion of cyanogen with oxygen, when we made the observation which led to the present research. We found that the flame could be sharply photographed on EASTMAN'S films without the addition of any metallic salts, and that the films could be rotated very rapidly on a wheel without damage. In the experiments we then made, a mixture of cyanogen with oxygen was fired in a long vertical leaden pipe having a short piece of glass tube let into it to serve as a window. This window was focussed on to the vertically moving film. When the explosion passed through the glass tube an illuminated image of the window was thrown on the photographic film, and was drawn out to a length depending on the rate of rotation of the film and the time during which the gas in the glass tube was photographically luminous. We found that cyanogen with its own volume of oxygen (burning to carbonic oxide) gave a much brighter and shorter flame than cyanogen burning to carbonic acid, a result in accord with the hypothesis that carbon (in carbon

* "On the Explosion of Cyanogen," 'Journ. Chem. Soc.,' 1896.

compounds) burns first to carbonic oxide. In the earlier of these experiments we were puzzled by a re-duplication of the image which constantly appeared in the photographs, until at last this was found to be due to an unsuspected constriction in the lead pipe, which had sent back a reflected wave sufficiently intense to re-illuminate the window. This led us to examine more precisely the detonation-wave and its reflexions by means of the rotating film. The camera and film being arranged as before, so that the image was thrown on the film as the latter moved vertically downwards, and the explosion-tube being fixed horizontally, the photograph showed an inclined line of light compounded of the horizontal movement of the image of the flame and the vertical movement of the film. When the explosion-tube was placed at such a distance from the camera that the length of the image was $\frac{1}{30}$ that of the tube, a velocity of the flame of 3000 metres per second corresponded with a horizontal velocity of the image of 100 metres per second. When the wheel was rotated twenty-five times per second this caused the film to move vertically at a rate of 25 metres per second, the circumference of the wheel being 1 metre. The line described by the image on the film thus made an angle with the horizontal whose tangent was $\frac{1}{4}$ (nearly 14°); or when the wheel was rotated at twice this velocity (50 metres per second) the angle was nearly 27°. For most experiments a rate of rotation between these limits was used, although the wheel could be rotated 80 to 100 times per second.* On account of the slip of the catgut cord it was not found possible to determine the rate of the wheel from the gear and the rate of the motor. The true velocity of the wheel was determined by the trace of a tuning-fork, which showed that several revolutions were made at a sensibly uniform speed, and therefore that the speed of the film might be taken as rigorously uniform during its movement through the small arc affected by the photograph. The films were slowly developed in a long trough, which was set rocking by suitable gear. For the brighter photographs an hour was generally required for proper development, for the fainter images two or three hours were required. After fixing and washing, the films were soaked in glycerine and water, which prevented them from curling up on drying.

It was found that the detonation-wave of all the undiluted mixtures we tried could be photographed on the moving films, but the intensity of the images varied very considerably. Cyanogen, carbon disulphide, and acetylene fired with oxygen gave the brightest flames, hydrogen with chlorine and carbonic oxide with nitrous oxide gave the least bright flames. Thin strips of black paper were fastened round the explosion-tube to give reference marks on the photograph. These strips appear as black vertical bands on the prints, and are useful for measuring the angles made by the detonation or reflected waves.

Figs. 7, 8 and 9 (Plate 11) show the detonation-wave in a mixture of cyanogen with

* Our method of photographing on a rotating film has given most interesting results in Professor A. SCHUSTER'S research on the constitution of the electric spark. See 'Phil. Trans.,' A, vol. 193, 1900, p. 189.

two volumes of oxygen travelling from right to left at the bottom of each photograph. In fig. 7 the wave strikes the end of the tube (a metal stopper being used), and a reflected wave is thrown back. The dark band was 35 centims. from the stopper. Fig. 8 shows the reflected wave between 35 and 70 centims. from the closed end, and fig. 9 shows the reflected wave travelling between marks placed at 70 and 105 centims. from the closed end. The film was moving slower when fig. 7 was photographed than in the other two cases.

The photographs in figs. 10, 11, 12, and 13 show the reflected wave (in different mixtures of gases) travelling backwards (from left to right) between 35 and 70 centims. from the closed end. When the end of the tube is open only a faint flame is projected from the tube, and no bright reflected wave is seen (fig. 14). A cork, loosely fitted, is sufficient to send back a bright reflected wave (fig. 15). Even when the tube is fractured by the explosion, the detonation-wave can be photographed and an indistinct reflected wave is visible (fig. 16).

The first points noticed in the photographs were (1) the sharpness with which the luminosity is set up, and (2) the uniformity of the detonation-wave. There is no evidence of any gradual heating up of the gases, but on the contrary the temperature appears to spring to its maximum with abrupt suddenness. This is, of course, in accordance with the views published by BERTHELOT and by myself as to the character of the detonation-wave, which we believe to be propagated by the shock of the molecules themselves moving forward with the velocity due to the whole heat of the chemical combination. The gas ignited by the detonation-wave (including dust and particles knocked off the tubes) remains luminous for some time after the wave has passed. As had been shown in the "window" experiments (previously referred to), cyanogen burning to carbonic acid left a longer trail of light than when burnt to carbonic oxide only, and the most prolonged images were obtained with the two mixtures $C_2N_2 + 2O_2$ and $CS_2 + 3O_2$.

Many of the photographs show very distinctly the movements of the gas *en masse* as it follows up the detonation-wave, comes to rest, and swings back again. Fig. 17 (taken in a long tube) shows the movements of the gas undisturbed by any reflected wave. These movements are analogous to the forward and backward movements in air produced by a vibrating body. According to the kinetic theory, the mean motions of the molecules of a gas may be resolved in any direction into equal and opposite movements. When a compressed tuning-fork is released, the forward movements of the molecules in contact with the prong have added to them the motion of the fork, and by exchange of velocities this added velocity is propagated from molecule to molecule, each molecule swinging forward with the increased velocity and returning with its normal velocity. In a sound-wave a number of these forward impulses is imparted to the molecules as the prong moves forward, and therefore the molecules move forward, causing a compression-wave, and afterwards, as the prong moves backwards, the reverse effect is produced, and a rarefaction follows the compression-

wave. The curious stratification of the light-giving particles behind the detonation-wave (observed in many of the photographs) allows this movement to be followed, and indicates the length of the excursion made by each layer of gas.* When the detonation-wave hits the closed end of the tube it is reflected back in a distinctly marked luminous-wave. What is most remarkable about this reflected wave is its great luminosity. As the reflected wave starts back from the end wall it has at first to meet the gas moving bodily forward in the wake of the detonation-wave. As it continues backwards the gas it meets has less and less forward motion, and at a certain point (usually some 400 to 500 millims. from the reflecting end) the gas it travels in is stationary. From this point the motions of the reflected wave and of the gas it travels in are in the same direction. It follows therefore that the velocity of the reflected wave is at first retarded and afterwards increased by the motion of the medium. This is probably the reason why the reflected wave sometimes appears to travel faster as it proceeds backwards along the tube, as in figs. 10, 11, and 15, and sometimes appears to travel at a nearly uniform velocity, as in figs. 7, 8, and 9, in spite of the cooling by radiation and conduction going on. The effect of these movements of the gas appears again in the photographs taken in repeating the experiments of OETTINGEN and GERNET (p. 348).

The reflexion-waves can be readily photographed in the brighter explosions as far back as 120 centims. (4 feet) from the reflecting end, and when the gases are fired in short tubes, waves that have been reflected from the ends eighteen to twenty times can still be photographed.

Three views may be held in regard to these reflexion-waves :—

(1) The combustion continues for a considerable time after the detonation-wave has gone by, and the returning compression-wave may owe part of its luminosity to increased chemical combination taking place in its path ;

(2) The combustion is practically completed in a short time, and the reflected wave travels in the burnt gases as an intense compression-wave of the same nature as a sound-wave of large amplitude ;

(3) The reflexion-wave travels as in (2) through the still combining gases without materially affecting the chemical changes proceeding.

According to the first view the continuation of the combustion may be due either to dissociation, which permits the gradual formation of compounds (*e.g.*, CO_2) only as the gases cool down, or to the time required for the natural completion of the reaction

* In some of the photographs this stratification appears almost too regular to be accidental ; can it be due to vibrations in the gas causing the dust to arrange itself in transverse streaks along a ventral segment, as the lycopodium arranges itself in KUNDT'S tubes when the length of the tube is not an exact multiple of the wave-length ?

owing to the last uncombined molecules being surrounded by the products of combustion. In either case it is not probable that the passage of a compression-wave would greatly influence the chemical combustion.

(*a*) If combination were limited by dissociation, *e.g.*, in the explosion of cyanogen with twice its volume of oxygen, there might be in the vessel some little time after the passage of the detonation-wave a mixture of CO_2, CO, O_2, and N_2 at a temperature (let us say) of 3000° C. and a pressure of 15 atmospheres. Let us take as a probable number the figure calculated by LE CHATELIER* for the dissociation of CO_2 under the partial pressure of 10 atmospheres and 3000° C. About one-fifth of the carbonic acid would be dissociated. Now if gases were compressed adiabatically (even if we take the molecular specific heat of CO_2 as 20 and the molecular specific heat of the diatomic gases as 7 at constant volume and 3000° C.), the rise of temperature due to compression would more than counteract the increase in pressure, and the dissociation would tend to increase.

(*b*) We have found that the addition of an inert gas to the mixture of equal volumes of cyanogen and oxygen prolongs the luminosity of the explosion.† As the inert gas must lower the temperature, and therefore reduce the possible dissociation, this prolonged luminosity must be due to a combustion of residual gases not caused by dissociation. But in undiluted mixtures this residue is small, as is shown by the very rapid fall in luminosity, and therefore the action of a pressure-wave on this residue can have little chemical effect.

We are thus brought to the conclusion that the reflected wave produced by the collision of a detonation-wave with the end of the tube is mainly a compression-wave.

The velocity of the reflexion-wave may be readily compared with that of the detonation-wave, their relative velocities being as the sines of the angles made by the two waves with the horizontal. These angles have been measured by fixing the films on a glass plate (illuminated from behind), and covering the films with tracing paper, on which the lines could then be traced and extended by the ruler. When the reflexion-wave was curved, a line was drawn touching the curve as nearly as possible at the point where the movement of the gas itself was nil. The velocity of the detonation-wave being known, the velocity of the reflexion-wave could readily be calculated. By this means the velocities given in the following table were measured, each velocity being the mean of those obtained from four to eight photographs :—

* 'Zeit. Phys. Chem.,' vol. 2, p. 782 (1888).

† 'Journ. Chem. Soc.,' vol. 79, p. 772.

TABLE II.—Velocity of Reflexion-Waves in Gaseous Explosions.

Mixture of gases.	Velocity of detonation-wave in metres per second.	Velocity of reflexion-wave in metres per second.	Ratio of velocities.
$2H_2+O_2$	2820	1538	1·83
H_2+N_2O	2305	1383	1·67
$2CO+O_2$	1676	1078	1·56
$C_2N_2+O_2$	2728	1230	2·22
$C_2N_2+2O_2$	2321	1129	2·06
$2C_2H_2+5O_2$	2391	1133	2·11

Although the formula for the velocity of sound in gases is strictly valid for small displacements only, nevertheless it appeared of interest to calculate from the observed velocities of these reflexion-waves what temperature they indicated in the gas on the assumption that they were propagated as sound-waves. Of course, to calculate the temperature from the velocity of sound it is necessary to know the ratio of the specific heats γ, and since in the case of carbonic acid and steam this ratio is very doubtful, a corresponding uncertainty must exist in the temperature calculated. But in the case of cyanogen burning to carbonic oxide the products of combustion, carbonic oxide and nitrogen, are similar to air, and their specific heats either do not alter, or do not alter greatly with rise of temperature. The velocity of sound in such a gas would therefore give an approximation to the temperature.

Now the velocity of the reflexion-waves in cyanogen exploded with its own volume of oxygen is 1230 metres per second. Assuming γ to be unaltered by rise of temperature, and the velocity of sound in air at 0° C. to be 333 metres per second, the temperature of the gas where the reflexion-wave was measured is given by the formula:

$$T = \left\{ \left(\frac{v \sqrt{\frac{d_1}{d}}}{333} \right)^2 - 1 \right\} 273 = 3330^\circ \text{ C.},$$

where v is the velocity of sound, and d_1 and d the densities of the gas and air respectively under the same conditions. If, on the other hand, we assume (with LE CHATELIER) that the specific heat at constant volume of diatomic gases rises with the temperature and becomes 7 at the temperature of this experiment, then the ratio γ falls to 1·29, and the formula becomes:

$$T = \left\{ \left(\frac{v \sqrt{\frac{d_1}{d} \cdot \frac{\gamma}{\gamma_1}}}{333} \right)^2 - 1 \right\} 273 = 3672^\circ \text{ C.}$$

In the case of cyanogen exploded with twice its volume of oxygen the first reaction probably consists in the burning of the cyanogen to carbonic oxide, which

combines more slowly to form carbonic acid. How far this second reaction is completed when the reflexion-wave is measured it is impossible to decide. On the assumption that the specific heat of nitrogen is constant and that of CO_2 is 7·2, the velocity of the wave in the completely burnt mixture would indicate a temperature of 4200° C.; on the assumption that the specific heats of CO_2 and N_2 are 20 and 7, the temperature indicated is 4780° C. On the other hand, if no carbonic acid had yet been formed, the temperature indicated for the mixture of diatomic gases ($2CO$, O_2, N_2) is 2880° ($C_v = 4·8$).

In a similar manner, the temperatures corresponding to the velocity of the reflexion-waves have been calculated for the other mixtures, (1) assuming the ratio of the specific heats for a diatomic gas to be 1·41 and for a triatomic gas 1·28, and (2) assuming the ratio of the specific heats for a diatomic gas to be 1·29 and for a triatomic gas 1·11.

TABLE III.—Temperatures of Exploded Gases, Calculated from the Velocities of the Reflexion-Waves.

Mixture.	I. γ for diatomic gases = 1·41. γ for triatomic gases = 1·28.	II. γ for diatomic gases = 1·29. γ for triatomic gases = 1·11.
	° C.	° C.
$2H_2 + O_2$	3720	4830
$H_2 + N_2O$	3660	4130
$2CO + O_2$	4530	5250
$C_2N_2 + O_2$	3330	3670
$C_2N_2 + 2O_2$	4200	4780
$2C_2H_2 + 5O_2$	3980	4630

A glance at this table reveals the fact that, whether the specific heats vary or not, but on the assumption that combustion is complete in each case, the explosion of cyanogen to carbonic oxide (which according to all observers gives the brightest flash and the highest pressure) gives apparently the coolest combustion products a short time after the explosion-wave has gone by. Now I have found* that the velocity of the reflexion-wave is nearly equal to that of a true sound-wave of small displacement travelling through the flame produced by the explosion of cyanogen burning to carbonic oxide; it is not therefore open to us to reject the temperature calculated for this mixture as entirely wide of the truth. The natural inference to be drawn from the figures is, I think, that the combustion is not complete in the other mixtures (in all of which steam or carbonic acid, or both, are produced) at the moment the reflexion-wave is measured. If we suppose that the formation of carbonic acid and steam is incomplete, the densities of the products are less and γ is higher, and consequently the temperatures calculated from the velocities of the reflexion-wave would be lowered. For instance, if we assume in these several experiments that the hydrogen

* See Part III.

is two-thirds burnt, and the carbonic oxide is one-third burnt at the moment of measurement, then the velocities of the reflexion-waves correspond to the following temperatures :—

TABLE IV.

Mixture of gases.	Hypothetical state of reaction when wave is measured.	Temperature calculated from velocity of reflexion-wave. γ for diatomic gases = 1·41. γ for triatomic gases = 1·28.
		° C.
$6H_2 + 3O_2$	$4H_2O + 2H_2 + O_2$	3010
$6H_2 + 6N_2O$	$4H_2O + 2H_2 + O_2 + 6N_2$	3290
$6CO + 3O_2$	$2CO_2 + 4CO + 2O_2$	3070
$C_2N_2 + O_2$	$2CO + N_2$	3330
$6C_2N_2 + 12O_2$	$4CO_2 + 8CO + 4O_2 + 6N_2$	3220
$6C_2H_2 + 15O_2$	$4CO_2 + 8CO + 4H_2O + 2H_2 + 5O_2$	2850

It will be observed that the temperatures calculated as above, in Tables III. and IV., are of the same order as those calculated by BUNSEN as the maximum temperatures of the explosion. But the photographs plainly show that they do not represent the temperatures reached in the detonation-wave itself. These calculated temperatures correspond to a period of the explosion subsequent to the passage of the wave—the period during which BERTHELOT and LE CHATELIER measured the "effective" pressures produced. The photographs therefore confirm LE CHATELIER'S statement that the "effective" pressures measured in the French experiments are not the maximum pressures produced in the explosion.*

PART III.

VELOCITY OF A SOUND-WAVE IN THE FLAME OF EXPLODED GASES.

(In conjunction with R. H. JONES, *B.Sc., and* J. BOWER, *B.Sc.)*

The interest attaching to the determination (even approximately) of the temperatures produced in the explosion of gases led us to attempt the measurement of the rate of a true sound-wave (of small displacement) in the gases produced by the detonation-wave.

In our first experiments the glass explosion tube A (fig. 18), was fitted to a steel piece, B, containing a tap of large bore and a small bye-tap, and connected by a pipe

* Some of our photographs showing the reflexion-waves were exhibited before the Chemical Section of the British Association at Liverpool in 1896. 'B.A. Report,' 1896, p. 746.

to a steel bomb, C, in which a small charge of fulminate could be fired. The bomb and connecting pipe were filled with air, while A was filled with a mixture of cyanogen with two volumes of oxygen. The fulminate in its copper case, *f*, was

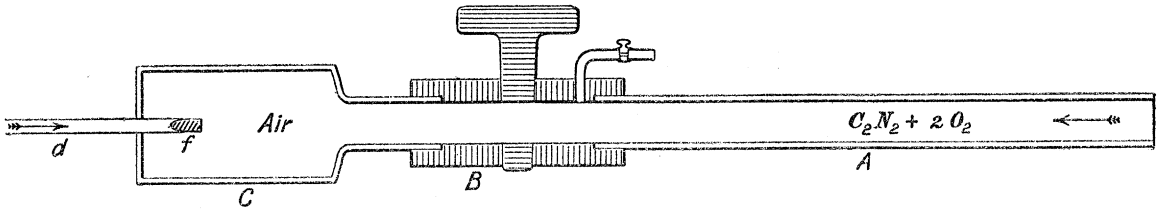

Fig. 18. Apparatus to make a sound-wave meet a detonation-wave.

inserted through a rubber stopper in the end of the steel tube, *d*, which was screwed into the bomb. A and *d* were connected with tubes fitted with firing wires, so that an explosion could be set up simultaneously in the cyanogen mixture in A and the electrolytic gas in *d*, the connecting tap being turned on immediately before the explosion. The lengths of the tube were so adjusted that the sound-wave started in the bomb by the detonation of the fulminate should be propagated through the air and cyanogen mixture so as to meet the detonation-wave coming in the contrary direction before the latter reached the end of the tube A. The detonation-wave was then photographed as it met the sound-wave.

In fig. 19 (Plate 12) the detonation-wave is seen advancing from right to left. The sound-wave strikes it near the centre of its path across the field of view, and the progress of the sound-wave is made visible as it traverses the heated gases from left to right. After meeting the sound-wave, the detonation proceeds some distance at full speed, and then its velocity slackens—as it meets the rush of air driven on to it from the detonation in the bomb. A second sound-wave, an echo of the first reflected from the ends of the bomb, next traverses the heated gas; and higher up the passage of a third sound-wave is registered on the photograph. The first sound-wave is no doubt retarded by the movement of the gas in the opposite direction, but the second wave appears to travel in almost stationary gas, while the third is only slightly retarded. The rates of these sound-waves have been measured, and the corresponding temperatures calculated. These values are given in Table V., on the assumption that the combustion was complete.

TABLE V.

Number.	Velocity of sound-waves in exploded mixture $C_2N_2 + 2O_2$.	Calculated temperatures. γ for diatomic gases = 1·41. γ for triatomic gases = 1·28.
		° C.
1st	1116 metres per second	4100
2nd	1014 „ „ „	3330
3rd	893 „ „ „	2530

It will be seen that the temperature calculated for the first sound-wave (4100°) is in close accordance with that calculated from the reflexion-wave in the same mixture (4200°) given in Table III.

The experiment was next varied by the introduction of a thin iron membrane between the air and the explosive mixture. The shock transmitted through the air from the fulminate struck the flexible plate, and so propagated a wave of small displacement through the explosive mixture. This wave had very little effect on the movements of the gas in the wake of the detonation-wave, but its passage through the luminous gas was plainly marked. The gases were ignited as before, the lengths of the tubes being so adjusted that the first sound-wave met the detonation-wave about 1 metre from the membrane. Several of these sound-waves (produced by echo in the bomb) are seen in fig. 20 traversing the flame produced by the explosion of cyanogen with its own volume of oxygen; these sound-waves apparently increase in velocity owing to the movements of the gas through which they pass.

It is not so easy to measure the angles of these faintly-marked sound-waves, but three photographs have given as the mean of several independent measurements made on each photograph the velocity of the sound-wave *in the stationary gas* as 1250 metres per second. This velocity corresponds to a temperature of 3460° ($\gamma = 1{\cdot}41$); a number in very fair agreement with that calculated from the reflexion-waves, viz., 3330° (Table III.). This agreement indicates that the reflexion-waves really travel with a velocity approximately equal to that of sound.

Similar sound-waves are shown in fig. 21, where the mixture was $CS_2 + 2O_2$.

Some other experiments were also made in which a compression-wave was made to follow closely behind a detonation-wave, both moving in the same direction.

A leaden tube had a by-pass inserted so that the explosion travelled both along the straight piece *a c* and along the curved piece *a b c*. When the flame travelling by the straight road reached the second opening of the by-pass *c*, it penetrated this opening and came into collision with the explosion travelling by the longer road. The reflected wave so produced followed the main detonation-wave into the glass tube *d*, where the two were photographed about 1 metre from the point *c*. The reflected wave is assisted by the forward movement of the gas, and consequently its apparent velocity is much greater than the sound-waves or reflexion-waves measured in stationary gas.

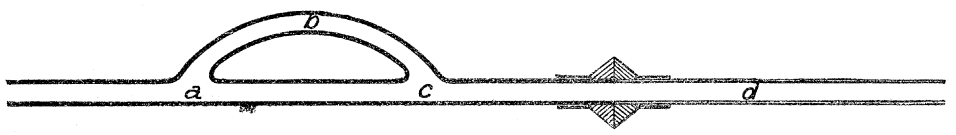

Fig. 22. Apparatus to make a sound-wave follow a detonation-wave.

In fig. 23, which shows the two waves in the explosion of cyanogen with two volumes of oxygen, the compression-wave is seen running alongside the detonation-

wave and inclined at a small angle to it. The velocity of the detonation-wave being 2320, the mean velocity of the following compression-wave is given by measurements of three photographs as 1635. The difference between this number and the velocity of the compression-wave measured in stationary gas (a difference of 500 metres per second) is due to the movements, and probably also to the higher temperature of the gas in the immediate wake of the detonation-wave.

PART IV.

On the Collision of Two Detonation-Waves and the Effect of Junctions in the Tubes.

(*In conjunction with* R. H. Jones *and* J. Bower.)

In 1897 we began the investigation (by means of the moving film) of the phenomena marking the collision of two explosion-waves meeting end-on in a glass tube. To make the two flames meet in the field of the camera, the glass firing piece A (fig. 24) was fastened to a lead pipe bifurcating at B into two arms of equal length, which were bent round at their extremities and opened out to hold the two ends of the glass tube. The junctions at C and D were made gas-tight by slipping pieces of rubber tubing over the ends of the glass tube and pushing them into the leaden caps. By shutting the tap B* and opening E, the whole apparatus could be filled through A with the explosive mixture; then the taps at A and E were shut and B was opened. On passing the spark the flame followed the two arms of the tube, and the two detonation-waves generated met in the centre of the glass tube C, D.

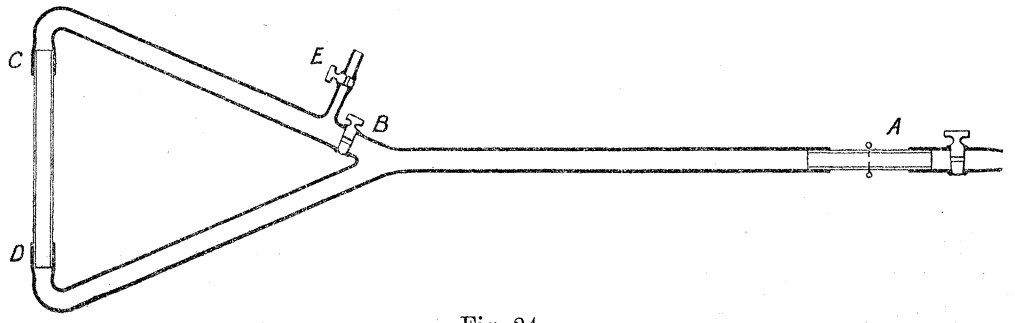

Fig. 24.

We were greatly puzzled by the photographs obtained with this apparatus. The first few experiments showed the rebound waves (after the collision) to be much brighter and to be travelling (backwards) much faster than the two detonation-waves themselves before the collision. Other photographs showed that the two flames were

* The bore of the tap B was the same size as the lead tube; it is shown in fig. 18.

not always symmetrical. Fig. 25 (Plate 12) shows the two flames meeting symmetrically, and giving rebound waves faster and brighter than the original waves before collision.

Fig. 26 shows the flame coming from the right hand to be much brighter and travelling much faster than that from the left hand (although the collision occurs only a little to the left of the centre of the tube). Fig. 27 shows these phenomena reversed. On repeating the experiments it was found that the faster flame had usually been affected by some impulses causing a sudden increase in its brightness and velocity, and also producing a backward wave (analogous to a reflected wave). Sometimes the impulses were exhibited by the left-hand flame, as in figs. 28 and 29 (Plate 13); sometimes by the right-hand flame, as in figs. 30 and 31. In some experiments a single impulse only is observed, as in figs. 29 and 31; in others several such impulses can be traced, as in fig. 30. Figs. 32 and 33 show both flames affected by these impulses; in fig. 32 symmetrically, in fig. 33 unsymmetrically.

The explanation of these appearances that first occurred to us was that the flame was preceded by invisible sound-waves, travelling more quickly than the flame in its initial phases; that these sound-waves became visible as soon as they met the flame moving towards them in the opposite direction (as in our previous experiments on sound-waves), and that, on the other hand, the visible flame meeting the sound-wave was affected by the sudden increase of pressure, and continued its journey with greater speed and luminosity. This explanation was at once destroyed when we found similar impulses in a flame which was sent through the apparatus in one direction only (the tap B being closed), as is shown in fig. 34.

It next occurred to us that these impulses might be due to the explosion *catching up its own sound-waves*. If sound-waves are propagated through the gas from the point of ignition, the flame might lag behind the sound-waves at first and catch them after a run more or less prolonged. The sound-waves when overtaken might cause reflected sound-waves (made visible in the luminous gases), and the explosion itself might become more intense owing to the collision.* Many experiments were undertaken to verify or disprove this hypothesis, but it will not be necessary to reproduce the large number of photographs we took in the course of this investigation. We found that no addition to the length of the lead pipe between the firing point and the bifurcation, and no addition to the length of the two arms affected the result. Finally, it was found that the explosion was affected as it passed through the junctions between the lead and the glass, and the impulses recorded in our photographs were due to the detonation-wave, damped down at the junction, being regenerated by fits and starts. One of the photographs showing this most plainly is reproduced in fig. 35. This was obtained in the following way:—Three straight glass tubes were fixed horizontally one above another and were joined together by curved lead tubes, into which the

* LE CHATELIER has published a similar hypothesis to explain the apparent break in the curve where the detonation is started; see p. 347.

glass was packed gas-tight by indiarubber, as in fig. 36. The gases were ignited by the spark at a, and the flame travelled towards b. Fig. 35 shows the result of firing equal volumes of cyanogen and oxygen in this apparatus. The photograph does not show the spark or first part of the flame. The flame, starting from the right-hand lower corner, is seen to become more luminous, and to move faster as it approaches the middle of the tube. The detonation-wave is then set up, its initiation being marked by a luminous-wave thrown backwards from the point where the detonation begins. To the end of the first glass tube the detonation-wave then travels with uniform speed and luminosity. On emerging from the lead bend into the second glass tube the flame is seen to be less luminous, but in a short period detonation is again set up, with the accompaniment of the backward thrust, and with the formation of a dark patch of gas, which is also characteristic. On passing the second lead bend the luminosity and speed are again reduced, and the detonation-wave is not again determined until the flame has traversed half the third glass tube. It was now evident that what had happened in our "collision" photographs was this damping down of the detonation-wave as it passed through the lead bend and entered the glass tube. It was, however, difficult to imagine that the curvature of the tube had affected the rate, for BERTHELOT had determined the rate of explosion of electrolytic gas in a leaden pipe with many sharp bends, and I had found the same velocity in a straight pipe and in one coiled round a small drum. An experiment made with a glass tube bent to the same curvature showed no retardation (fig. 37). BERTHELOT had also found the velocity of explosion unaltered in a rubber tube with many bends; and when we proceeded to substitute a stout rubber tube for a lead bend (fig. 38, Plate 14), we found the wave traversed it without retardation. Therefore it was also equally hard to imagine that the use of a rubber tube to make a gas-tight joint between the glass and the lead could affect the explosion, and yet this turned out to be the origin of the disturbance.

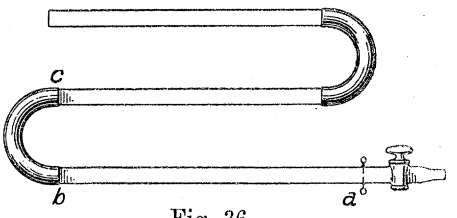

Fig. 36.

We had connecting-pieces made of different metals and of varying curves and angles, but after many trials we found that the only thing which mattered was the rigidity with which the glass and metal were connected together. Any packing (such as rubber) which gave to a shock caused a retardation; when the glass was firmly cemented to the metal no retardation occurred. Fig. 39 shows the explosion passing through two glass tubes rigidly connected to a copper junction, which was equally without retarding action whether curved or bent at a sharp angle. This retardation was not confined to curved junctions. When a straight piece of lead pipe was fastened by rubber to two glass tubes, the wave of detonation was damped down on traversing the junction; when the metal was cemented to the glass no retardation occurred.

The knowledge gained from these experiments with junctions made it now possible to investigate the phenomena of collisions, but the experiments had also shown that it would be of interest to explore photographically the region of the explosion prior to the initiation of the detonation-wave.

When two detonation-waves come into collision, the tube remains brightly luminous at the point of contact for some time,* and two reflected waves are sent backwards with velocities which increase at first, owing to the movement of the gas through which they are propagated.

The photographs of two detonation-waves meeting in collision are shown in figs. 40 and 41, the explosive mixture being cyanogen with two volumes of oxygen, and in fig. 42 (Plate 14), the mixture being two volumes of hydrogen with one volume of oxygen.

A comparison of all the photographs shows that the gases are more luminous after a collision than when the explosion-wave strikes a flat surface of metal fastened at the end of the tube. The reflected waves in the two cases are similar in character, but the reflexion generated by collision with another detonation-wave seems always to travel slightly faster. If we were dealing only with waves produced mechanically, the reflected waves would be exact copies of the incident-waves with velocities reversed in both cases. But in the detonation-wave we have chemical as well as mechanical action, while the reflected wave is mainly mechanical. We should expect therefore the reflected waves to travel more slowly than the incident-waves, but we should also expect the reflected waves to travel with the same velocity whether they were produced by collision with a rigid diaphragm or with a similar and equal wave travelling in the opposite direction, unless there was some chemical difference involved in the two kinds of collisions. Now in the hypothesis† I have advanced for the mode of propagation of the detonation-wave I have assumed that the explosion is propagated not only by the forward movements of the molecules produced by the chemical change, but also partly by the movement of the yet unburnt molecules. For instance, in the explosion of hydrogen and chlorine, molecules of hydrogen chloride just formed in the wave-front may move forward until they come into collision with molecules of unburnt hydrogen or molecules of unburnt chlorine. These molecules (by exchange) now move forward with increased velocity, and in turn meet molecules of the opposite kind, with which they combine. The combination therefore does not proceed between cold molecules entirely, nor between heated molecules entirely, but mainly between molecules half of which are at the ordinary temperature and half are heated by collision with the products of combustion. If this roughly represents the state of the wave-front, there would be a chemical difference between the collision with a diaphragm and with another explosion-wave. For in the latter case

* General HESS, of the Austrian artillery, has photographed a luminous band at the point of collision of the two compression-waves produced by exploding two cartridges suspended in the air a short distance apart. See 'Bulletin Soc. de l'Industrie Minérale,' Saint Etienne, 1900, vol. 14, 3, p. 116.

† 'Phil. Trans.,' A, vol. 184, p. 131 (1893).

the unburnt molecules would meet, at the moment of impact, the unburnt molecules travelling with an equal velocity in the opposite direction, and chemical combination would ensue between molecules both of which were highly heated before they met.

The difficulty of obtaining an exact measure of the velocity of the waves reflected after collision is very considerable. With all the care we could exert, we found it impossible to obtain concordant readings for the angles made by the collision-waves with the horizontal, but we believe that the difference between the rate of collision-waves and waves reflected from the end of the tube is sufficiently large to be fairly evident from a number of observations. For instance, six experiments with cyanogen and two volumes of oxygen gave as the ratio of the velocity of the detonation-wave (D) to the collision-wave (C) :—

$$\frac{\text{sine of angle of C}}{\text{sine of angle of D}} = \left\{\begin{matrix} 1{\cdot}58 \\ 1{\cdot}40 \\ 1{\cdot}38 \\ 1{\cdot}19 \\ 1{\cdot}44 \\ 1{\cdot}47 \end{matrix}\right\} \text{Mean . . } 1{\cdot}41,$$

whereas measurements of the reflexion-wave with the same mixture gave :—

$$\frac{\text{sine of angle of R}}{\text{sine of angle of D}} = \left\{\begin{matrix} 2{\cdot}11 \\ 2{\cdot}03 \\ 2{\cdot}32 \\ 2{\cdot}11 \\ 1{\cdot}97 \end{matrix}\right\} \text{Mean . . } 2{\cdot}11.$$

In a similar manner, measurements made on the relative rates of the collision-wave and the reflexion-wave in the mixture of cyanogen with one volume of oxygen, gave :—

$\frac{\text{sine of angle of C}}{\text{sine of angle of D}}$	$\frac{\text{sine of angle of R}}{\text{sine of angle of D}}$
1·91	2·22
1·79	2·15
2·13	2·33
1·98	2·08
	2·22
Mean . . 1·95	Mean . . 2·20

In this case the numbers are too near for us to draw any certain conclusion, but in the first case it is difficult to suppose that the difference of 50 per cent. can be entirely experimental error. This inequality is an argument in favour of the view that there is a difference between a collision with a wall and with an approaching wave, but I would not lay stress on it to support my hypothesis of detonation.

Our photographs have shown that the wave of detonation has certain characteristics by which it may be readily recognised :—

(1) It starts suddenly, throwing back a strongly luminous wave through the burning gases and leaving a dark space where it started;

(2) It travels with constant velocity, unless it traverses a junction not rigidly attached; after being damped down by such an obstacle, it recoups itself and again starts with abruptness;

(3) On collision with a similar detonation-wave moving in the opposite direction, or with a rigid diaphragm, it sends back a reflected wave not so rapid as itself, and as a rule not so luminous.

In the case of the more luminous explosions, *e.g.*, those of cyanogen, acetylene, and carbon disulphide mixtures, the reflected waves were less luminous than the detonation-wave; but in the case of the less luminous explosions, *e.g.*, those of hydrogen and carbonic oxide, which depend largely for their light on the particles detached from the tubes, the waves reflected from a collision were sometimes more luminous than the detonation-waves themselves, for instance in fig. 42.

With regard to the pressures produced in the detonation-wave, our experiments have repeatedly shown that glass tubes more readily fracture at the point of collision of two detonation-waves than when the detonation-wave traverses the tube in one direction only.* A tube has stood half-a-dozen passages of the detonation-wave in one direction, and has been shattered by the first collision. A closed tube breaks most frequently at the end furthest from the firing point. Again, the point at which the detonation-wave is set-up (and at which the corresponding "retonation-wave" is driven backwards) is frequently found to be the place where the tube is broken. Of course with a weak tube this would mean nothing but that the tube would be fractured by the detonation, as it would naturally break at the point where the fracturing force was first applied. But we have found that strong tubes have withstood the passage of the detonation-wave which was already determined before entering the tube, and have been fractured when the detonation-wave was started in the tube itself. Again, the tube has broken at the point where the detonation began, and has for the rest of its length withstood the passage of the detonation (as shown photographically).†

* In 1894 I was unable to show this experimentally ('Manch. Memoirs,' IV., 8, p. 180). In the experiments then made the flame was not photographed, and it is possible that the explosions were damped down at the junctions.

† Messrs. JONES and BOWER have made many attempts to obtain quantitative measurements of the pressures produced in the detonation of gaseous mixtures by the method of fracture of glass tubes, but the results cannot be regarded as certain. They found for the detonation of the mixture $C_2N_2 + O_2$ a pressure between 58 and 75 ats., while Dr. CAIN and I found for the same detonation a pressure between 60 and 140 ats. For the mixture $C_2N_2 + O_2 + 2N_2$, Messrs. JONES and BOWER found the pressure between 74 and 93 ats., while Dr. CAIN and I found it between 63 and 84 ats. *Cf.* 'Manch. Memoirs,' 1894 IV., 8, p. 174, and 1898, No. 7.

PART V.

On the Initiation of the Detonation-Wave and on the Wave of "Retonation."

(*In conjunction with* R. H. Jones *and* J. Bower.)

Several of the photographs previously described have illustrated the abrupt spring with which the detonation-wave is started. Sometimes, apparently, one such abrupt change alone occurs, marking the place where the gradual acceleration of the explosion changes; on other photographs one or more abrupt changes occur in the acceleration before the final spring which marks the detonation-wave. Figs. 29, 30, and 33 show one or more such sudden changes in the curve always accompanied by a luminous wave thrown back through the ignited gases.

The strongly luminous wave thrown back from the point where the detonation is started I propose (*nominis egestate*) to call the *retonation-wave.* This wave has not the same constant characteristics that mark the detonation, but when generated under certain conditions it resembles detonation most closely. Fig. 43 (Plate 14) shows a wave of retonation travelling parallel with and therefore at the same velocity as the collision-wave. Fig. 44 shows a retonation-wave travelling more quickly than the wave reflected from the end of the tube. A study of a number of photographs leads to the conclusion that the retonation is faster and more luminous when no other bright waves have been thrown back by the advancing flame before the point of detonation is reached.

In considering the cause of the intensity of the retonation-wave we must remember the facts illustrated in many of our photographs on collisions. The collision of two flames, in which detonation had not yet been determined, gave rise to reflected waves more rapid and more luminous than the incident waves. Fig. 25 shows this for both. Now these reflected waves could not owe their increased velocity to the mechanical impact, which could only result in the reflected waves being copies of the incident waves. It is evident then that chemical action must occur to assist these reflected waves, and therefore the combustion is obviously not complete when these waves return. From this it would appear probable that the period before the detonation is distinguished not only by a slower propagation of the flame, *i.e.*, of ignition, but also by a slower process of combustion. In the initial period the molecules of the gas might meet many times before chemical reaction occurred; in the detonation-wave the molecules might be so intensely agitated that most collisions between chemically opposite molecules would result in chemical change.

At the point of detonation the rise of pressure must be exceedingly rapid owing to

the increase of chemical action, and this pressure would produce not only the forward wave of detonation, but also a sudden backward wave of compression into the gases still slowly burning behind it. This compression-wave must raise the temperature of the ignited gases and so quicken the residual burning; its propagation would then be analogous to that of the detonation-wave, but modified by the extent to which the slow combustion has proceeded. I believe this view accounts for the facts described and also for the phenomena observed in the initial period of the explosion (see Part VI.).

The retonation-wave attains its greatest rapidity and brightness when it is developed at the closed end of a tube, *i.e.*, when the gas is fired at such a distance from the closed end that the explosion, gradually increasing in intensity, just reaches the detonation point as it arrives at the stopper. Under such conditions the reflected wave is superposed on the wave of retonation, and the result is a wave which cannot be distinguished from a true detonation. Fig. 45 shows the retonation-wave developed at the closed end of the tube in the mixture $C_2H_4+2O_2$.

Fig. 46 shows the formation, propagation, and collision of two retonation-waves produced by firing the gases in the middle of a long tube. The picture shows the two flames travelling from the spark to the right and the left, and the two points of detonation at either edge of the film. The two retonation-waves return symmetrically to the centre and there come into collision, producing reflected waves. If we compare this photograph with fig. 47 or with fig. 48, we see the effect of the retonation-waves starting from the two ends of the tube. If the point of detonation occurs just before the end of the tube is reached, the reflected wave runs back nearly parallel with the retonation-wave, as is shown in fig. 49.

In order to make a direct comparison of the velocity of the retonation-wave starting from the end of the tube with the detonation-wave, two tubes were fixed parallel one above another, and were filled with the same gases. One tube was connected with a long leaden pipe, in which the explosion was started, so that the detonation-wave alone traversed the glass tube; the second glass tube was fitted with firing wires at one extremity, so that the initial phase of explosion up to the detonation point should just occupy its length. The two flames were then photographed simultaneously on the moving film.

Fig. 50 shows the detonation-wave in the mixture $C_2H_2 + O_3$ moving from right to left in the lower tube, and just above the point where it meets the closed end of its tube the beginning of the explosion in the second tube can be seen. The second flame travels slowly from left to right, striking the end of the tube at the detonation point. Its intense retonation-wave, returning from right to left, travels in a line parallel with the detonation in the first tube, *i.e.*, their velocities are apparently equal. The same thing is shown in fig. 51, where the mixture used was $CS_2 + 3O_2$. In the lower portion of the picture the flame is seen travelling slowly from left to right in the first tube; it crosses the image of the detonation-wave, which is travelling

from right to left in the second tube, and sends back a wave of retonation when it reaches the end of the tube. The retonation and detonation-waves are apparently parallel.

As regards the dark space formed at the point where the detonation and retonation-waves originate, it is no doubt a space of cooler gas. It persists for some time, and its damping effect on the passage of the collision-wave can be observed in several of the photographs. In fig. 31 this effect is evident just before the collision-wave cuts the black reference line on the right of the picture.

In 1898, a few of our photographs showing the point of detonation and the collision and reflexion of waves in explosion were published in the 'Manchester Memoirs.' Attention was drawn to the wave of retonation and the dark space. It was pointed out that the detonation "was represented by the straight and intensely-luminous line as distinct from the curved and less luminous line of the recouping period."

"Further, a new and very luminous wave is observed starting from the point of re-determination of the explosive-wave proper, and travelling in the opposite direction with a speed almost, if not quite, equal to that of the explosive-wave itself."

In June, 1900, LE CHATELIER published* an account of his photographs of the development and propagation of the detonation-wave (taken on a moving plate) Without knowing of our work, he observed and recorded the "wave of retonation" and the "dark space" formed in the explosion of acetylene with oxygen, and the waves reflected from the end of the tube and at the point of collision of two waves :—

"1. Au moment du développement spontané de l'onde explosive une onde condensée *rétrograde* est toujours lancée en arrière dans les gaz déjà brûlés ;

"2. L'arrêt complet ou partiel de l'onde explosive contre l'extrémité fermée (ou dans une région étranglée) d'un tube lance en arrière une onde condensée *réfléchie* ;

"3. Au point de rencontre d'ondes explosives allumées simultanément en différentes parties d'une masse gazeuse, leur extinction simultanée donne naissance à des ondes condensées *prolongées* qui progressent dans la même direction que les ondes explosives auxquelles elles succèdent."

For the velocities of these waves in the mixture $C_2H_2 + O_2$ LE CHATELIER gives the following values :—

Wave.	Rates, metres per second.
L'onde explosive (detonation-wave)	2990†
L'onde rétrograde (retonation-wave)	2300
L'onde réfléchie (reflexion-wave)	2250
L'onde prolongée (collision-wave)	2050

* 'Comptes Rendus,' vol. 130, p. 1755.

† I found the rate of detonation in the mixture $C_2H_2 + O_2$ to be 2961 metres per second, by measurements in a long tube ('Phil. Trans.,' 1893, A, p. 161), a rate in close agreement with LE CHATELIER'S number.

While our observations and those of LE CHATELIER are mainly in accord, we differ from him in his conclusion that the wave of retonation (l'onde rétrograde) is propagated in the *burnt* gas; we believe it is propagated in the *still burning* gas. With regard to the effect of collisions between two detonation-waves, LE CHATELIER appears to consider the *act of crossing* of one wave by another to be sufficient to damp down their velocity; we, on the other hand, regarding the "prolonged wave" of the one as the reflected wave of the other (which is a mere verbal distinction), and attribute the retardation of the reflected wave to its altered character and to the movement of the gas which meets it.

PART VI.

ON THE INITIAL PHASES OF THE EXPLOSION.

(*In conjunction with* R. H. JONES *and* J. BOWER.)

The interest attaching to the development of the explosion, as well as a desire to investigate the anomalies shown by some of our pictures, led us to attempt to photograph the flame from the beginning.

In fig. 28 (Plate 13), the initial flame, starting from the left-hand lower corner of the photograph, is overtaken by a faster-moving flame. Fig. 39 (Plate 14) shows a similar phenomenon in the right-hand corner. On photographing in a straight glass tube the region of explosion prior to the detonation, we found (fig. 52, Plate 16) the initial flame was overtaken by a bright and well-marked faster flame, and, at their point of meeting, a reflected wave was driven back, and the advancing flame of explosion became faster and more luminous. What is the origin of this faster wave which overtakes the advancing flame?

A mixture of cyanogen with twice its volume of oxygen was found to give a sufficiently luminous flame from its start to be photographed on the moving film, but mixtures of carbon disulphide with oxygen gave still better images. Fig. 53 (Plate 16) with the cyanogen mixture, and fig. 54 with the carbon disulphide mixture, showed that the bright wave which overtook the initial flame *came from the end of the tube near the firing wires.* The wires in the tube used were sealed through the glass 3 inches from one end, and the glass had been so much distorted at the point of sealing that a dark band was shown on the photograph where the wires were inserted.

Another tube was prepared with firing wires inserted 4 inches from one end; the slight distortion at the wires acted like a convex lens and increased the light at this point. Fig. 55 shows the development of the explosion with $CS_2 + 5O_2$; fig. 56

with $C_2N_2 + O_2$, and fig. 57 with $C_2N_2 + 2O_2$. In all cases the flame begins to travel right and left from the wires with equal velocity in both directions. In fig. 56 the flame develops the retonation-wave at the near end of the tube (on the left) as is shown by the intense-wave running nearly parallel to the detonation, which is started at about the same distance on the other side of the firing point. In the less rapid explosions it is seen that the flame does not travel direct to the near end of the tube, but while still a short distance from it recedes and again approaches with an oscillatory motion which is repeated before the flame finally reaches the end of the tube. From the point where the flame is first checked, a luminous wave is seen (in fig. 55) running back and overtaking the main flame, which at this point acquires greater brightness and velocity. How does this new "return-wave" arise?

Now, when an explosive mixture in a tube is fired by a spark, the suddenly ignited gases must expand and transmit a compression-wave in both directions. This travels with the velocity of sound in the unburnt gas, and will be reflected from the end of the tube. The propagation of the flame from the firing point is in most gaseous mixtures less rapid than the velocity of sound in the unburnt gas, but the rate of propagation of the flame augments much more rapidly in some mixtures than in others. If the tube is a long one the flame will overtake the sound-wave after a more or less prolonged chase, according to the nature of the mixture. But if the tube is short, the sound-wave may reach the end of the tube and return as a reflected-wave to meet the flame which is still advancing. This seems to be the origin of the "return-wave."

Fig. 57A gives in outline the movements of the flame in fig. 57. The flame, starting at A, moves to the left, tracing the curve A to C. At C the detonation is set up, and the retonation-wave C D is thrown back. Now the velocity of sound in the unburnt mixture $C_2N_2 + 2O_2$ is about 312 metres per second. If a sound-wave of this velocity had started towards the left-hand from A at the same time as the flame, it would have been overtaken by the flame at the point B; but the sound-wave starting to the right-hand would reach the end of the tube at E and been reflected to G before meeting the flame. On constructing the figure from the approximately-known velocities of the film and the flame, the point G is seen to be the spot where the movement of the flame is retarded and the "return"-wave is visible—within the limits of experimental error.

The photograph 58 permits this point to be determined with considerable accuracy. The gases $C_2N_2 + O_2$ were fired *close** to one end of a tube 8 inches long (205 millims.). In a second tube, parallel with the first, the detonation-wave in the same mixture was set up and the two explosions photographed together. The detonation is shown at the top of the picture. Fig. 58A gives an outline of the explosion of the first tube. Starting at A, the flame moves to the left, but is checked

* The spark was passed between wires which just penetrated the stopper.

at C, where a "return"-wave is propagated backwards. The return-wave is reflected at E and meets the flame (which has slightly receded) at D. The flame then advances rapidly to the end of the tube and sends back a retonation-wave from G. Now in this mixture a sound-wave travels about 300 metres per second. If a sound-wave started from A at the same time as the flame, it would reach the end of the tube at B and be reflected before meeting the advancing flame. On constructing the figure this reflected sound-wave was found to hit the point C.

In another experiment the mixture $C_2N_2 + O_2$ was fired *at* one end of a tube $8\frac{1}{2}$ inches long (215 millims.). No slackening of the flame was found, and no return-waves are visible. A very intense retonation-wave was thrown back from the end of the tube. On setting out the sound-wave from the firing point we find that the sound is overtaken before it reaches the end of the tube (fig. 59.)

In fig. 60 we see the effect of firing the mixture $C_2N_2 + O_2$ 4 inches from one end of a tube 13 inches long. Fig. 60A shows the outline of the visible waves and the path of the two sound-waves. The sound starting from A reaches the near end of the tube just before the flame; its reflexion coalesces with the intense retonation-wave. The sound-wave marching to the left is overtaken about $5\frac{1}{2}$ inches from the spark. In fig. 61 the same mixture is fired in the centre of a tube 8 inches long. It confirms the result obtained in fig. 60; two intense retonation-waves are started simultaneously at either end. From these experiments we should infer that, if this mixture were fired at a point less than 4 inches from the end, the flame would be checked and return-waves would become visible. Fig. 62 shows this mixture fired in the centre of a tube 6 inches long. The flame is checked symmetrically and the sound-waves produced cross and recross with great intricacy.

With the less rapid mixture $C_2N_2 + 2O_2$ some experiments were made by firing the gas at the extreme end of the tube. A sound-wave starting at the firing point and travelling at the rate of 312 metres per second would be overtaken by the flame just before reaching the end of the tube, which was 12 inches long (fig. 63). On the other hand, when the tube was shorter the flame is checked by the returning sound-wave, which becomes visible as it traverses the incandescent gases (fig. 64). When the same mixture was fired in the centre of a tube 12 inches long, the sound-waves reach the two ends first, and produce symmetrical reflexions (fig. 65).

These measurements afford, I think, conclusive evidence that compression-waves advance in front of the flame at the beginning of the explosion. When the mixture is fired the gases, as they ignite, expand and send a series of pulses through the unburnt gas, driving the molecules at every pulse bodily forward, and so increasing the pressure in the column of gas ahead. When the firing point is near the end of the tube, the head of this compression-wave returns and meets the advancing flame, and, of course, is propagated with increased velocity through the ignited gases. The return of the compression-wave, of course, checks and may reverse the bodily forward movement of the molecules in the flame, and thus oscillations are set up.

Many of the photographs show what appears to be a definite inferior limit to the flame in its initial phase, *e.g.*, figs. 46, 59, 63, and 64, as if the flame died out promptly. We attempted to explore the dark region left inside the flame by passing sparks through it. But no effect whatever was produced in the photographs—doubtless because the gases were still burning. Indeed, most of the photographs show that the region is only comparatively dark.

I would draw attention to the fact that when no sound-waves interfere with the flame, the retonation-wave is very brilliant; when the flame is crossed several times by reflected waves, the light is more evenly distributed. Nos. 63 and 64, taken under the same conditions, illustrate this fact. The phenomenon is explained on the assumption that in the region traversed by the flame the gases are still burning, and the sound-waves, when they enter this region, bring about an increase in the rate of combination. They are, therefore, of the same nature as, but differ in degree from, the wave of retonation. The more intense the compression-wave, the more rapid the combustion in its path, and the more rapid the cooling in its wake.

The "kick-off" which the explosion gets when the gases are fired near one end of a tube considerably modifies the initial progress of the flame, especially when this is comparatively slow: compare fig. 66 where the spark is passed *at* the end of the tube, with fig. 67, where the spark is passed 4 inches from the end of a similar tube. For this reason the experiments made on the time required in different gases to develop the detonation showed anomalies which only disappeared on firing the gases by means of wires which just penetrated through the stopper at the end of the tube. The mean distance in which the detonation is developed in different gases is shown in the following table, according to the position of the spark:—

TABLE VI.—Distance from the spark at which Detonation is set up.

Mixture.	Spark *at* end.	Spark 3 inches from end.
$2H_2+O_2$	4 feet	12 inches
$2H_2+O_5$	—	4 feet
$6H_2+O_2$	—	16 „
$C_2N_2+O_2$	$8\frac{1}{2}$ inches	4 inches
$C_2N_2+2O_2$	12 „	10 „
$2C_2H_2+3O_2$	$4\frac{1}{2}$ „	$2\frac{1}{2}$ „
$C_2H_4+2O_2$	9 „	5 „

The mixtures most affected by the position of the spark among those experimented with are those of hydrogen and oxygen. The considerable "run" required before the detonation is set up when electrolytic gas is diluted, confirms my previous experiments on the rate of explosion of these mixtures.

The facts established above concerning the initial phases account for the great difference observed in the appearance of an explosion produced by a spark in the

centre of a tube. If the flame overtakes the sound-wave before it reaches the ends of the tube, as in fig. 61, the explosion exhibits intense retonation-waves followed by rapid cooling; but when the sound-waves are first reflected from the ends of the tube, as in fig. 65, the explosion shows less intense waves and a longer illumination.* These differences in the mode of burning must affect the maximum temperatures and pressures produced in an explosion.

Gases Fired at Open End of Tube.

We have made a few experiments on the appearances presented when gaseous mixtures are fired at or near the open end of the tube.

As is well known, from Le Chatelier's researches on the vibratory period, a mixture of carbon disulphide and nitric oxide gives oscillations of large amplitude. We show one photograph of the explosion of the mixture $CS_2 + 8NO$ fired at the open end of a tube 5 feet long and 1 inch bore. Only the last foot of the tube is shown in fig. 68.

The effect of firing the mixture $C_2N_2 + O_2$ 3 inches from an *open* end is the same as that of firing it *at* the closed end. Fig. 69 shows the detonation set up in about 8 inches, and of course no rebound from the open end. The mixture $2C_2H_2 + 3O_2$ lighted at the open end produced the detonation in $4\frac{1}{2}$ inches; lighted by a spark 3 inches from the open end, it set up the detonation in $2\frac{1}{2}$ inches from the spark.

PART VII.

Further Experiments on the Initial Phases.

(*In conjunction with* B. Dawson, *B.Sc.*, *and* L. Bradshaw, *B.Sc.*)

1. Le Chatelier's *Hypothesis of Discontinuity in the Explosion.*

Many of the photographs previously referred to show a peculiarity at the point where a less luminous line is succeeded abruptly by a more luminous one. The lines photographed do not appear *continuous*, but the more luminous line appears to start from a point not yet reached by the less luminous one. Figs. 28 to 31 (Plate 13) illustrate this discontinuity. The point of collision also of two waves appears to project in front of the waves which are meeting. Figs. 29 to 31 illustrate such a collision. It appeared to me at first as if these appearances might be due to invisible waves advancing in front of the visible ones, but as I found that they only showed

* The very interesting photographs, obtained by Mr. Petavel, of the movements of a piston connected with a chamber in which gases under high pressure are exploded, show vibrations which may be due to reflexion-waves.

where the luminosity of the lines was in marked contrast, and disappeared entirely when the films were less sensitive, or the contrast of luminosity was diminished for other reasons, as in figs. 40 and 41 and many other photographs (which are not reproduced), I came to the conclusion that the effect was due to halation on the photograph, the brighter lines being enlarged.

But in 1900 LE CHATELIER, relying on the same kind of evidence, put forward the view that the wave of detonation starts *in front of* the variable wave (which is increasing in velocity), and originates in an invisible wave, which is proceeding in front of the visible wave and with a velocity equal to it. He says :—

" Il n'y a, dans aucun cas, continuité entre la période variable et l'onde explosive. Celle-ci prend naissance à une certaine distance en avant de la flamme à vitesse variable, à 0·05 mètre dans le mélange $C_2H_2+O_2$. Ce fait est accusé par un ressaut de la courbe photographique enregistrée ; . . . . Dans cette période variable, la flamme est précédée d'une onde comprimée qui marche devant elle avec une vitesse égale, comme le font à la surface de l'écran les ondulations qui précèdent la proue d'un navire. Une fois l'onde explosive développée, les deux phénomènes se superposent, c'est-à-dire que le front de l'onde comprimée coïncide avec la tranche gazeuse en combustion, au lieu de la précéder."

This definite judgment of the brilliant French experimenter compelled us to re-examine the question. We attempted at first to decide the matter by photographing an explosion as it passed from a less luminous mixture into a more luminous one ; but we could not succeed in making the transition sufficiently sudden. However quick we were in pushing a short column of $C_2N_2+O_2$ into one end of a tube filled with $2H_2+O_2$, and firing the latter, the gases had diffused enough to prevent any abrupt change in the brightness of the explosion. We did, however, succeed in obtaining sudden changes of brightness by introducing a layer of " Welsbach " salts (a mixture of thoria and ceria), and having the rest of the tube quite clean. Although to raise the salt from the glass and to render it incandescent must take some time, nevertheless the photograph shows a small but distinct break in the line of detonation similar to that in question. Figs. 70 and 71 show the passage of the wave of detonation in electrolytic gas through such a " salted " tube. If the salts could be raised instantaneously, it is possible that the break would be as well-marked as any observed in the development of the detonation.

It is of course easy to show the enlargement due to brightness. If a tube is filled with a mixture giving a luminous explosion, and the explosion is photographed while half the tube is covered over, and if the tube is then filled with a mixture giving a less luminous explosion, which is photographed on the same film while the first half of the tube is covered, a photograph is obtained (fig. 72) which shows a greater discontinuity than any of those in question.

Another way of showing the same thing is to photograph a thin platinum wire

stretched by weights and rendered luminous by an electric current. If a second wire is brought to touch the first so as to divide the current, the portion of the wire which carries the whole current is more luminous than the other portion, and the photographs make it appear of far greater diameter. Fig. 73 is a photograph taken in this way, with the same camera and films as were employed for the explosions. If the effect in the explosions is due to halation, we ought never to see the bright line displaced so much as not to overlap the duller line *on both sides*. None of our photographs show such a displacement, the effect might therefore be caused by halation alone.

We may thus summarise the evidence against the existence of Le Chatelier's "invisible wave":—

1. Its supposed effect is only seen when the contrasts are strong, and not on photographs of the same phenomena in which the contrasts are not brought out.
2. It can be imitated in various ways by means of contrasts.
3. The same effect is seen in the collision of two detonation-waves, but Le Chatelier does not suppose that the "invisible wave" can precede the detonation.

2. *Repetition of* v. Oettingen *and* v. Gernet's *Experiments.*

The very short time required for the explosion in electrolytic gas to raise the Welsbach oxides to incandescence (as shown in figs. 70 and 71) was strong evidence against the view held by v. Oettingen and v. Gernet, viz.: that the detonation of electrolytic gas is invisible, and that the salts present in their experiments only became luminous after the combustion had been for some time complete. Our previous experiments had also shown conclusively that the detonation is not set up *at once*, but only after the flame has run some distance, which varies with the nature of the mixture and the position of the spark. But to place the matter beyond all doubt we have repeated their experiments, using a tube of the same size and construction as theirs, filled with electrolytic gas, but without the addition of any salts. By careful development, the course of the flame can be seen on the negatives from the firing wire. In all cases the explosion begins slowly, and has slight luminosity until the retonation-waves are started by reflexion from the ends of the tube.

In fig. 74 the explosion was started in the centre of the tube (400 millims. long). Just as in v. Oettingen's "fig. 8" (our fig. 5, Plate 10), a line of light joins the spark to the more luminous portion of the explosion; but instead of a detonation-wave travelling three and a half times the length of the tube before the first visible compression-wave descends from the top of the tube (as in their explanation), the flame is seen to travel slowly right and left until it meets with the return sound-wave from the end of the tube. The flame is checked while these two sound-waves cross the ignited gases,

and then moves on rapidly from the point where the reflected sound-wave reaches the front of the flame. The movement on each side is now seen to be unsymmetrical; the flame to the left does not reach its end of the tube before it is again checked, that to the right reaches the end of the tube and sends back a powerful retonation-wave. The consequence of this dissymmetry is the greater intensity and rapidity of the wave started from the right over that from the left. Although the reflexions of these waves at first run nearly parallel, yet after four journeys to and fro the stronger wave catches the weaker and coalesces with it, and the rest of the picture shows only repeated reflexions of a single wave. A similar coalescence of two waves is shown in fig. 7 of v. OETTINGEN and v. GERNET, and this figure closely resembles a portion of our photograph. It is thus evident how "secondary" waves running parallel with the "primary" are produced; there is no need to invoke any "successive partial explosions" to account for them.

Fig. 74 shows in outline the path of the flame and the sound-waves, which may be compared with the "schema" of fig. 8, according to v. OETTINGEN and v. GERNET.

In fig. 75 the gas was also fired in the middle, but the explosion is more symmetrical, and "nearly parallel" waves can be seen to be produced by reflexion from both ends of the tube.

Our next photograph (76) shows the effect of firing the gas near one end of the tube. The flame proceeds with increasing velocity to the further end, where a strong wave is sent back; this single wave shows less complications than the double wave started in 74.

In 77 the gases are fired at one-fourth the length from one end. Very complicated reflexions are produced, which only gradually become absorbed. In this photograph the mode of formation of "nearly parallel waves" can easily be traced.

In fig. 78 is seen the effect of lighting the explosive mixture at one end, and at a point one-quarter from the further extremity simultaneously. The effect of the sound-wave proceeding from each point of ignition is plainly seen when it reaches the *other* flame. The *reflected*-waves, visible in the burning gases, cross the unignited mixture, and again become visible in the flames beyond. When the two flames coalesce the picture resembles the other photographs. In fig. 79 the gases were ignited simultaneously at each end of the tube.

[The last three photographs, reproduced in figs. 80, 81, and 82, show the detonation-wave set up in a long tube reaching a portion of gas which (having been independently ignited) is still in the initial stage of combustion. In fig. 80 the gas was lighted in the centre of the tube just before the detonation-wave arrived. The detonation is slightly damped down on meeting the already ignited gas. In fig. 81 the detonation-wave strikes a flame started *at* the end of the tube. In fig. 82 the initial flame had spread considerably before the detonation struck it near the left-hand edge of the photograph. In each case the wave is propagated through the already burning gas like a retonation-wave.—H. B. D. and L. B., *October*, 1902.]

Description of the Plates.

PLATE 10.

Mallard and Le Châtelier's photographs of explosions in tubes fixed *vertically*.

Fig. 1. Explosion of the mixture $CS_2 + 6NO$ ignited at the open end of a tube 3 metres long and 20 millims. in diameter.
Fig. 2. Same mixture fired at open end of a tube 10 millims. in diameter.
Fig. 3. Mixture of $CS_2 + 6NO$ fired near closed end of tube 2 metres long. A "rebound-wave" from the further end of the tube is shown.
Fig. 4. Mixture of CS_2 and oxygen fired at open end of tube. A detonation-wave is set up.

Von Oettingen and von Gernet's photographs of explosions in a *vertical* tube containing metallic salts.

Fig. 5. Electrolytic gas fired in centre of tube 400 millims. long.
Fig. 5A. Supposed path of waves in fig. 5.
Fig. 6. Electrolytic gas fired 50 millims. from one end of tube.
Fig. 6A. Supposed path of waves in fig. 6.

PLATE 11.

Photographs of explosions in *horizontal* glass tubes.

Fig. 7. Reflexion of wave from closed end of tube ($C_2N_2 + 2O_2$).
Fig. 8. Reflected wave proceeding backwards ,,
Fig. 9. ,, ,, ,, ,, ,,
Fig. 10. ,, ,, in mixture $2H_2 + O_2$.
Fig. 11. ,, ,, ,, $2CO + O_2$.
Fig. 12. ,, ,, ,, $C_2N_2 + O_2$.
Fig. 13. ,, ,, ,, $2C_2H_2 + 5O_2$.
Fig. 14. Explosion reaching open end of tube.
Fig. 15. ,, ,, end of tube loosely corked.
Fig. 16. Tube broke as explosion reached end of tube.
Fig. 17. Explosion passing through long tube; movements of the gas are not affected by reflexions.

PLATES 12 and 13.

Fig. 19. Sound-waves *meeting* detonation ($C_2N_2 + 2O_2$).
Fig. 20. ,, wave meeting ,, ($C_2N_2 + O_2$).
Fig. 21. ,, ,, ,, ,, ($CS_2 + 2O_2$).
Fig. 23. ,, ,, *following* ,,
Fig. 25. Two explosions meeting end-on.
Fig. 26. ,, ,, ,, ,,
Fig. 27. ,, ,, ,, ,,
Fig. 28. ,, ,, ,, ,,
Fig. 29. ,, ,, ,, ,,
Fig. 30. ,, ,, ,, ,,
Fig. 31. ,, ,, ,, ,,
Fig. 32. ,, ,, ,, ,,
Fig. 33. ,, ,, ,, ,,

} Showing irregularities and sudden increments of brightness and velocity.

Fig. 34. Sudden increment shown by flame travelling one way only.

Fig. 35. Detonation passing through three parallel glass tubes joined together by lead junctions. In passing each junction the explosion is damped down and recoups itself suddenly.

PLATE 14.

Fig. 37. Detonation passing through glass bend *without* retardation.

Fig. 38. ,, ,, ,, flexible rubber junction *without* retardation.

Fig. 39. ,, ,, ,, rigid copper junction ,, ,,

Fig. 40. Collision of true detonation-waves ($C_2N_2 + 2O_2$).

Fig. 41. ,, ,, ,, ,, ,,

Fig. 42. ,, ,, ,, ,, ($2H_2 + O_2$).

Fig. 43. "Retonation"-wave running parallel with collision-wave.

PLATE 15.

Fig. 44. Retonation-wave and reflexion-wave.

Fig. 45. ,, ,, started at end of tube.

Fig. 46. Explosion started in centre of long tube; retonation-waves return from points where the detonation-waves are set up.

Fig. 47. Explosion started in centre of short tube; retonation-waves are set up at either end of tube ($C_2N_2 + O_2$).

Fig. 48. Explosion started in centre of short tube; retonation-waves are set up at either end of tube ($2C_2H_2 + 3O_2$).

Fig. 49. Velocity of retonation and reflexion-wave compared.

Fig. 50. ,, detonation and retonation-waves (in separate tubes) compared.

Fig. 51. ,, ,, ,, ,, ,, ,, ,,

PLATE 16.

Fig. 52. Explosion showing initial wave overtaken by faster wave.

Fig. 53. ,, ,, that the overtaking flame comes from the near end of the tube.

Fig. 54. ,, ,, ,, ,, ,, ,,

Fig. 55. ,, ,, ,, ,, ,, ,,

Fig. 56. ,, of $C_2N_2 + O_2$, showing retonation-wave started from near end of tube and running nearly parallel with detonation-wave.

Fig. 57. Explosion of $C_2N_2 + 2O_2$, showing reflexion of *sound* from near end of tube checking the flame and producing a visible wave in the burning gases.

Fig. 57A. Plan of 57, showing path of waves.

PLATES 17 AND 18.

Fig. 58. Explosion of $C_2N_2 + O_2$ in lower tube, showing reflexion of sound-wave from further end of tube. Upper photograph shows detonation of same mixture in another tube.

Fig. 58A. Plan of 58, showing path of sound-wave.

Fig. 59. $C_2N_2 + O_2$ fired *at* one end of tube $8\frac{1}{2}$ inches long.

Fig. 60. Mixture $C_2N_2 + O_2$ fired 4 inches from one end of tube 13 inches long.

Fig. 60A. Plan of 60, showing paths of sound-waves.

Fig. 61. $C_2N_2 + O_2$ fired in centre of tube 8 inches long; intense retonation-waves are sent back from each end.

Fig. 62. $C_2N_2 + O_2$ fired in centre of tube 6 inches long; the flames are checked symmetrically by sound-waves reflected from the ends of the tube.

Fig. 63. Explosion of $C_2N_2 + 2O_2$ where sound-wave is overtaken by explosion before reaching end of tube.

Fig. 64. Explosion of $C_2N_2 + 2O_2$ where sound-wave reaches end of tube first.

Fig. 65. ,, ,, ,, sound-waves return from both ends of tube and cross flame symmetrically.

Fig. 66. Explosion of $C_2N_2 + 2O_2$ fired *at* closed end of tube.

Fig. 67. ,, ,, ,, 4 inches from closed end.

Fig. 68. Oscillations of flame in explosion of $CS_2 + 8NO$ after passing 4 feet down tube.

Fig. 69. $C_2N_2 + O_2$ fired 3 inches from open end of tube.

PLATE 19.

Fig. 70. Effect of "salting" part of tube traversed by detonation of $2H_2 + O_2$, showing "break" in line of detonation.

Fig. 71. Effect of "salting" part of tube traversed by detonation of $2H_2 + O_2$, showing "break" in line of detonation.

Fig. 72. Glass tube magnified by halation.

Fig. 73. Platinum wire magnified by halation.

Fig. 74. Explosion of electrolytic gas in centre of short tube, showing effect of reflected sound-waves.

Fig. 74A. Plan of 74, showing path of sound-waves.

Fig. 75. Explosion of electrolytic gas in centre of short tube. The reflexions are nearly symmetrical.

Fig. 76. ,, ,, ,, fired near one end of short tube. The flame is less complicated.

PLATE 20.

EXPLOSIONS of the mixture $CS_2 + 3O_2$.

Fig. 77. Mixture fired at one-fourth the length from one end: nearly parallel waves are produced by reflexions.

Fig. 78. Mixture fired at same time at one end and at one-fourth the distance from other end. The sound-waves are visible as they cross the burning gases.

Fig. 79. Mixture fired at both ends of the tube at same time.

Fig. 80. Explosion started in centre of tube, and the initial flame struck by detonation coming from left hand.

Fig. 81. Explosion started at one end of tube, and initial flame struck by detonation coming from left hand.

Fig. 82. The explosion has spread considerably before it is struck by detonation as before.

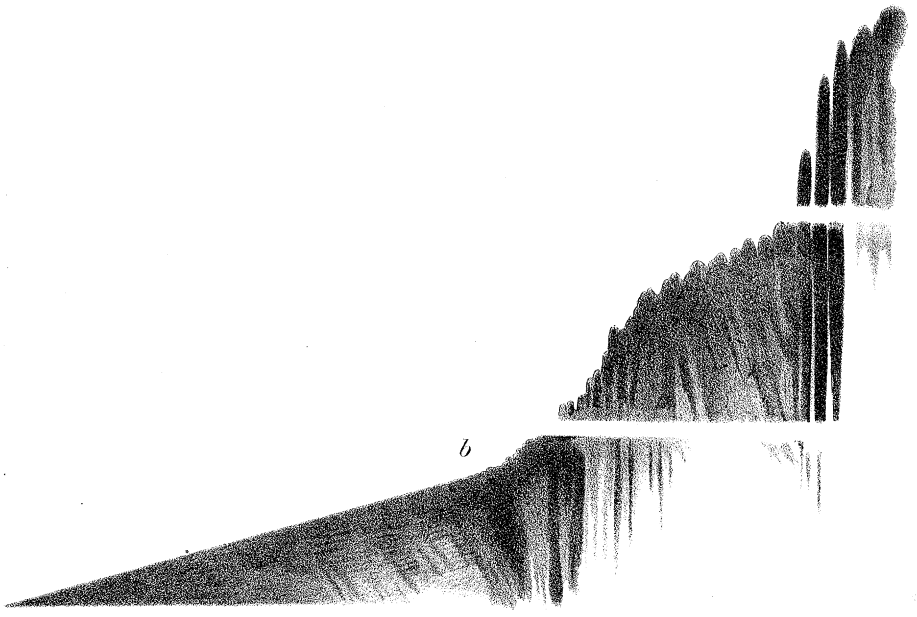

Fig. 1.

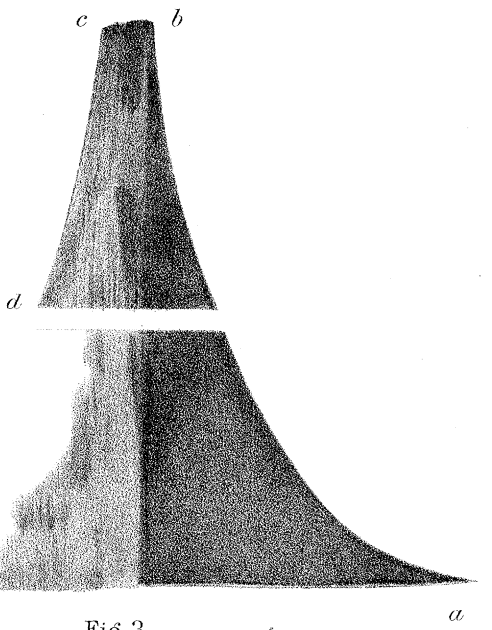

Fig. 3.

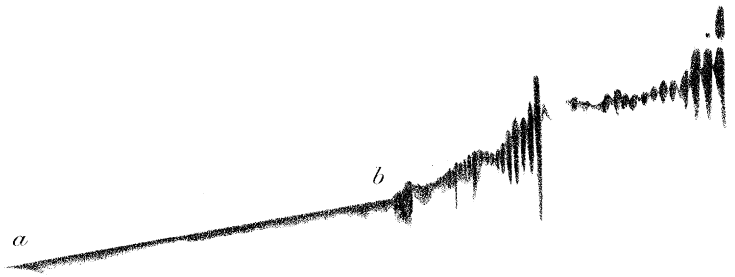

Fig. 2.

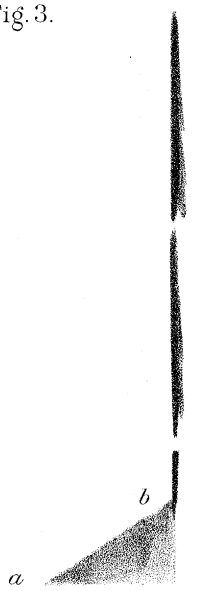

Fig. 4.

Mallard and Le Chatelier's Photographs.

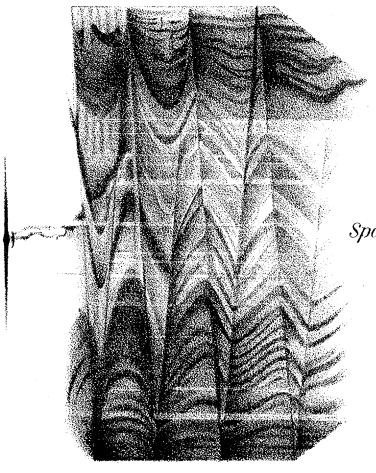

Fig. 5.

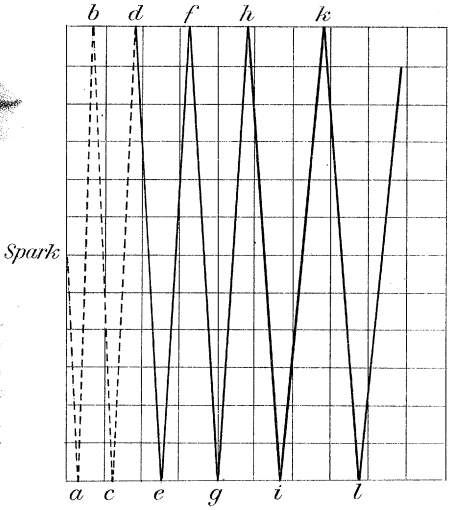

Fig. 5a.

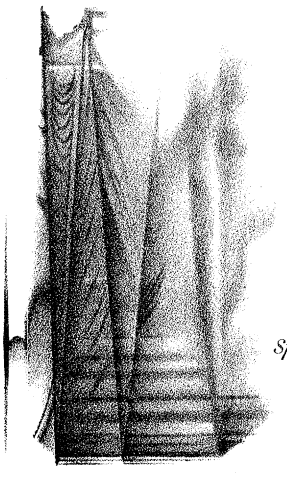

Fig. 6.

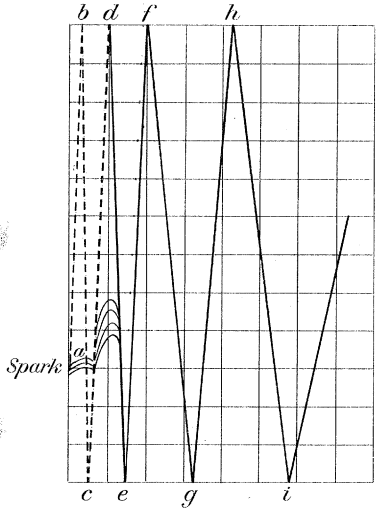

Fig. 6a.

von Oettingen and von Gernet's Photographs.

West, Newman lith.

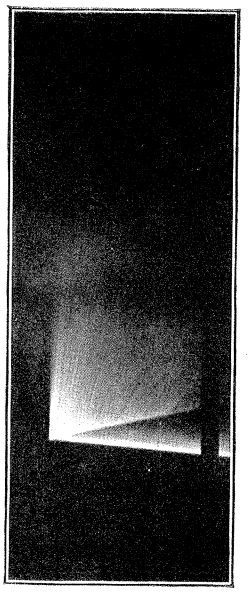

Fig. 7.

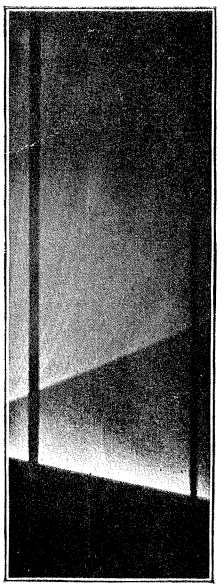

Fig. 8.

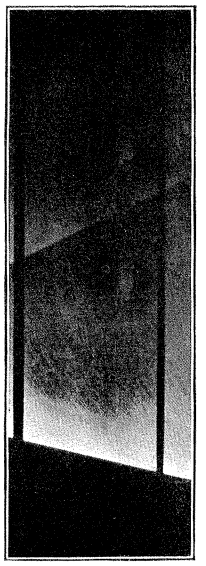

Fig. 9.

Explosions of mixtures of $C_2N_2 + 2O_2$, showing waves reflected from closed end of tube.

Fig. 10. $2H_2 + O_2$.

Fig. 11. $2CO + O_2$.

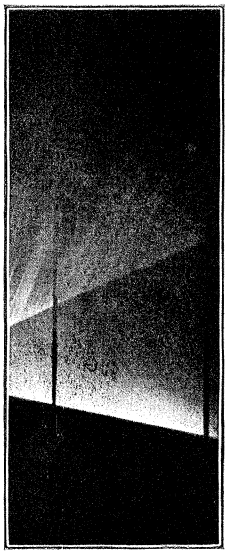

Fig. 12. $C_2N_2 + O_2$.

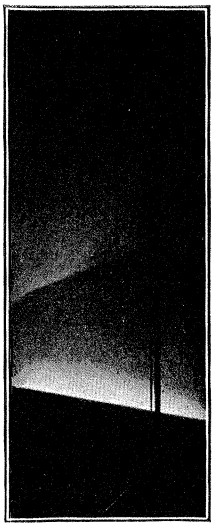

Fig. 13. $2C_2H_2 + 5O_2$.

Fig. 14.—With end open.

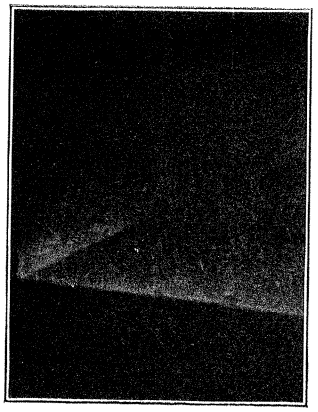

Fig. 15.—End loosely corked.

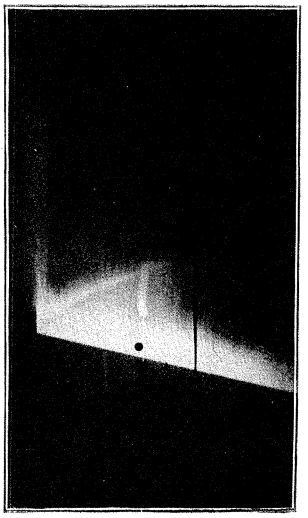

Fig. 16.—Tube broke.

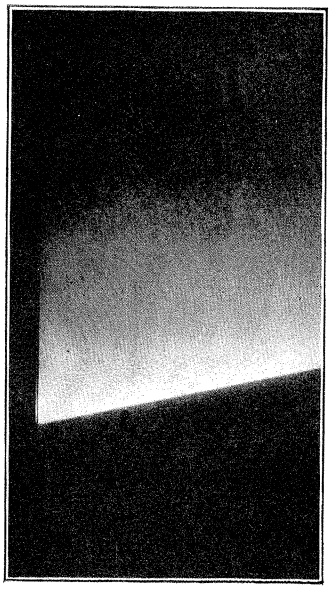

Fig. 17.—Movements of gas following detonation-wave.

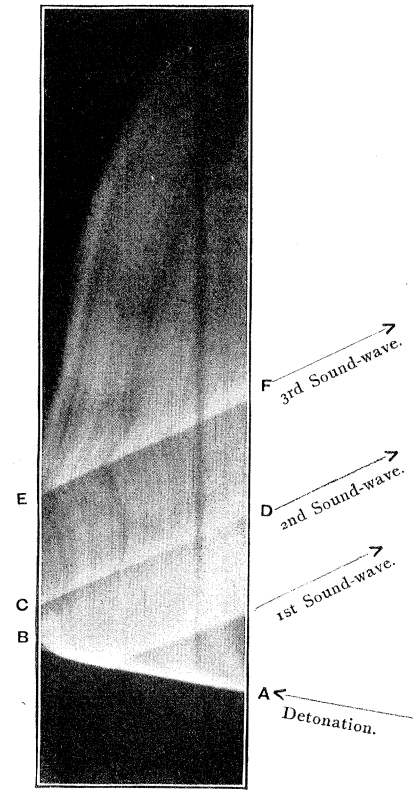

Fig. 19.—Sound-waves meeting detonation of $C_2N_2 + 2O_2$.

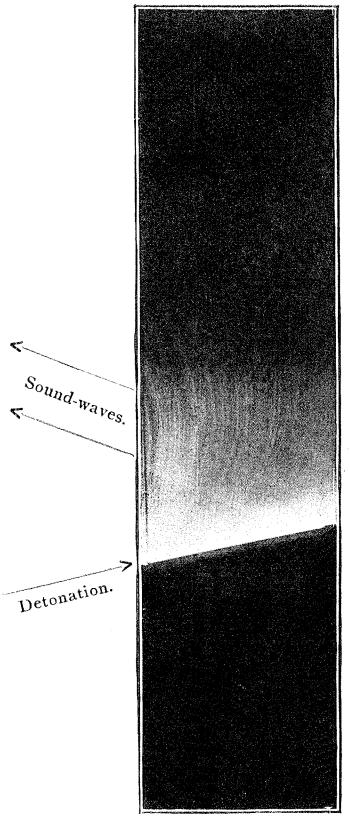

Fig. 20.—Sound-waves meeting detonation of $C_2N_2 + O_2$.

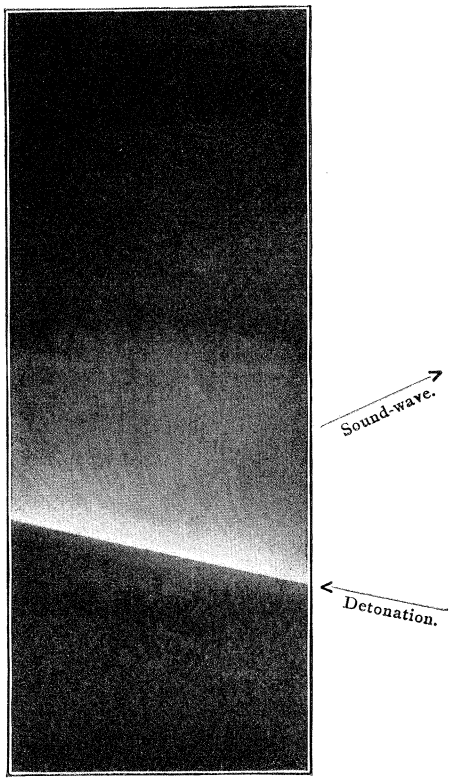

Fig. 21.—Sound-wave meeting detonation of $CS_2 + 2O_2$.

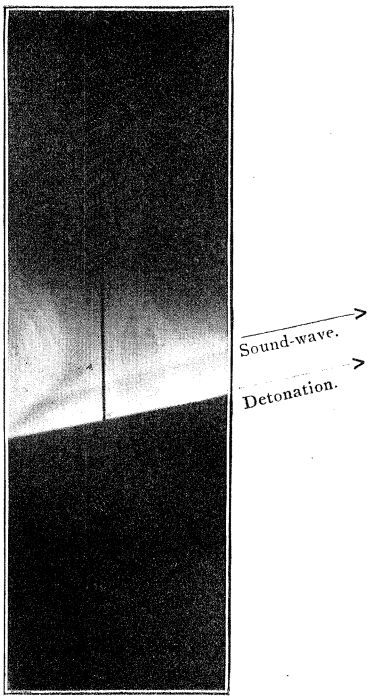

Fig. 23.—Sound-wave following detonation of $C_2N_2 + 2O_2$.

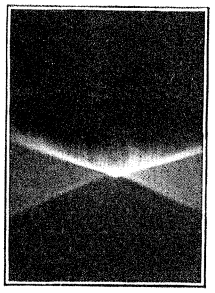

Fig. 25.—Two Explosions meeting.

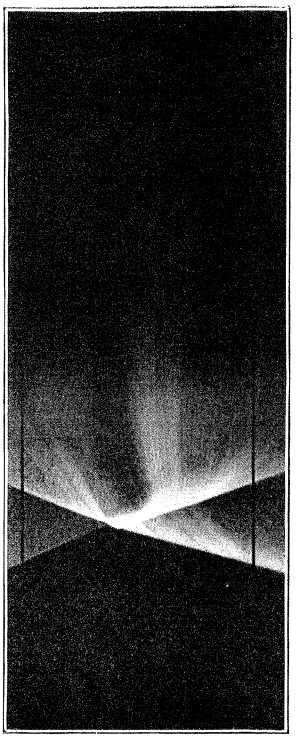

Fig. 26.—Two Explosions meeting.

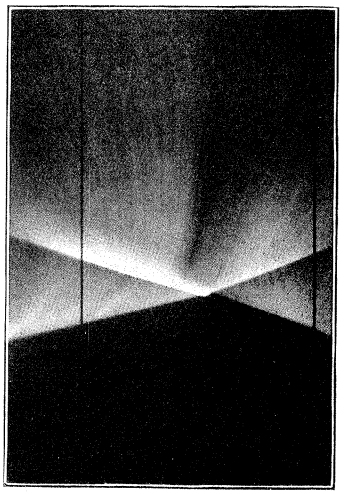

Fig. 27.—Two Explosions meeting.

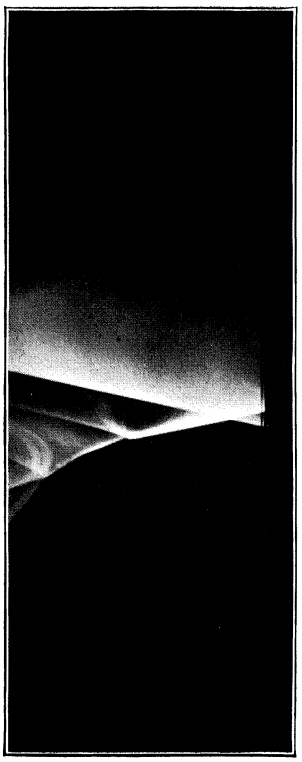

Fig. 28.—Two Explosions meeting.

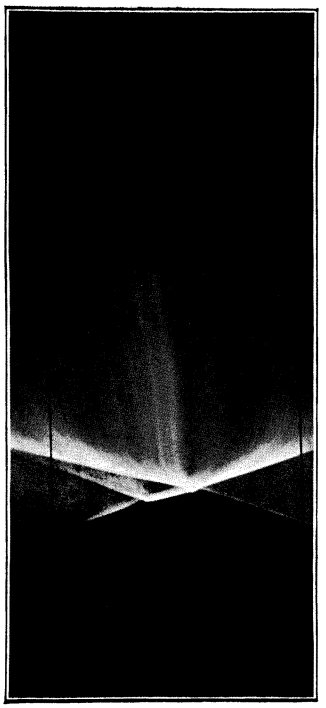

Fig. 29.—Two Explosions meeting.

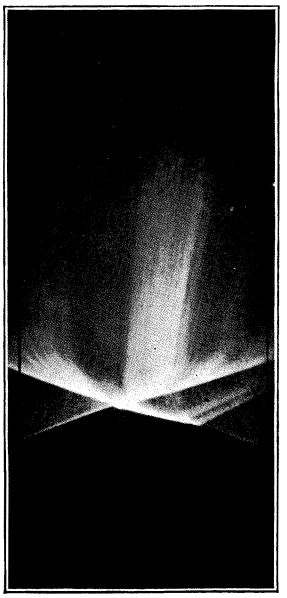

Fig. 30.—Two Explosions meeting

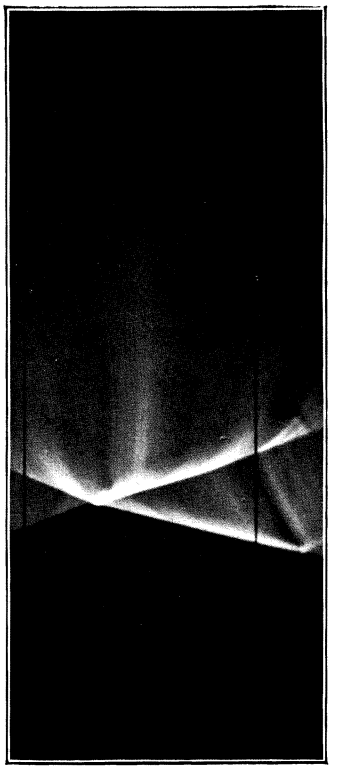

Fig. 31.—Two Explosions meeting.

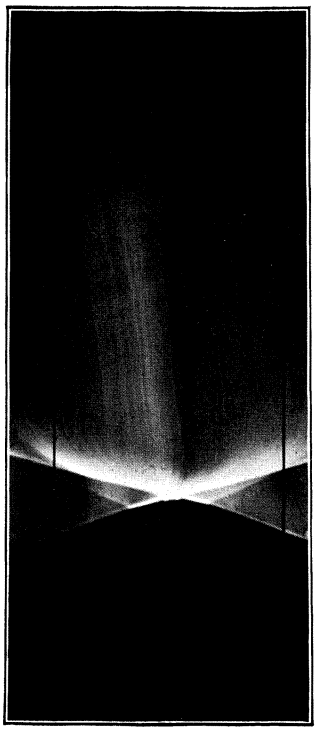

Fig. 32.—Two Explosions meeting.

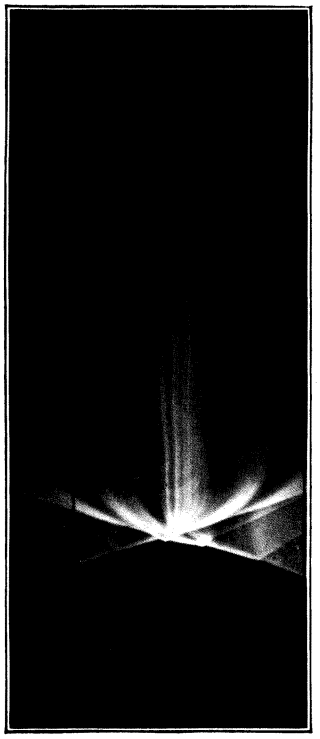

Fig. 33.—Two Explosions meeting.

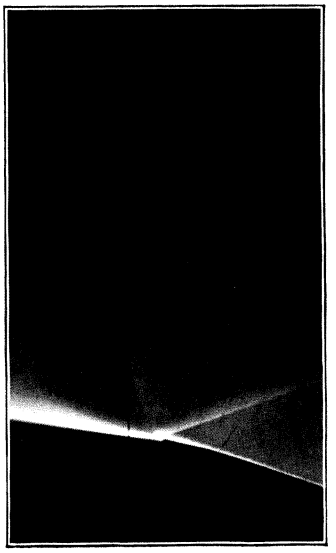

Fig. 34.—Explosion going one way only.

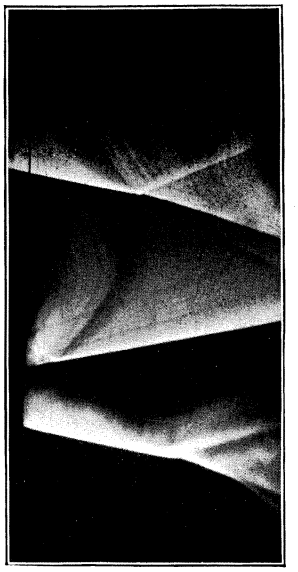

Fig. 35.—Detonation passing through three tubes with lead junctions.

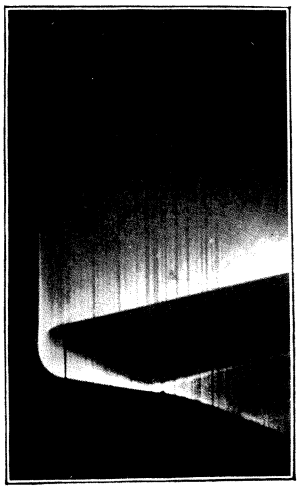

Fig. 37.—Detonation passing through glass bend.

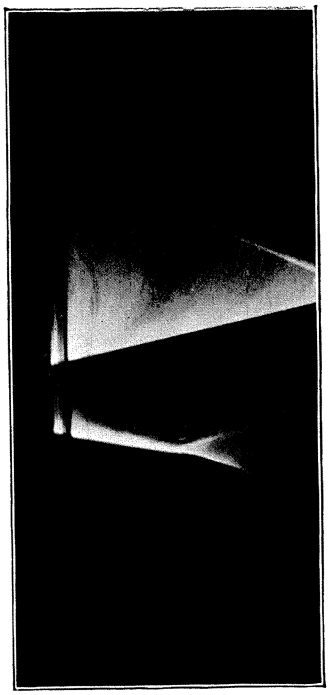

Fig. 38.—Detonation passing through flexible rubber junction without retardation.

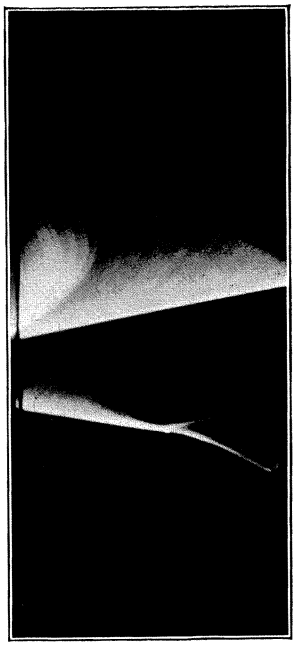

Fig. 39.—Detonation passing through rigid copper junction without retardation.

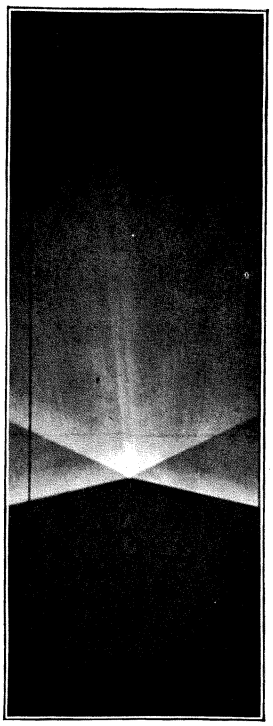

Fig. 40.—Collision of two detonation-waves.
$C_2N_2 + 2O_2$.

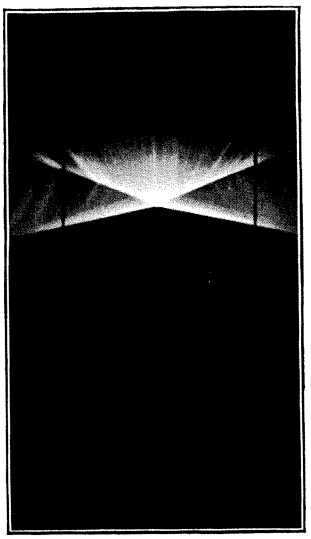

Fig. 41.—Collision of two detonation-waves.
$C_2N_2 + 2O_2$.

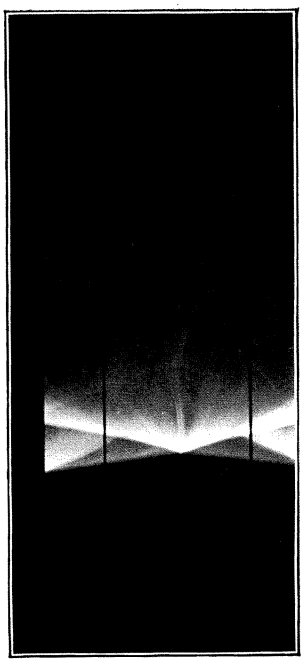

Fig. 42.—Collision of two detonation-waves.
$2H_2 + O_2$.

Fig. 43.—Retonation-wave running parallel with collision-wave.

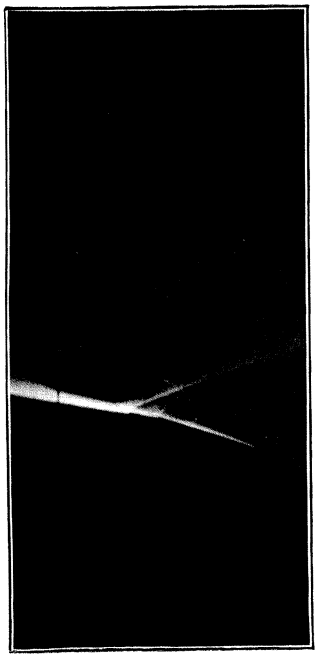

Fig. 44.—Retonation-wave and Reflexion-wave.

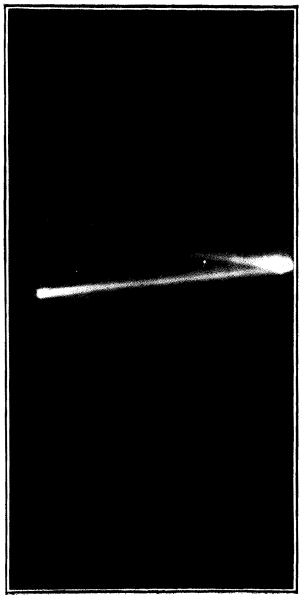

Fig. 45.—Retonation-wave started at end of tube.

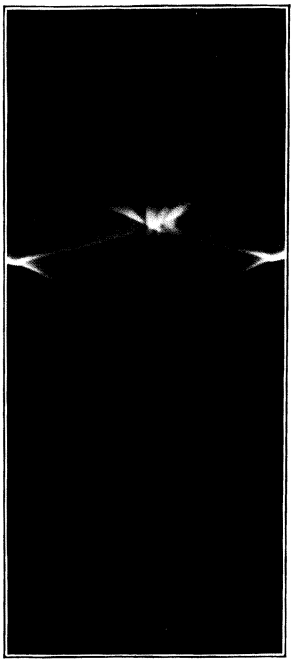

Fig. 46.—Retonation-waves formed by explosion in centre of long tube.

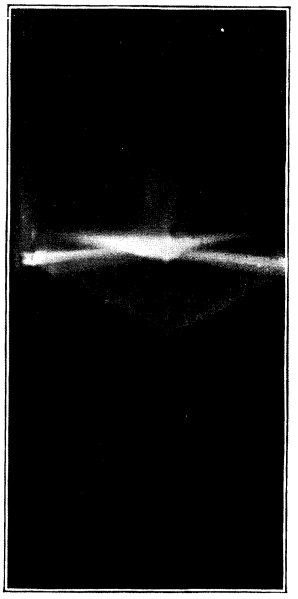

Fig. 47.—Retonation-waves formed at ends of short tube. $C_2N_2 + O_2$.

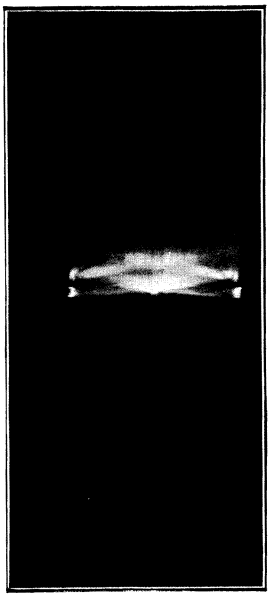

Fig. 48.—Do. $C_2H_2 + O_3$.

Fig. 49.—Retonation-wave and Reflexion-wave.

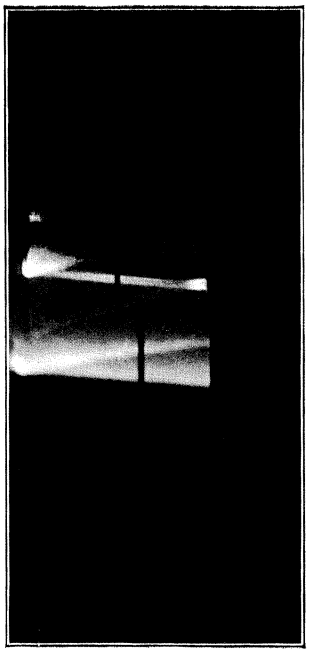

Fig. 50.—Detonation in lower tube. Retonation in upper tube.

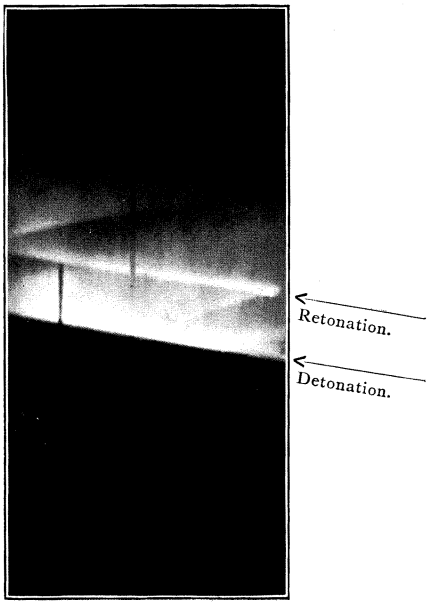

Fig. 51.—Detonation in one tube; Retonation in other tube.

Fig. 52.—Initial wave overtaken by faster wave.

Fig. 53. $C_2N_2 + 2O_2$.

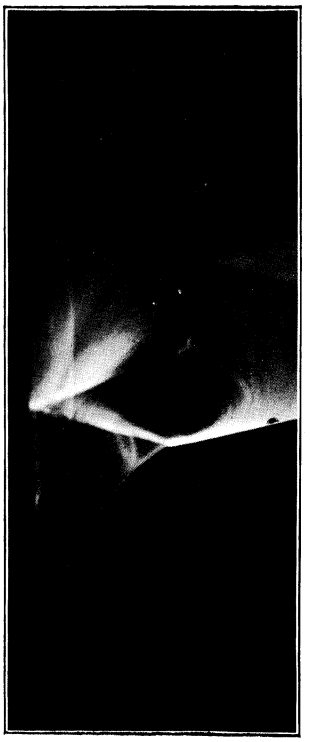

Fig. 54. $CS_2 + 3O_2$.

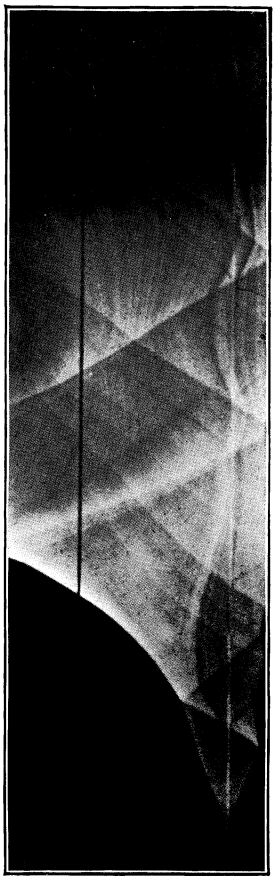

Fig. 55. $CS_2 + 5O_2$.

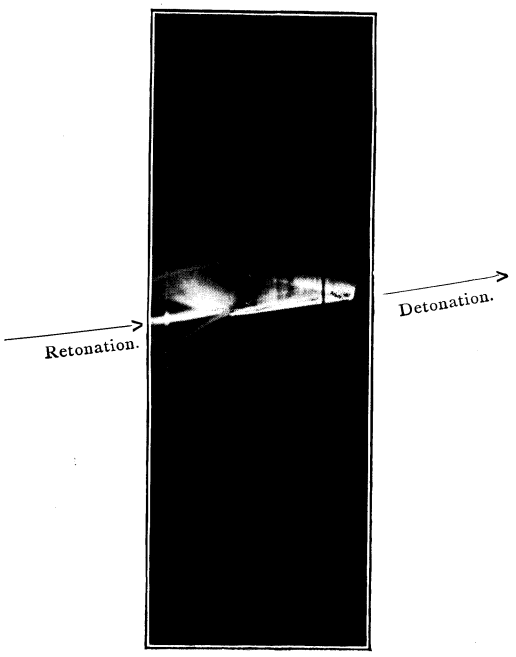

Fig. 56. $C_2N_2 + O_2$.

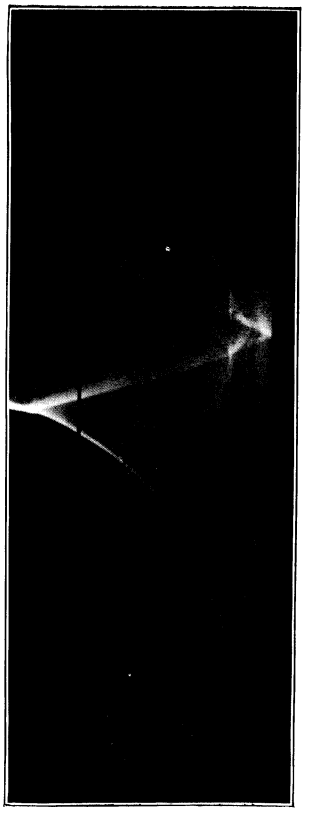

Fig. 57. $C_2N_2 + 2O_2$.

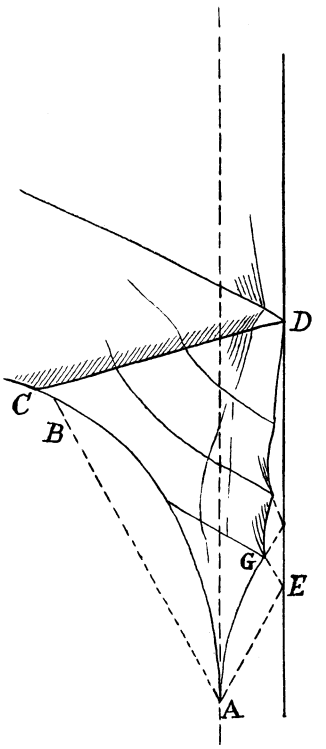

Fig. 57A.

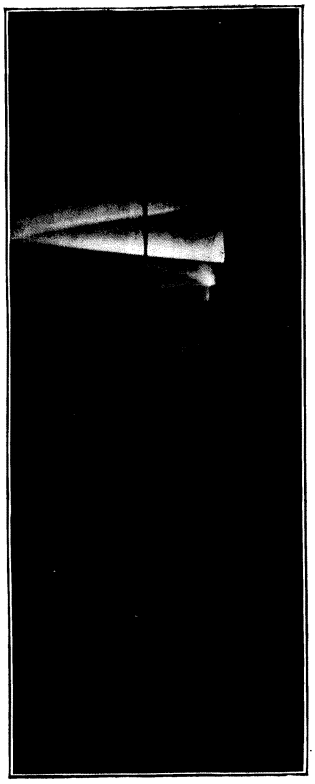

Fig. 58. $C_2N_2 + O_2$.
Detonation in upper tube.
Initial flame in lower tube.

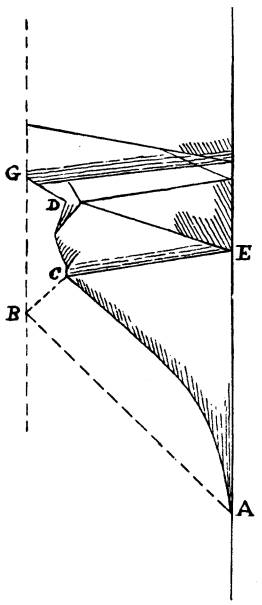

Fig. 58A.

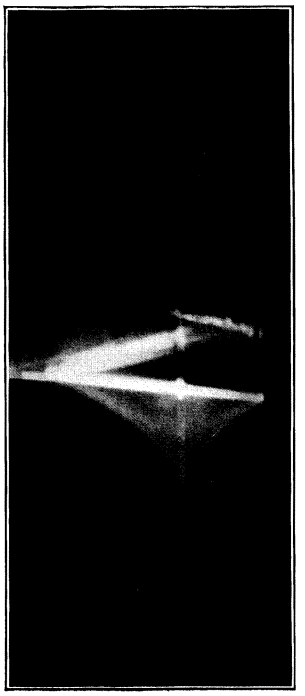

Fig. 60. $C_2N_2 + O_2$.

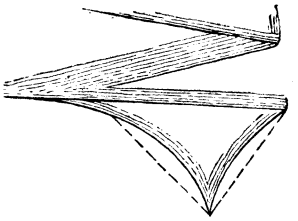

Fig. 60A.

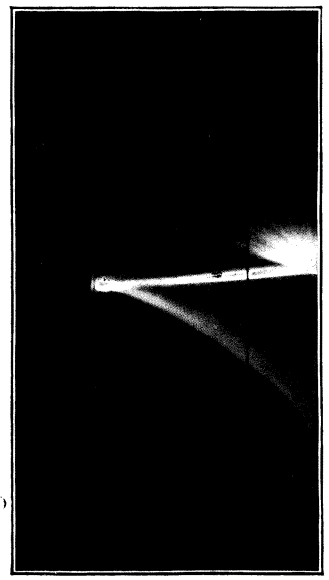

Fig. 59. $C_2N_2 + O_2$.

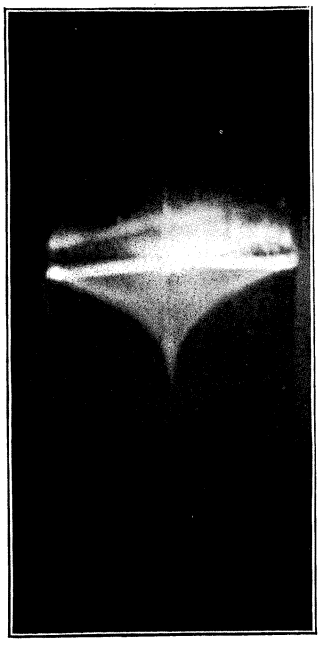

Fig. 61. $C_2N_2 + O_2$.

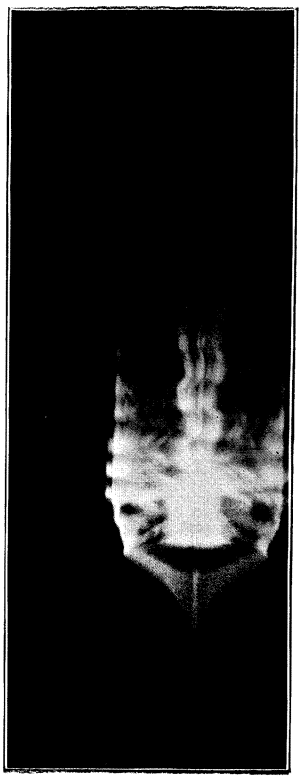

Fig. 62. $C_2N_2 + O_2$.

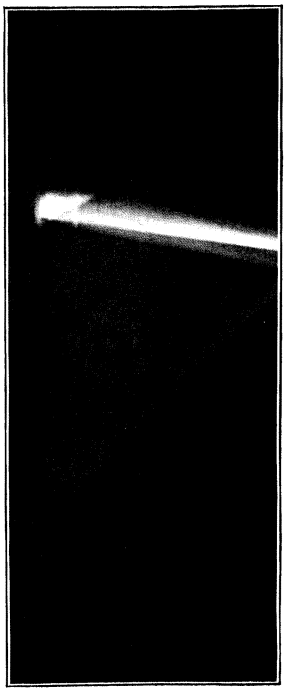

Fig. 63. $C_2N_2 + 2O_2$.

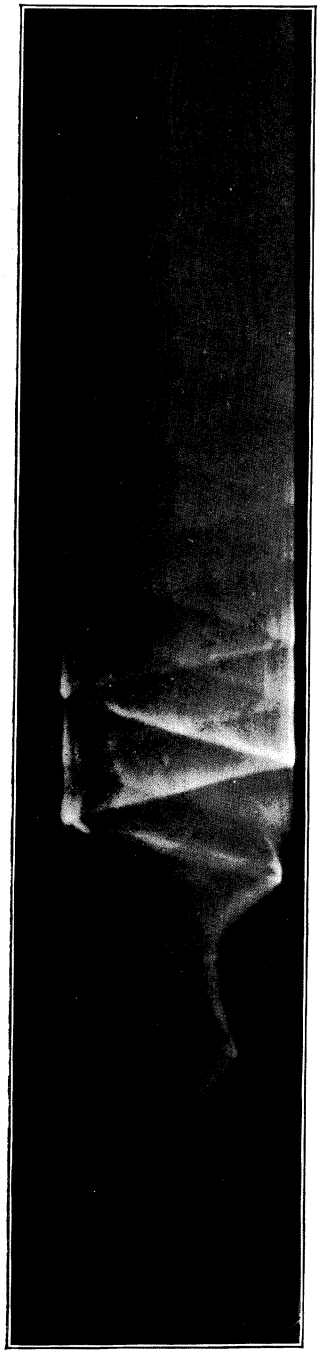

Fig. 64. $C_2N_2 + 2O_2$.
Showing sound-wave returning from right-hand end.

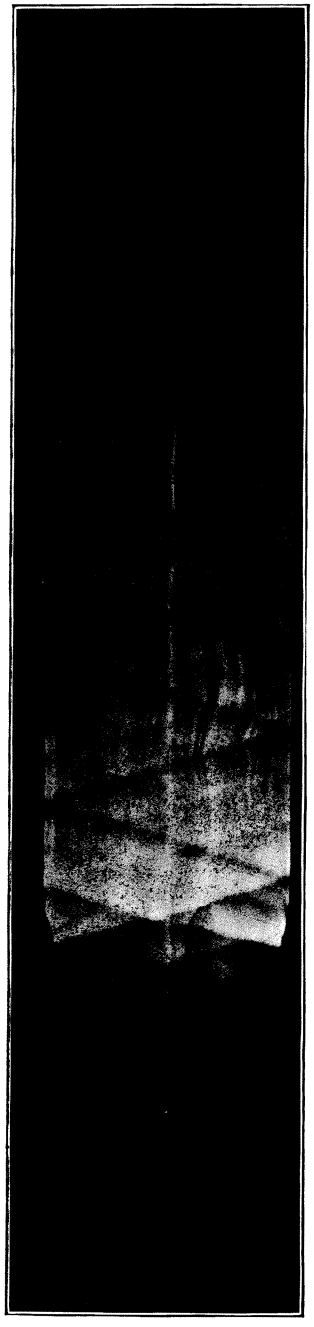

Fig. 65. $C_2N_2 + 2O_2$.
Showing sound-waves returning from both ends.

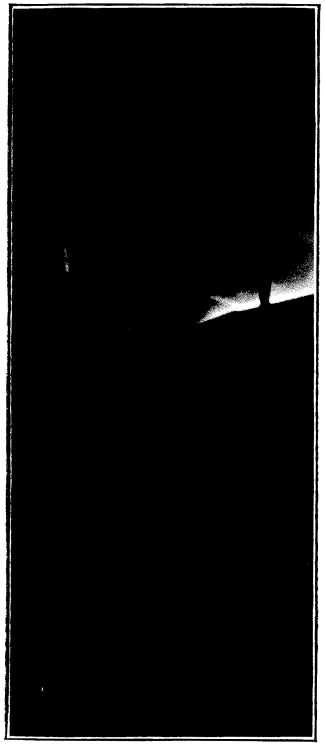

Fig. 66. $C_2N_2 + 2O_2$.
Fired at closed end.

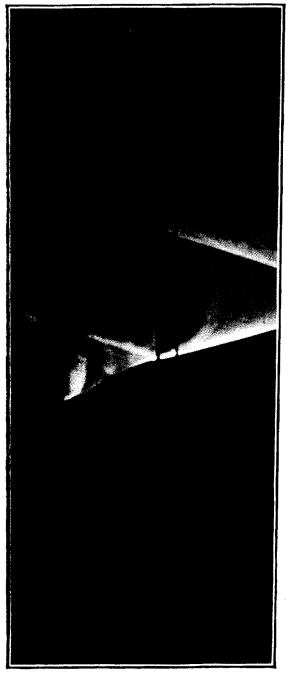

Fig. 67. $C_2N_2 + 2O_2$.
Fired 4 inches from closed end.

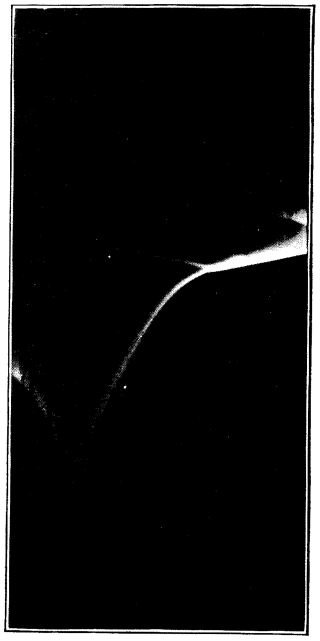

Fig. 69. $C_2N_2 + O_2$.
Fired 3 inches from open end.

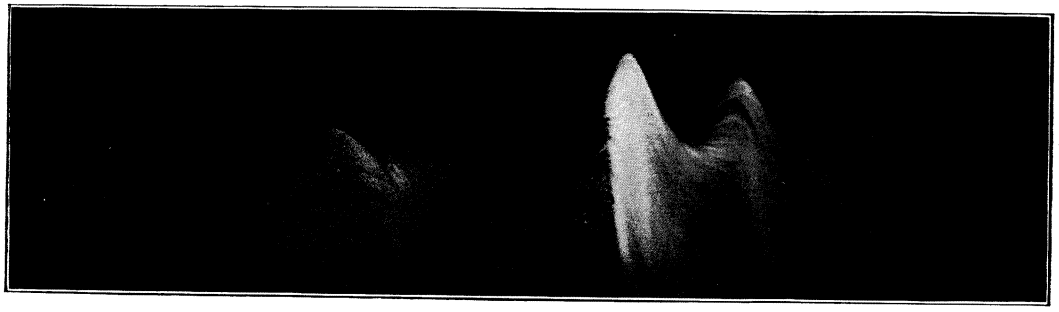

Fig. 68. $CS_2 + 8NO$.
Oscillations of flame between 4 and 5 feet from firing-point.

Fig. 70.—Part of tube salted. $2H_2 + O_2$.

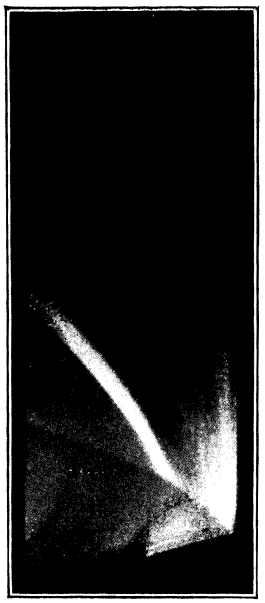

Fig. 71.—Part of tube salted. $2H_2 + O_2$.

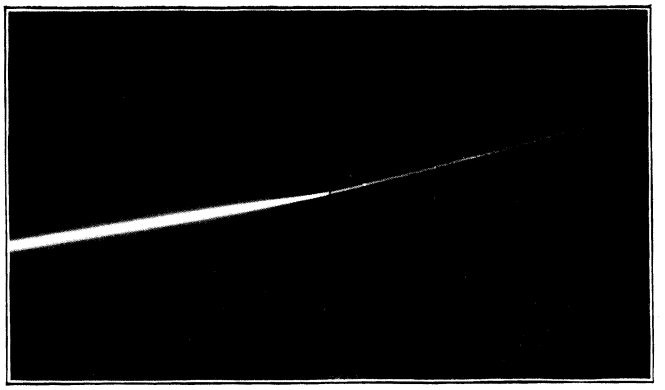

Fig. 73.—Platinum wire magnified by halation.

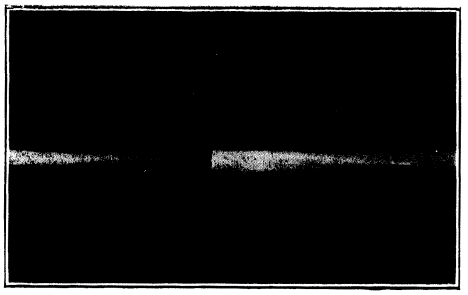

Fig. 72.—Glass tube magnified by halation.

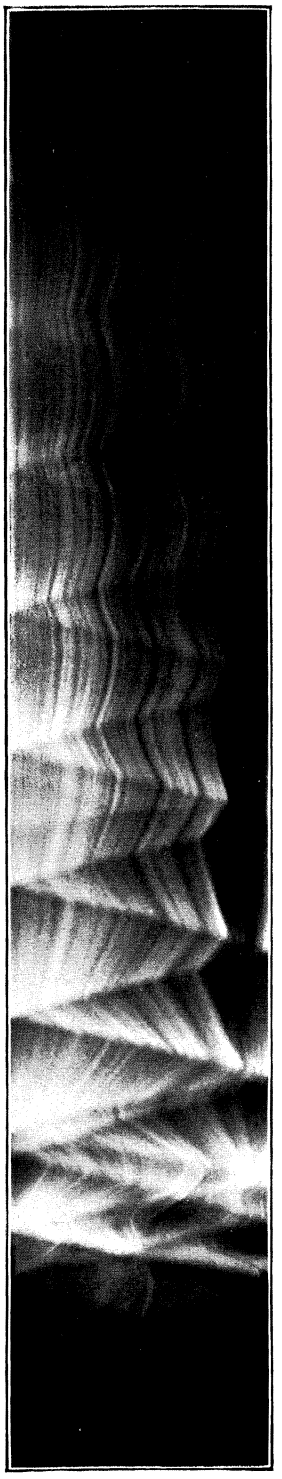

Fig. 74. $2H_2 + O_2$.

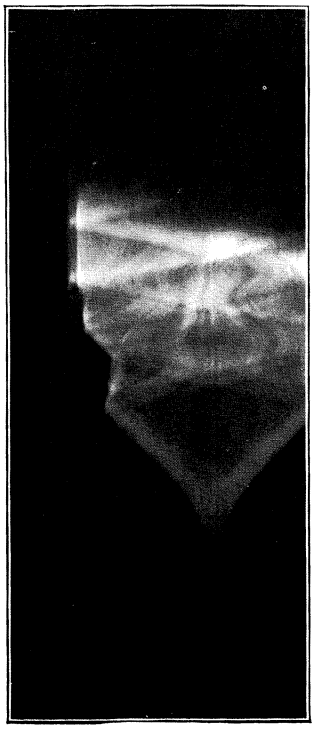

Fig. 75.

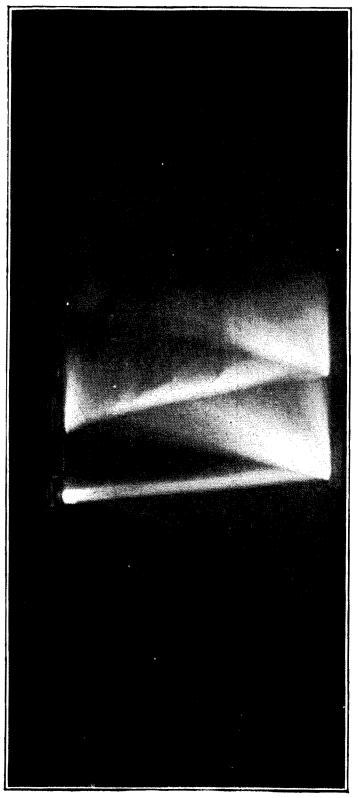

Fig. 76.

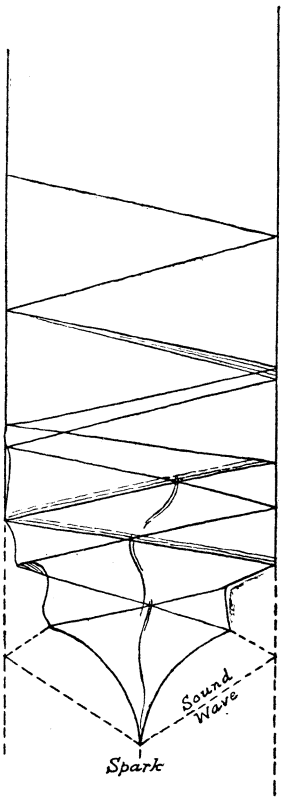

Fig. 74A.

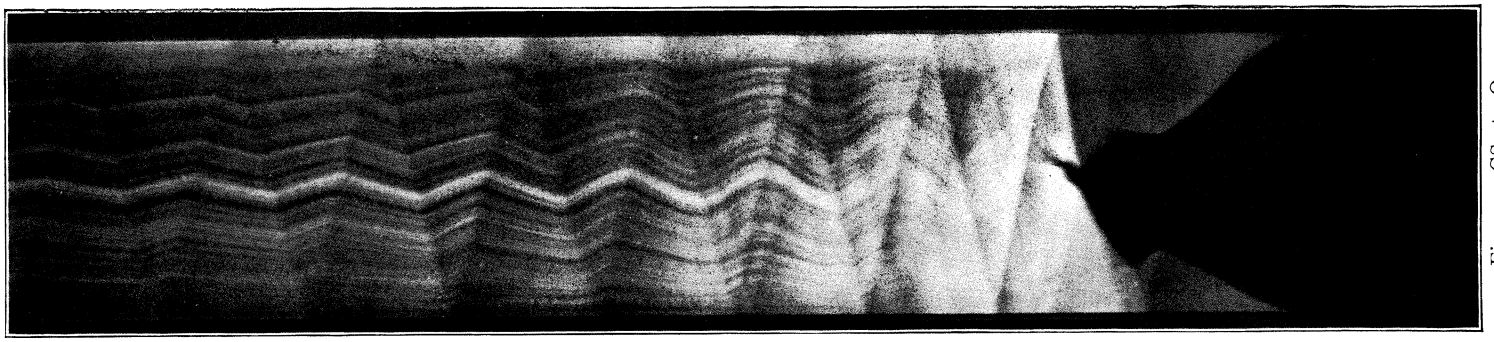

Fig. 79. $CS_2 + 3O_2$.

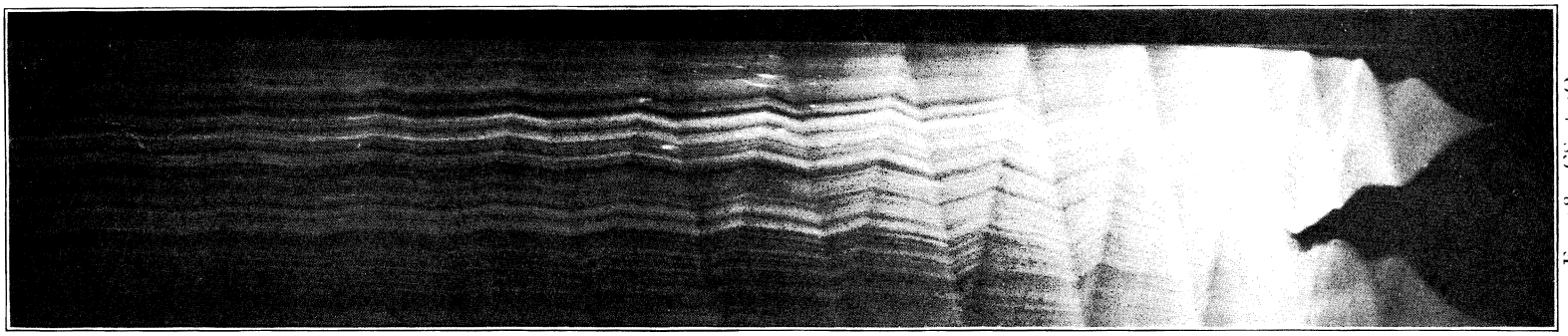

Fig. 78. $CS_2 + 3O_2$.

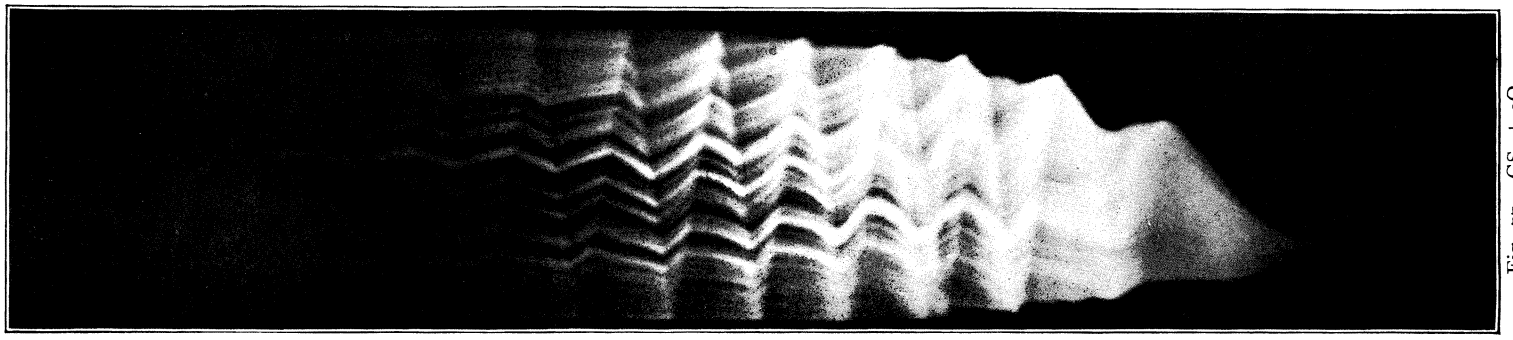

Fig. 77. $CS_2 + 3O_2$.

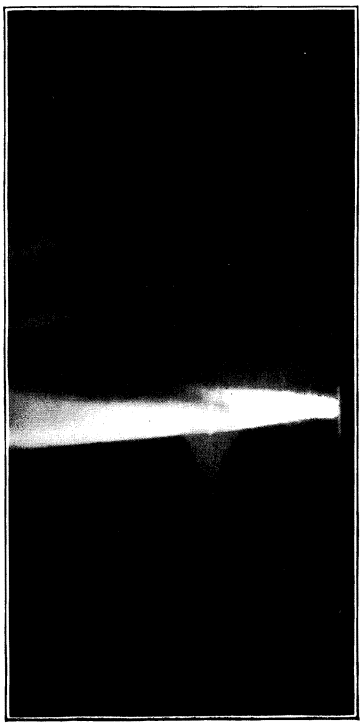

Fig. 80.

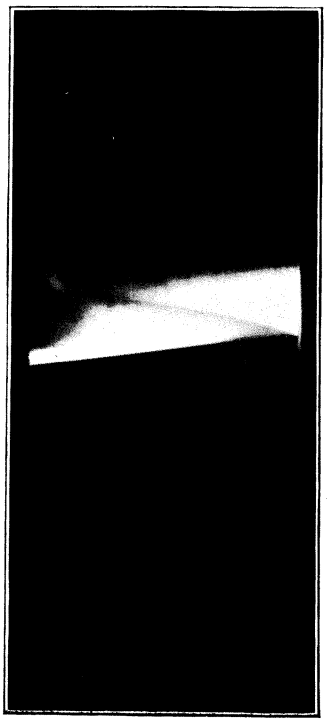

Fig. 81.

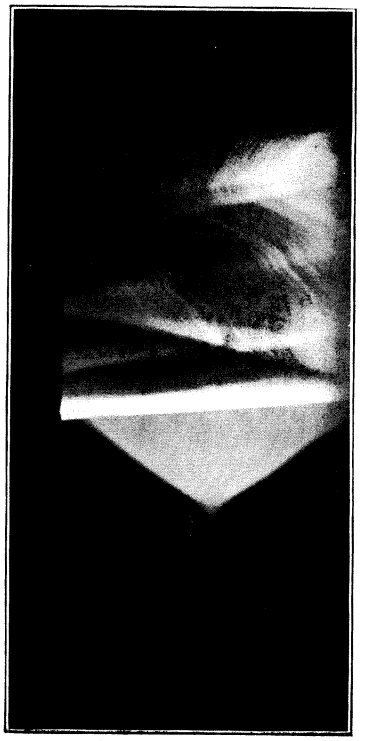

Fig. 82

Detonation-wave passing through flames of gas ignited independently.

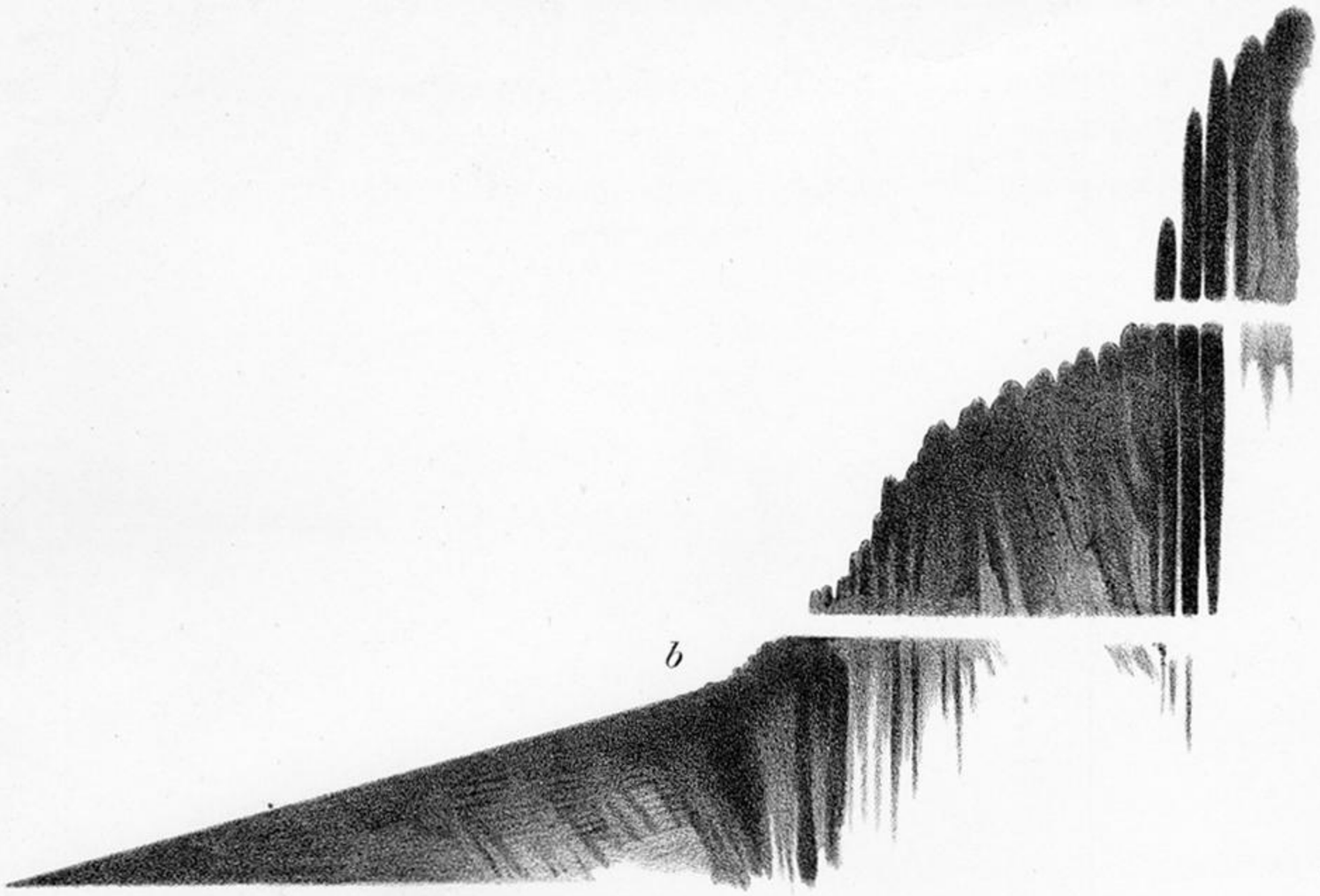

Fig. 1.

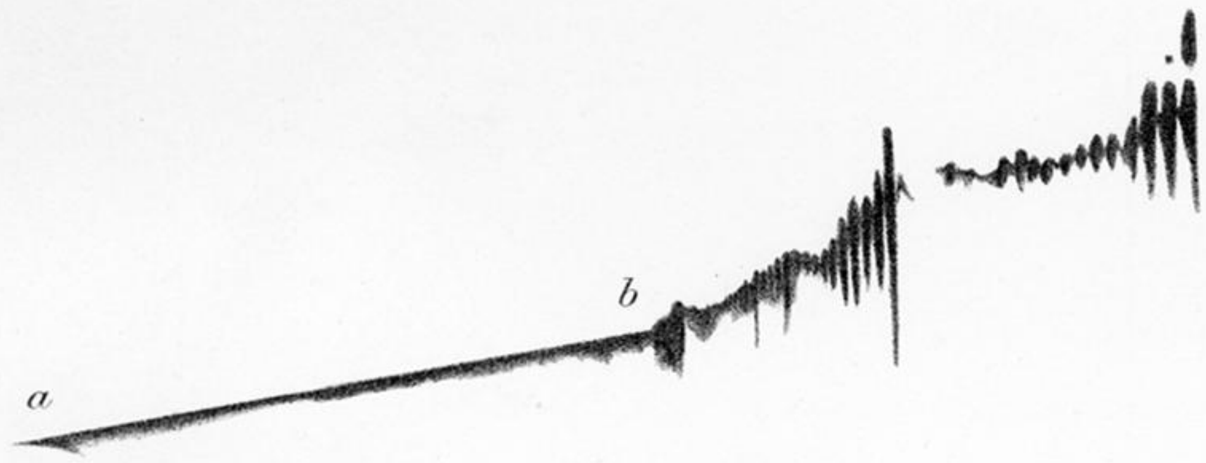

Fig. 2.

Mallard and Le Chatelier's Photographs.

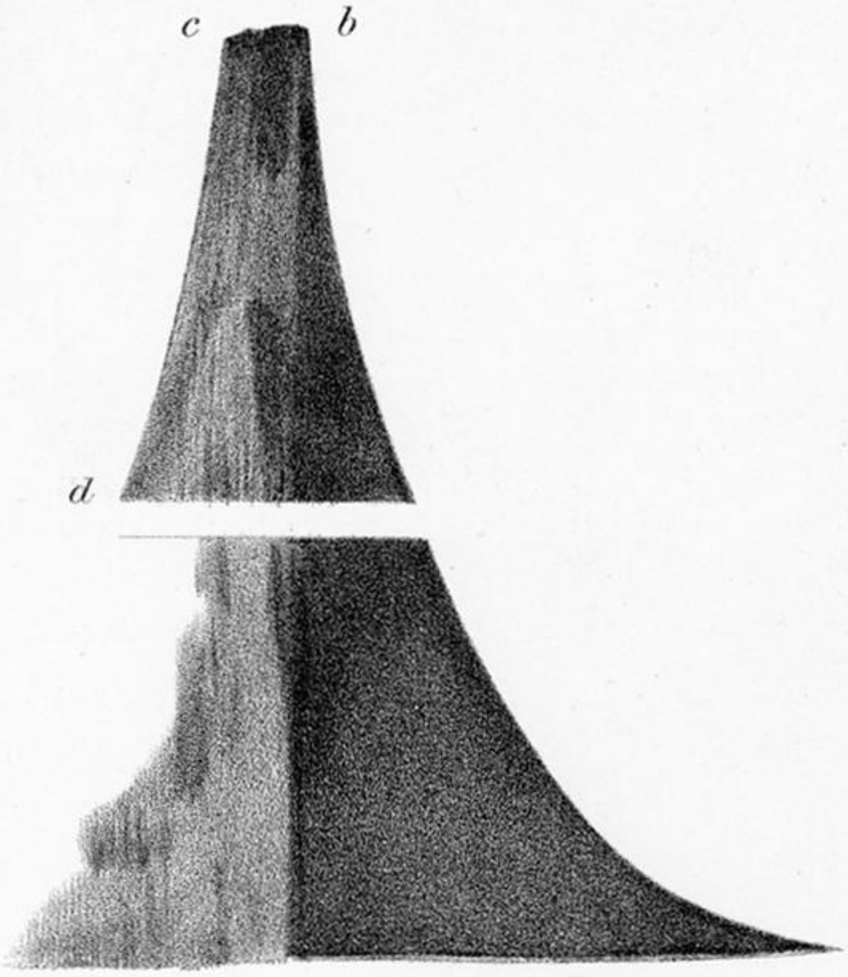

Fig. 3.

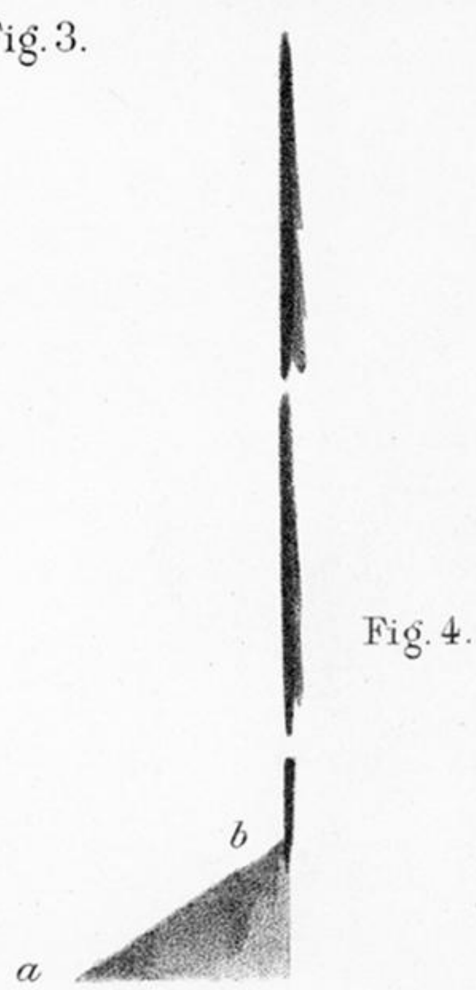

Fig. 4.

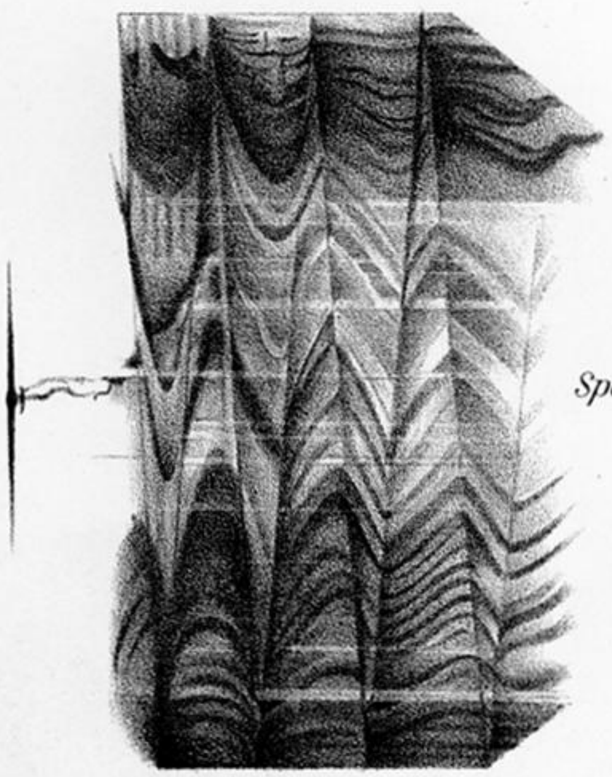

Fig. 5.

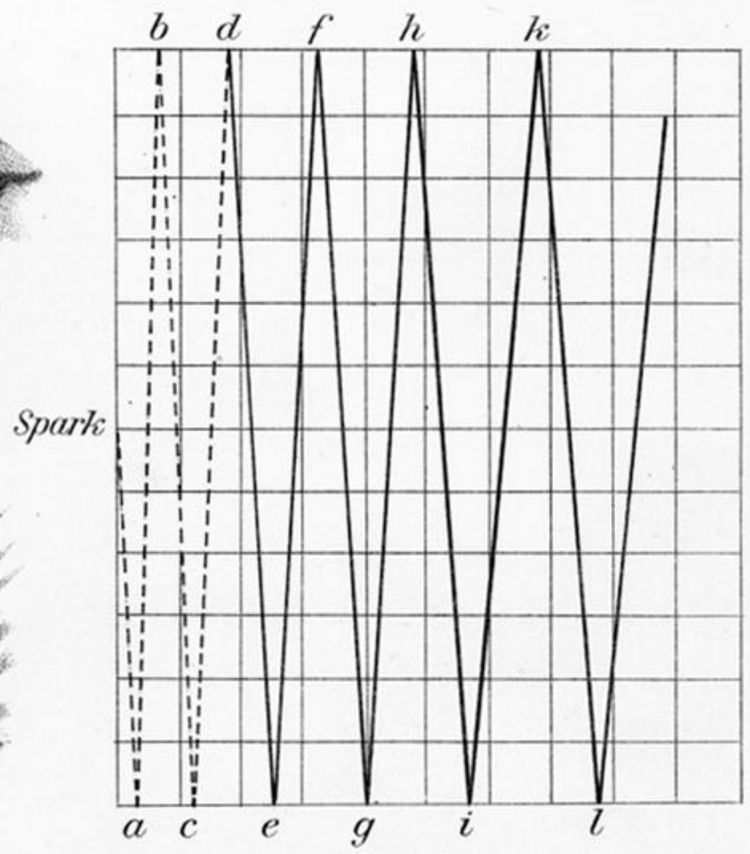

Fig. 5a.

Fig. 6.

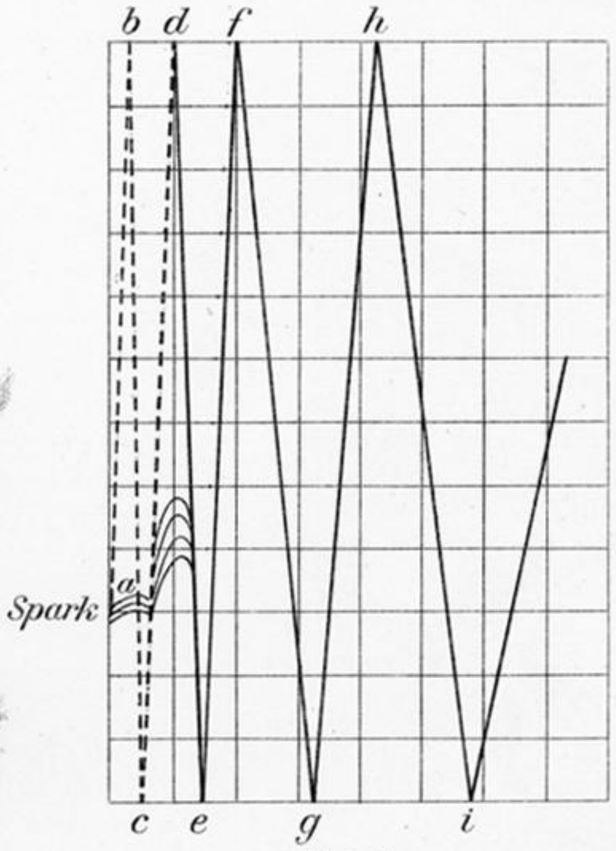

Fig. 6a.

von Oettingen and von Gernet's Photographs.

West, Newman lith.

Fig. 7.

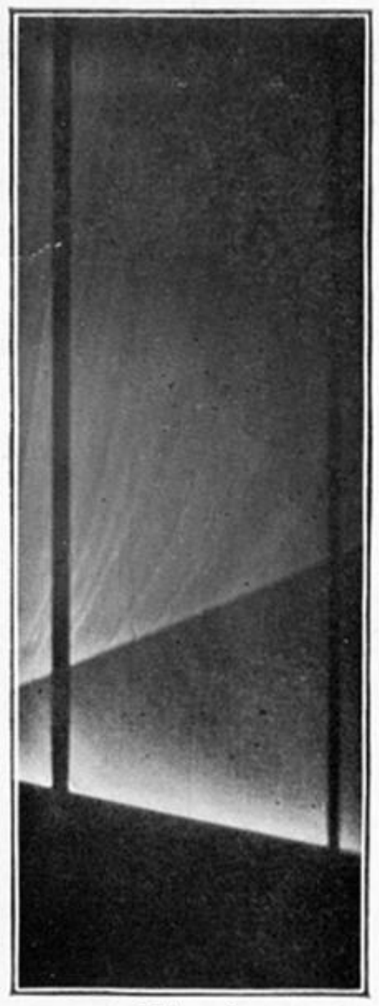

Fig. 8.

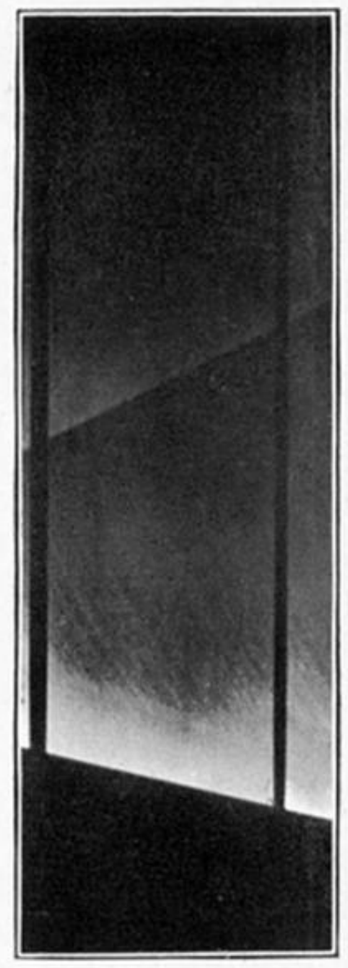

Fig. 9.

Explosions of mixtures of $C_2N_2 + 2O_2$, showing waves reflected from closed end of tube.

Fig. 10. $2H_2 + O_2$.

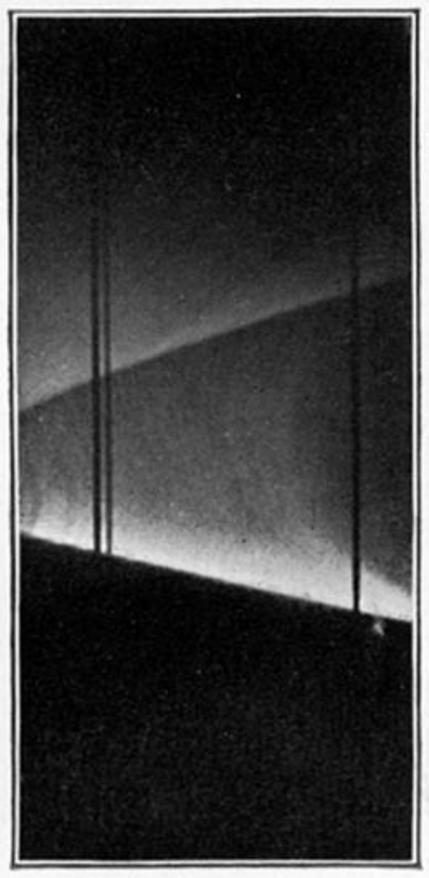

Fig. 11. $2CO + O_2$.

Fig. 12. $C_2N_2 + O_2$.

Fig. 13. $2C_2H_2 + 5O_2$.

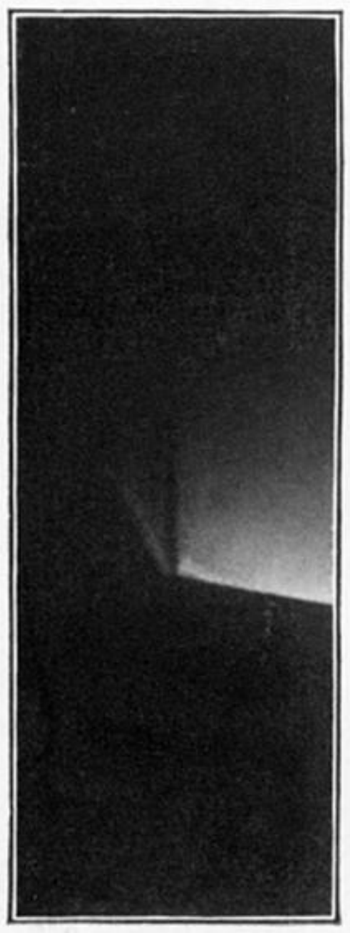

Fig. 14.—With end open.

Fig. 15.—End loosely corked.

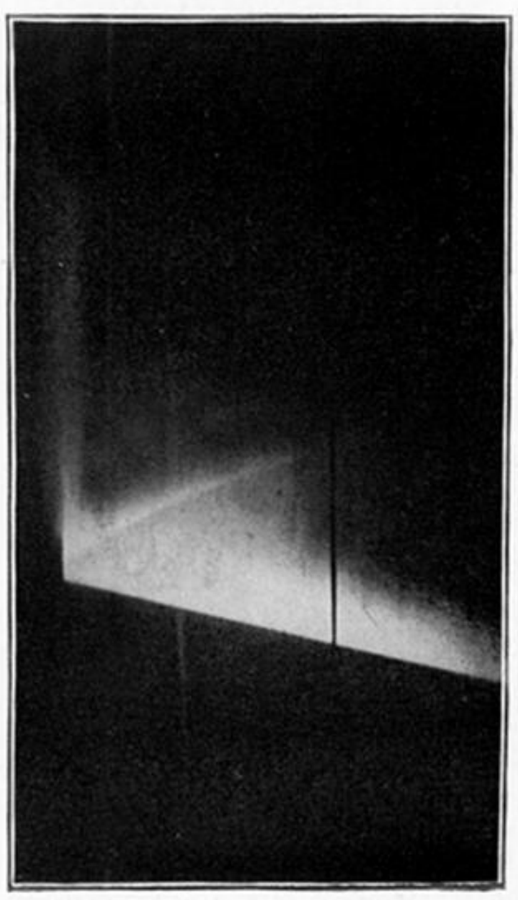

Fig. 16.—Tube broke.

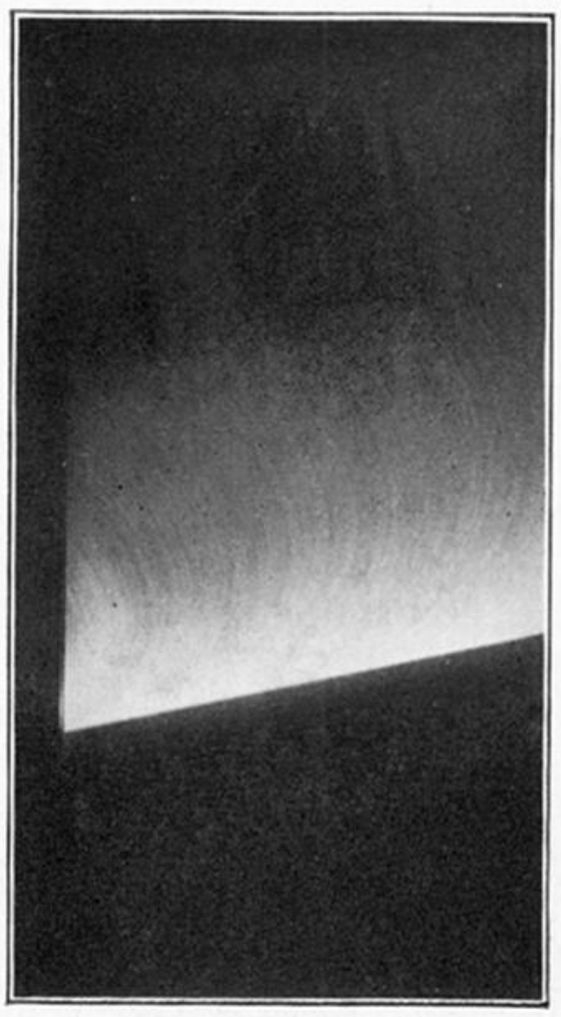

Fig. 17.—Movements of gas following detonation-wave.

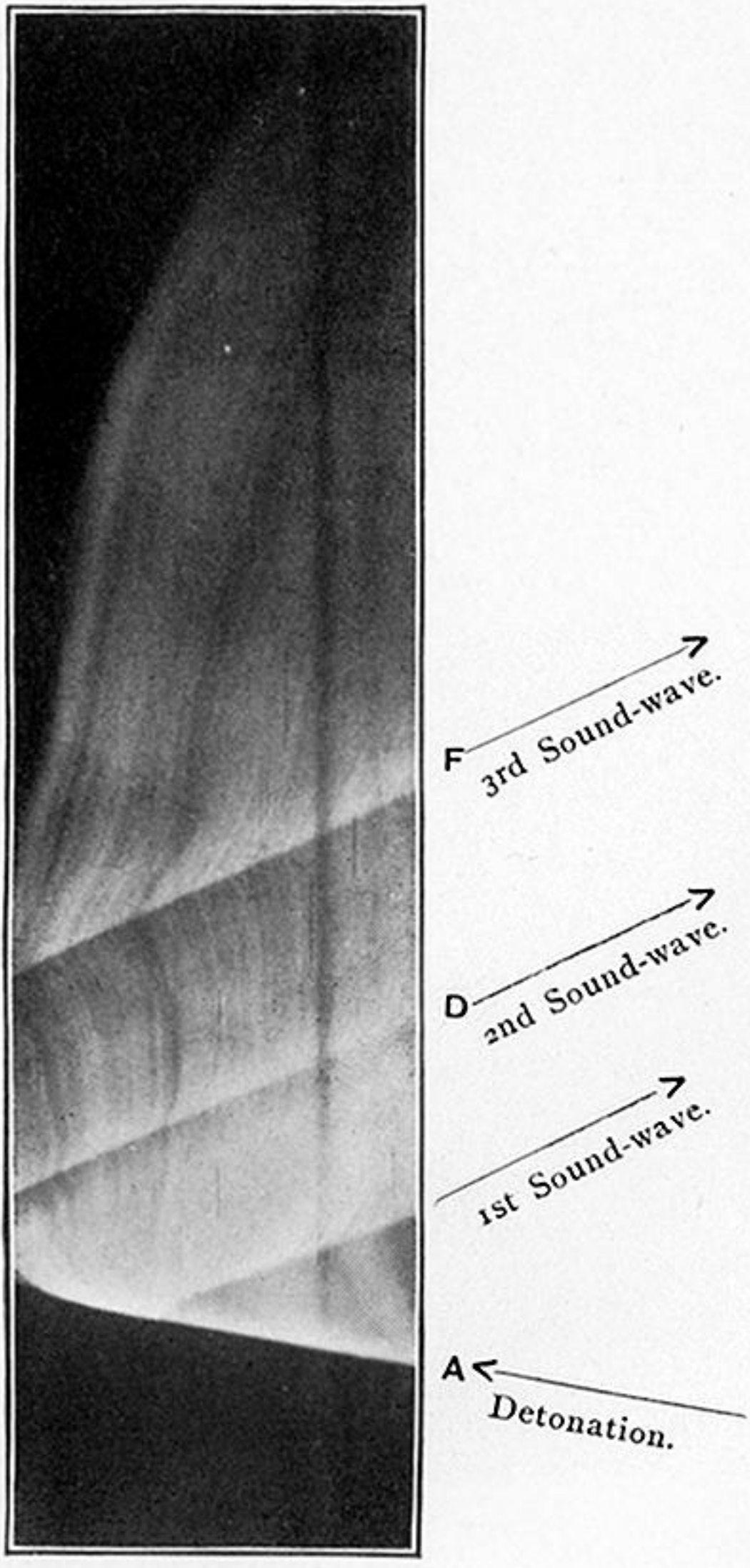

Fig. 19.—Sound-waves meeting detonation of $C_2N_2 + 2O_2$.

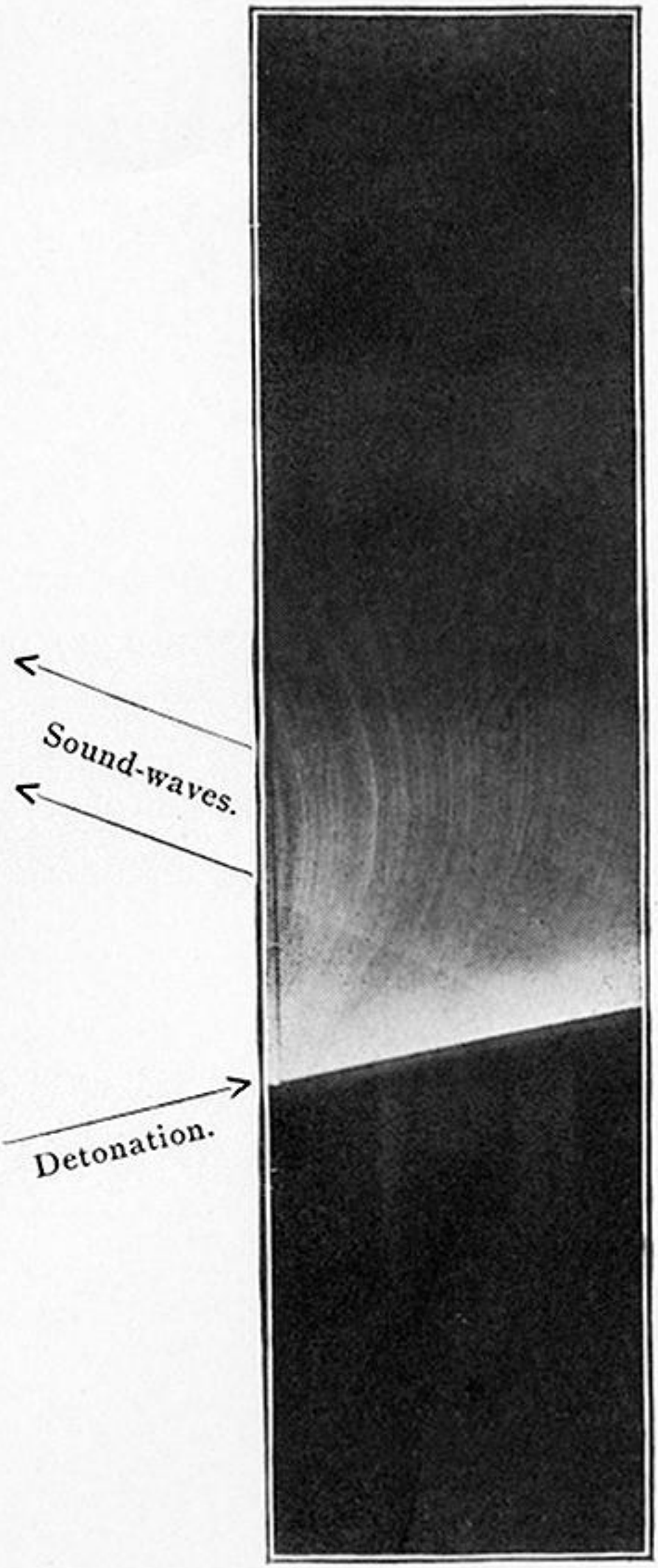

Fig. 20.—Sound-waves meeting detonation of $C_2N_2 + O_2$.

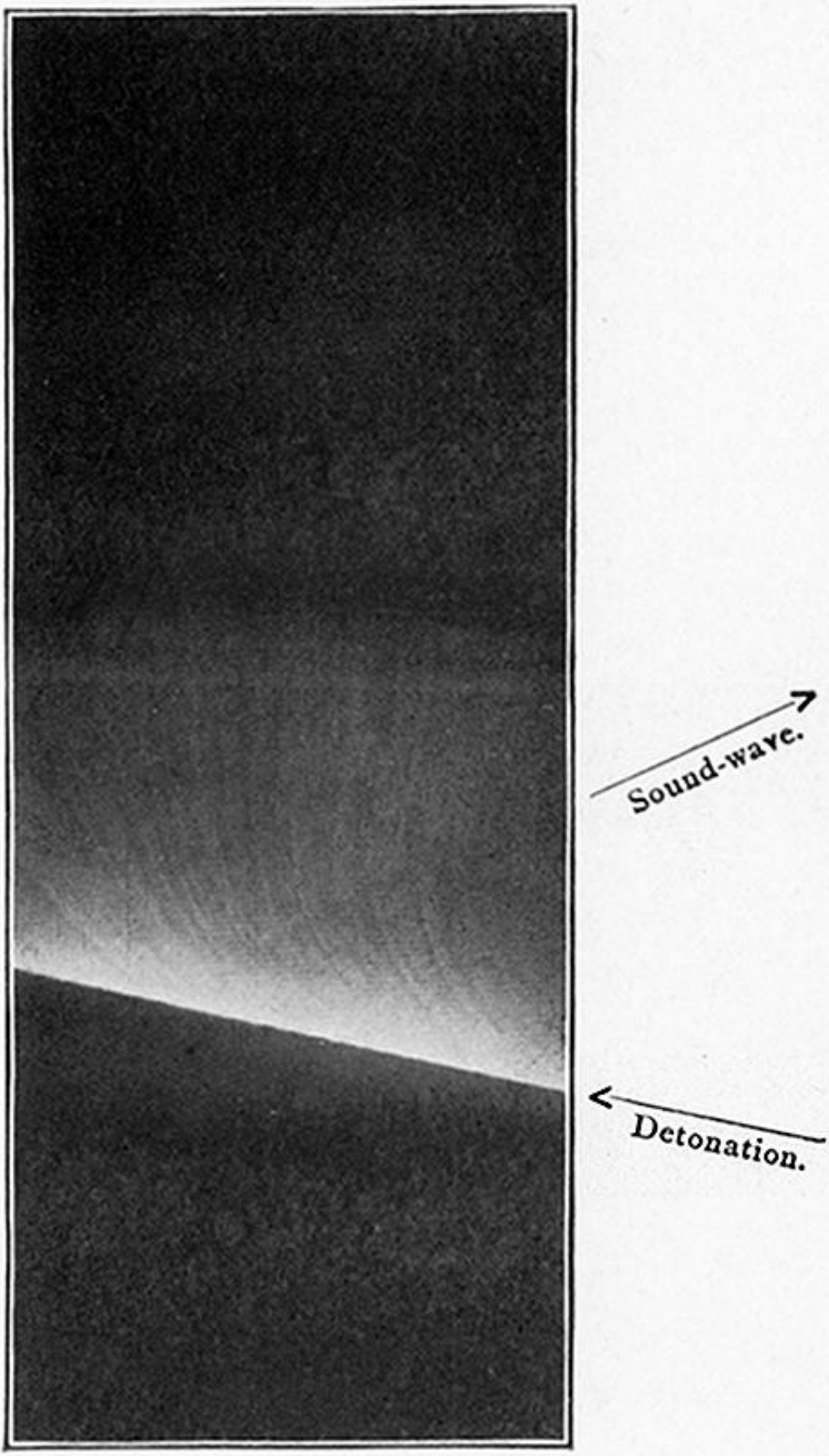

Fig. 21.—Sound-wave meeting detonation of $CS_2 + 2O_2$.

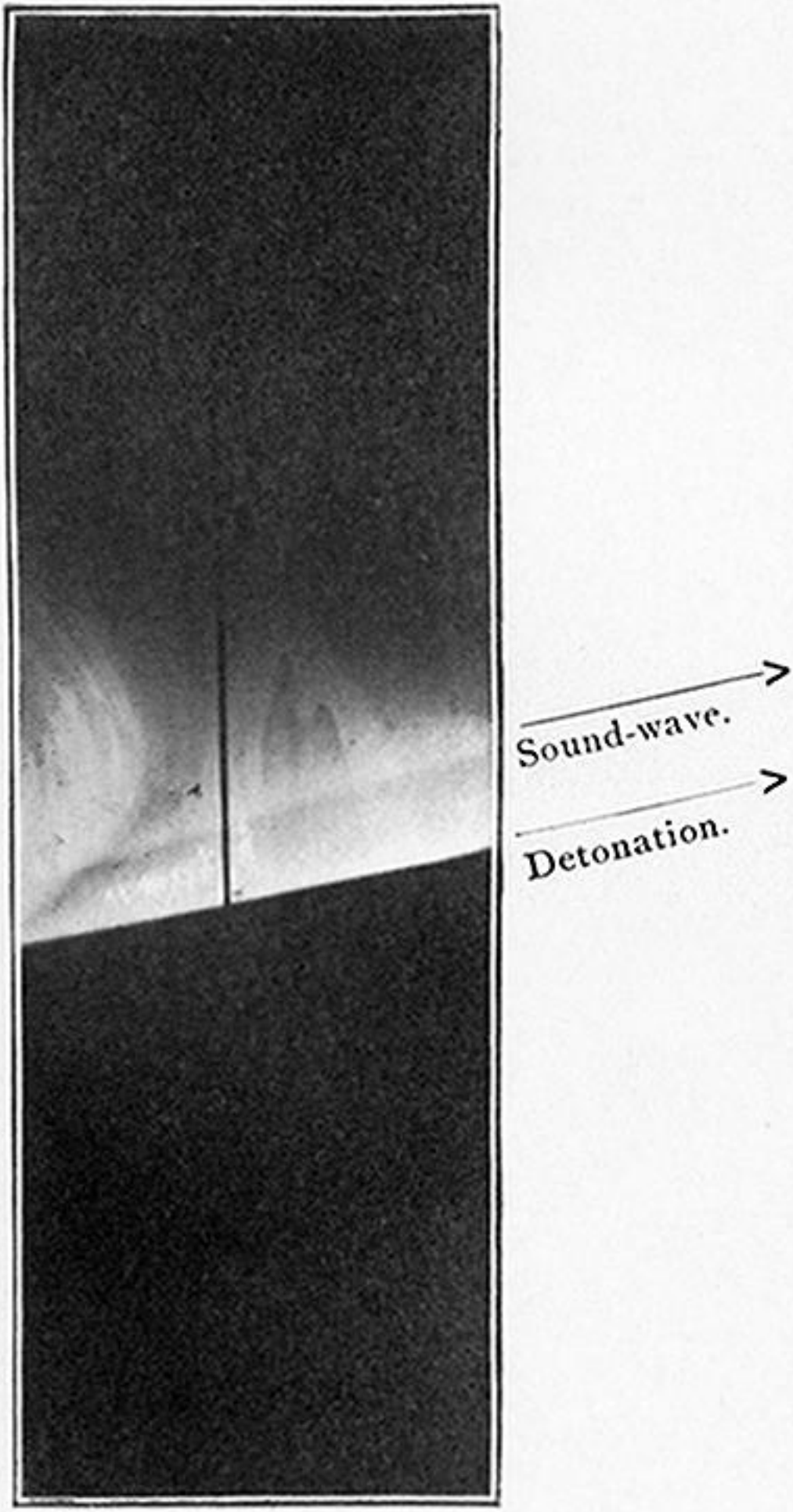

Fig. 23.—Sound-wave following detonation of $C_2N_2 + 2O_2$.

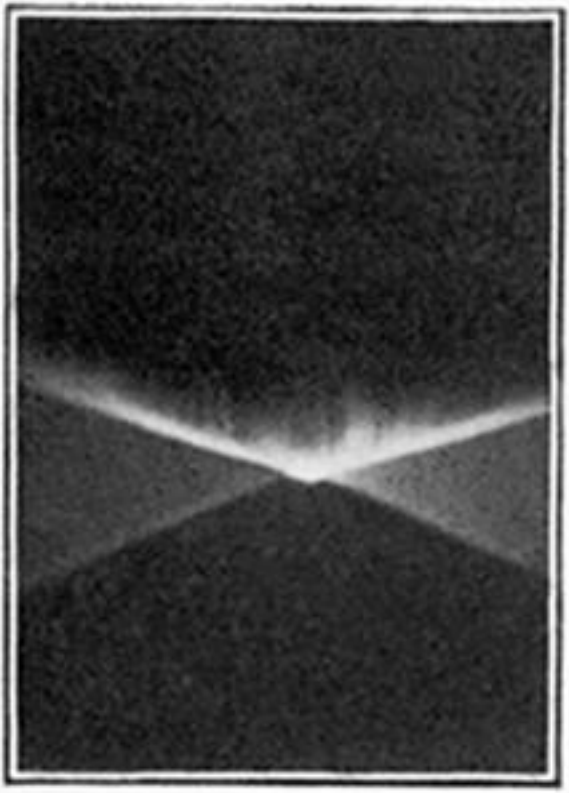

Fig. 25.—Two Explosions meeting.

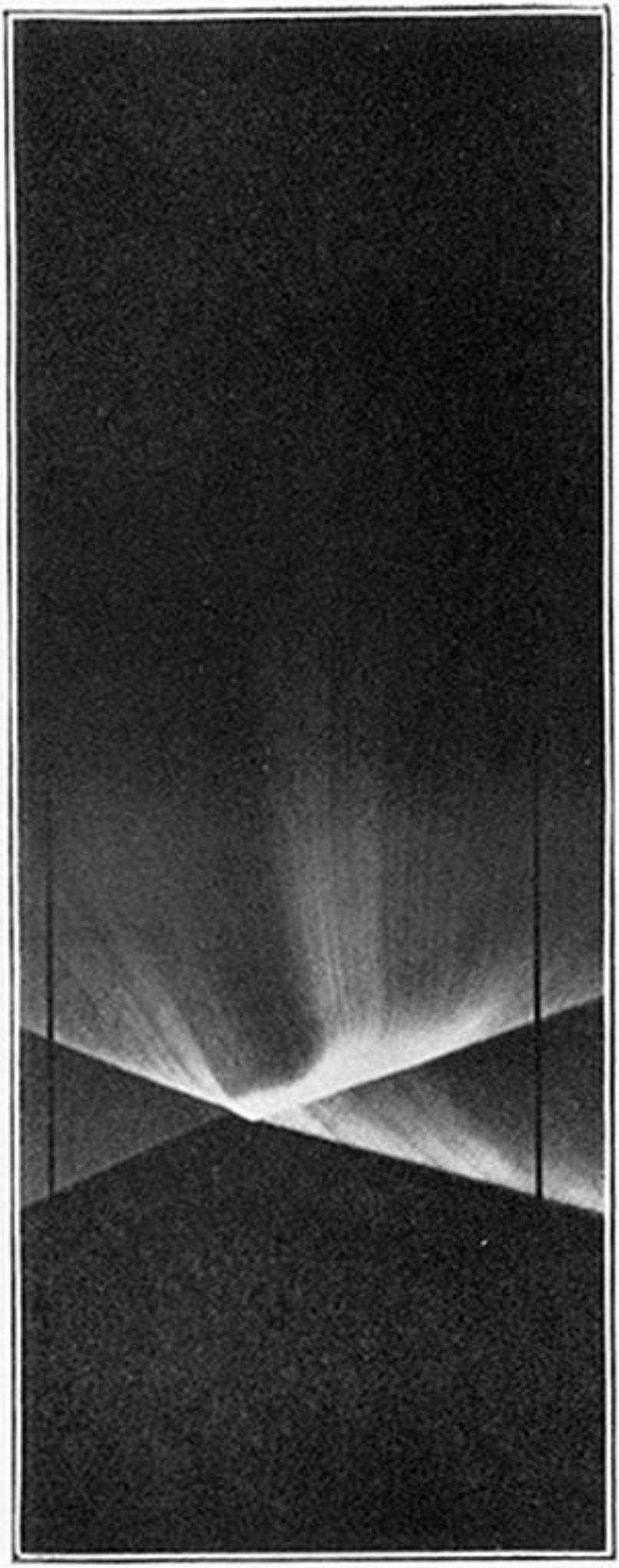

Fig. 26.—Two Explosions meeting.

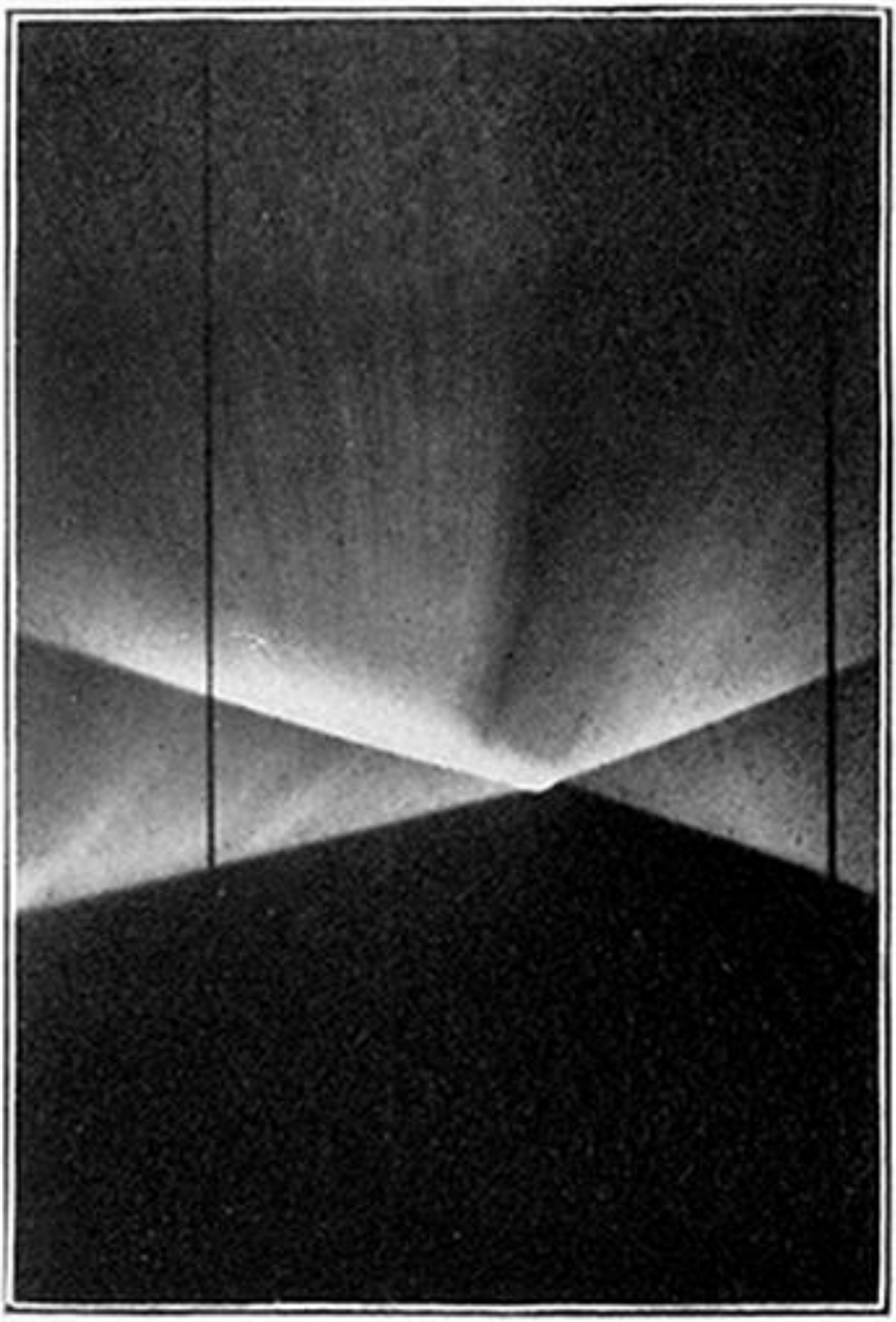

Fig. 27.—Two Explosions meeting.

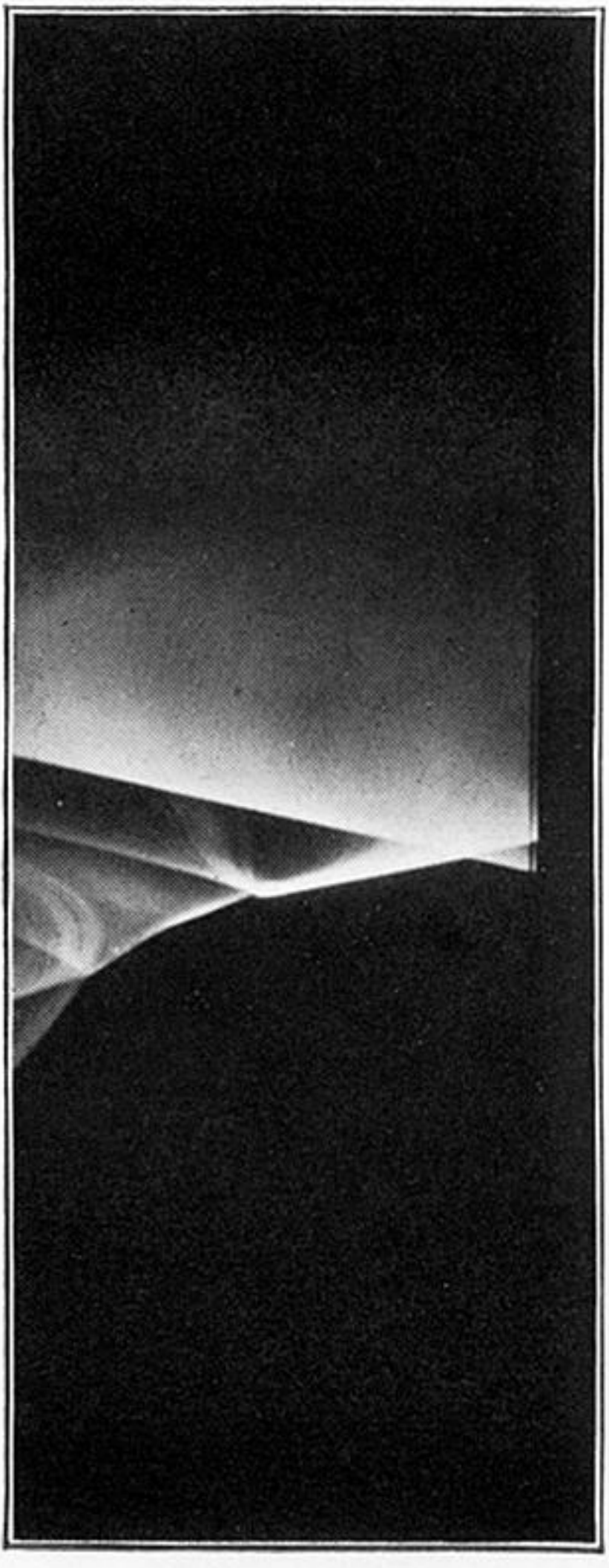

Fig. 28.—Two Explosions meeting.

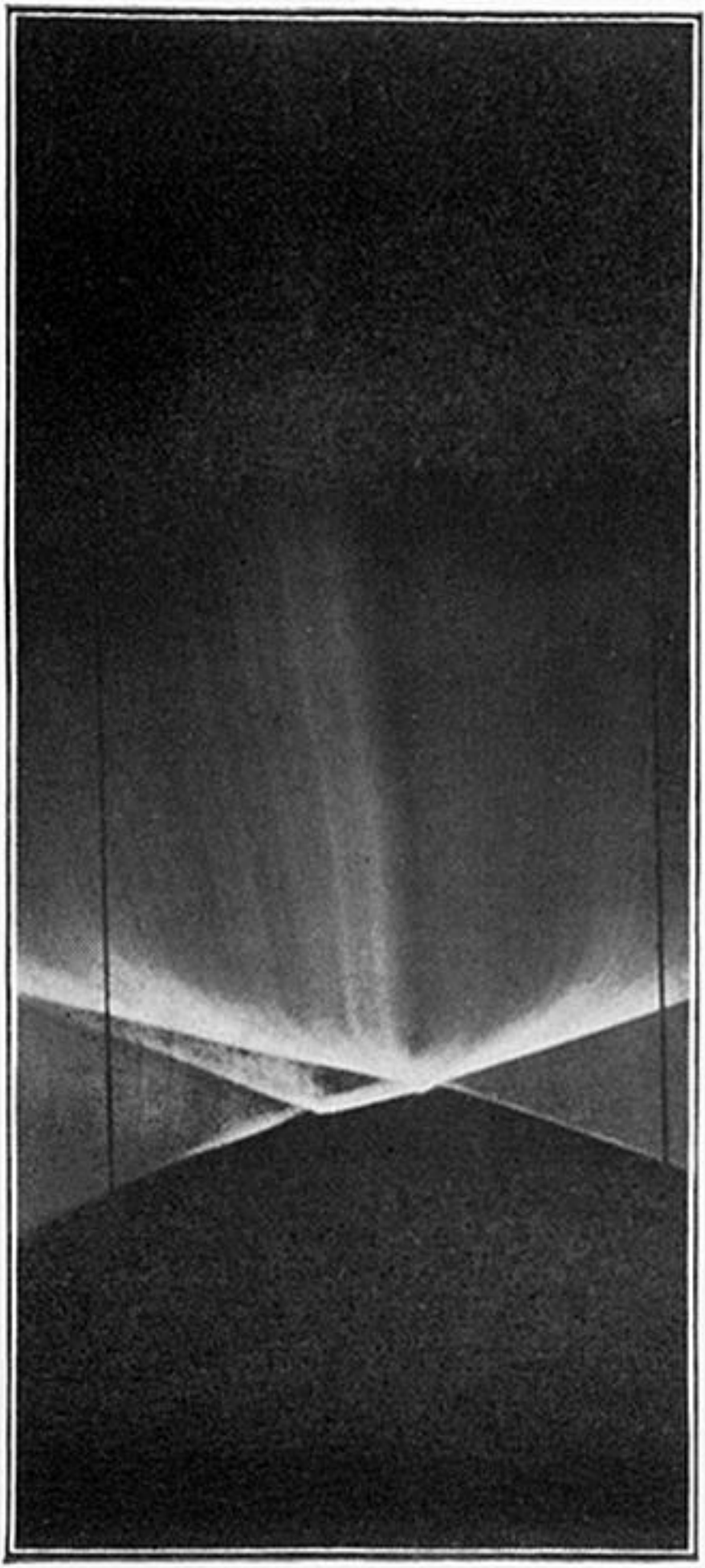

Fig. 29.—Two Explosions meeting.

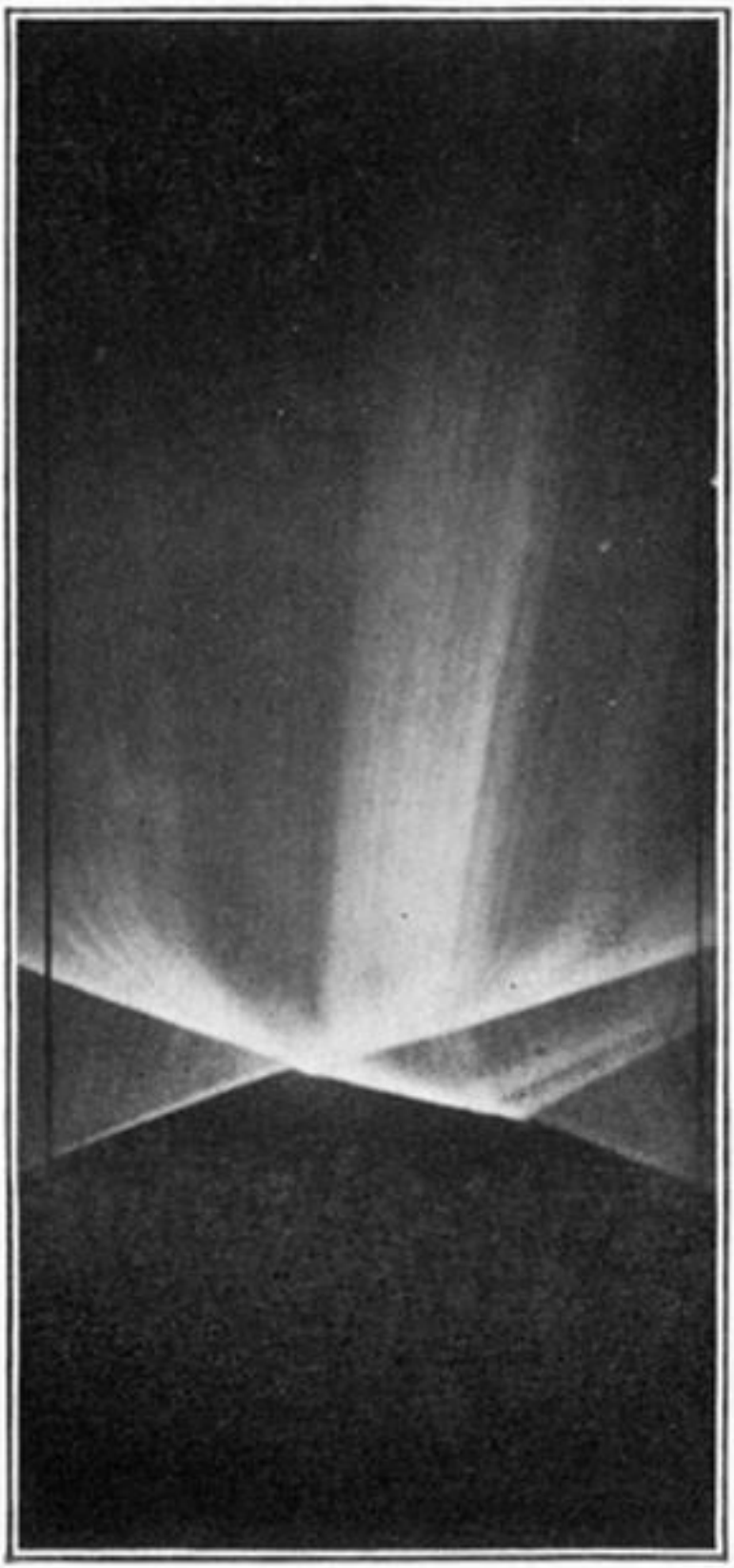

Fig. 30.—Two Explosions meeting

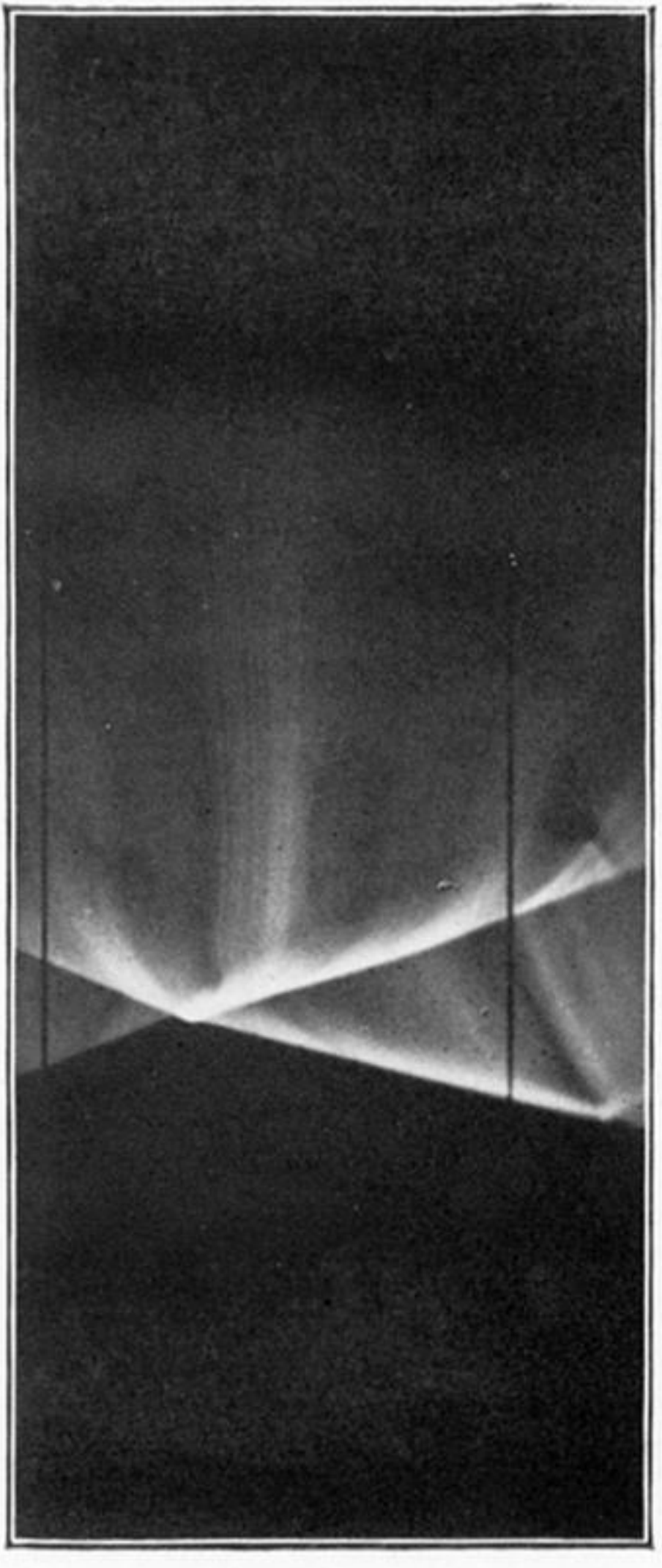

Fig. 31.—Two Explosions meeting.

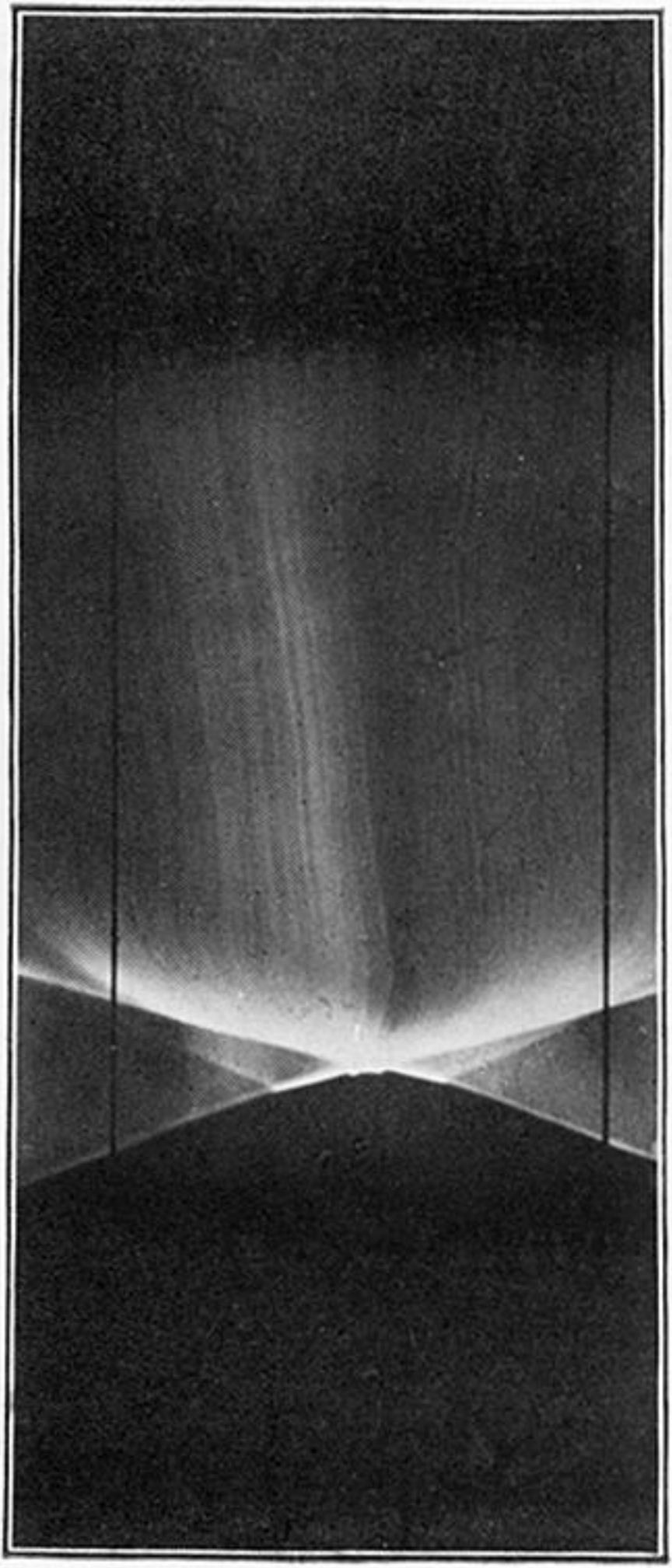

Fig. 32.—Two Explosions meeting.

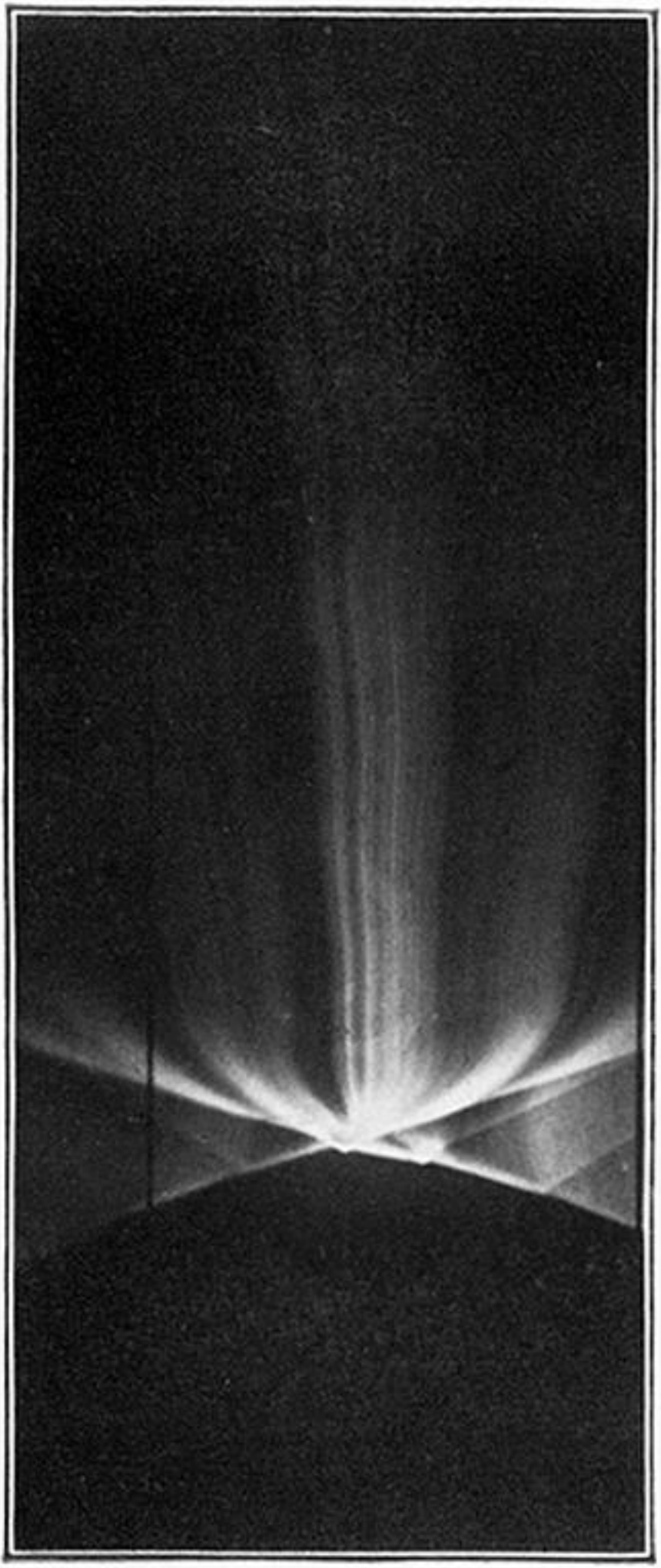

Fig. 33.—Two Explosions meeting.

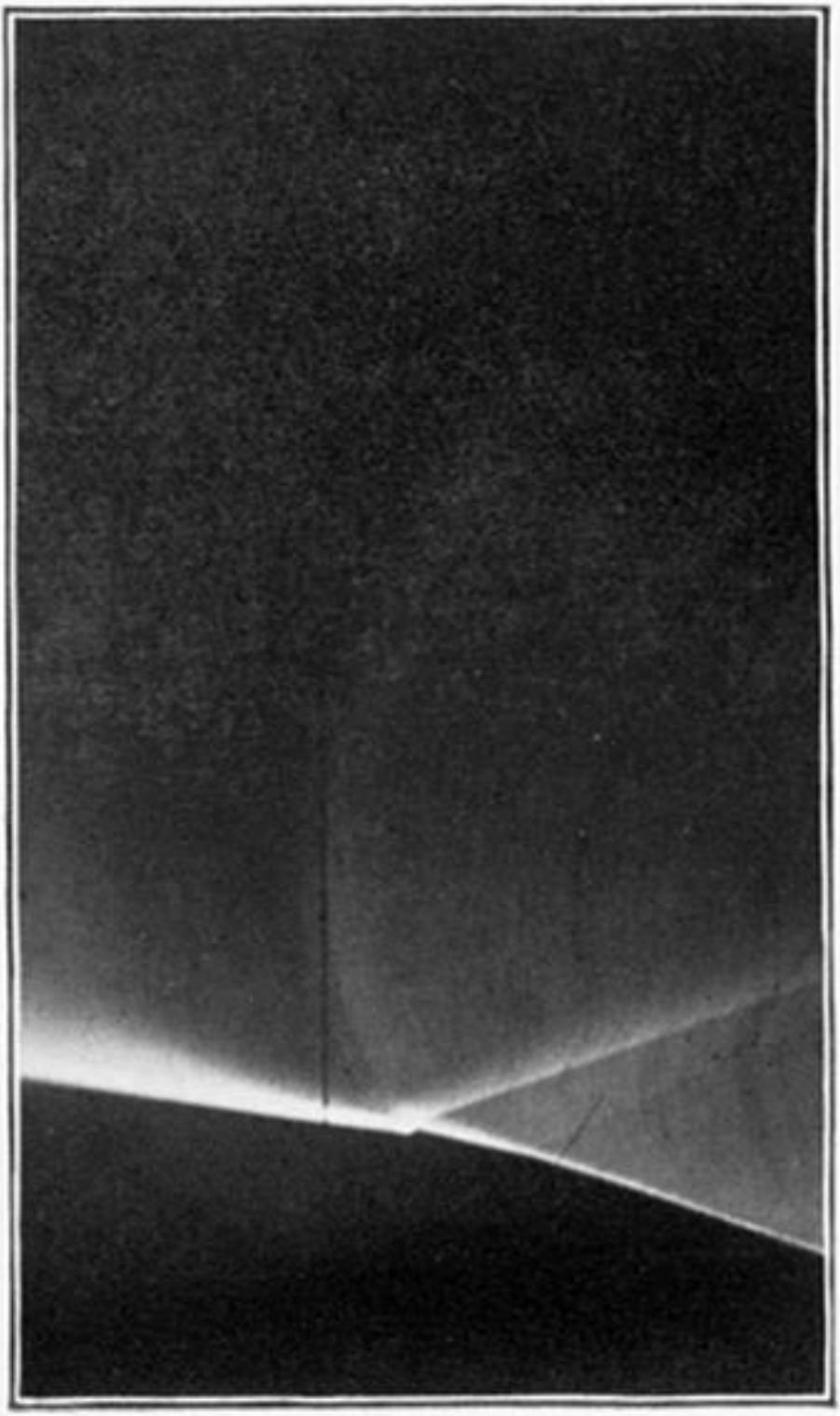

Fig. 34.—Explosion going one way only.

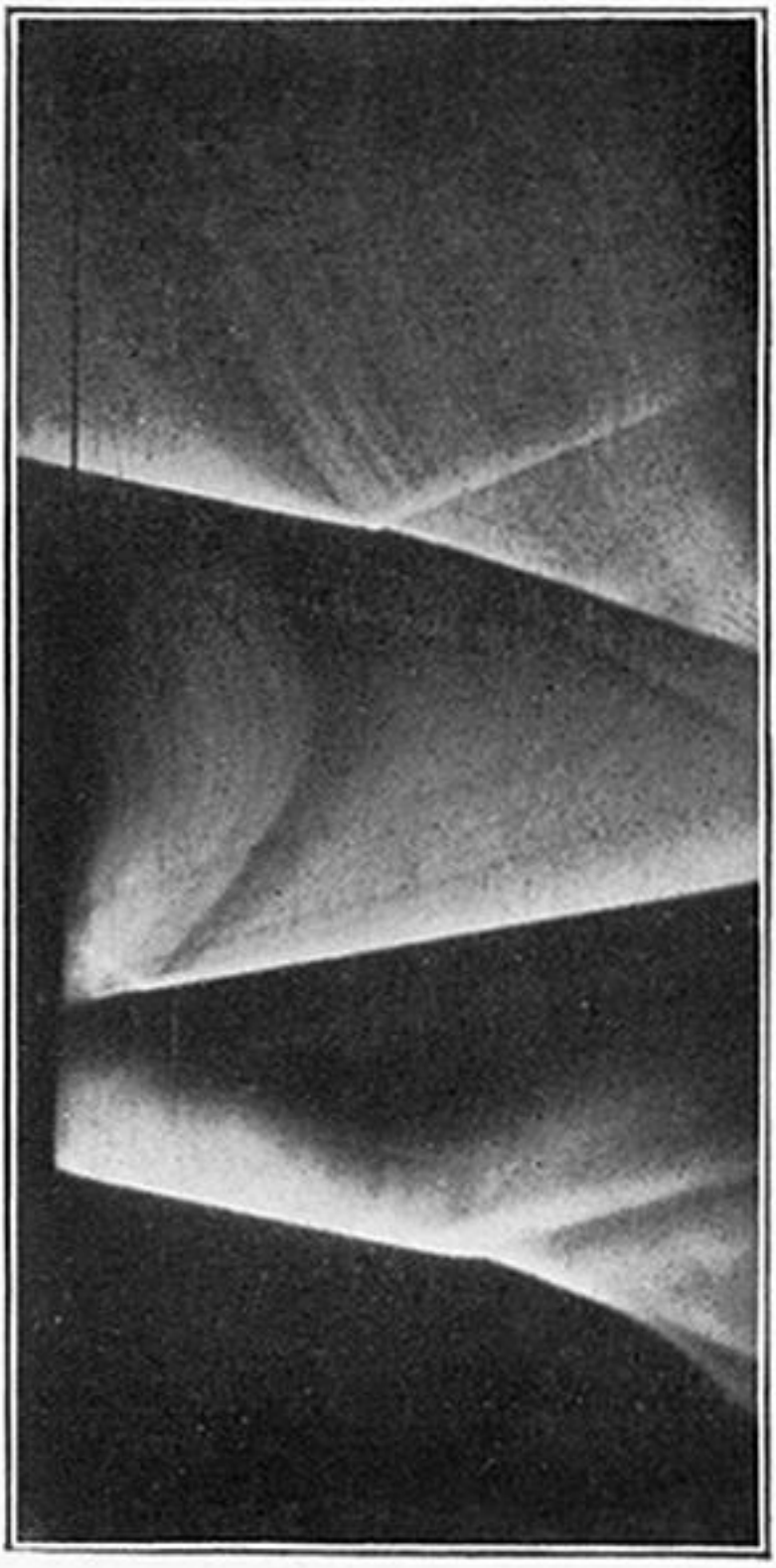

Fig. 35.—Detonation passing through three tubes with lead junctions.

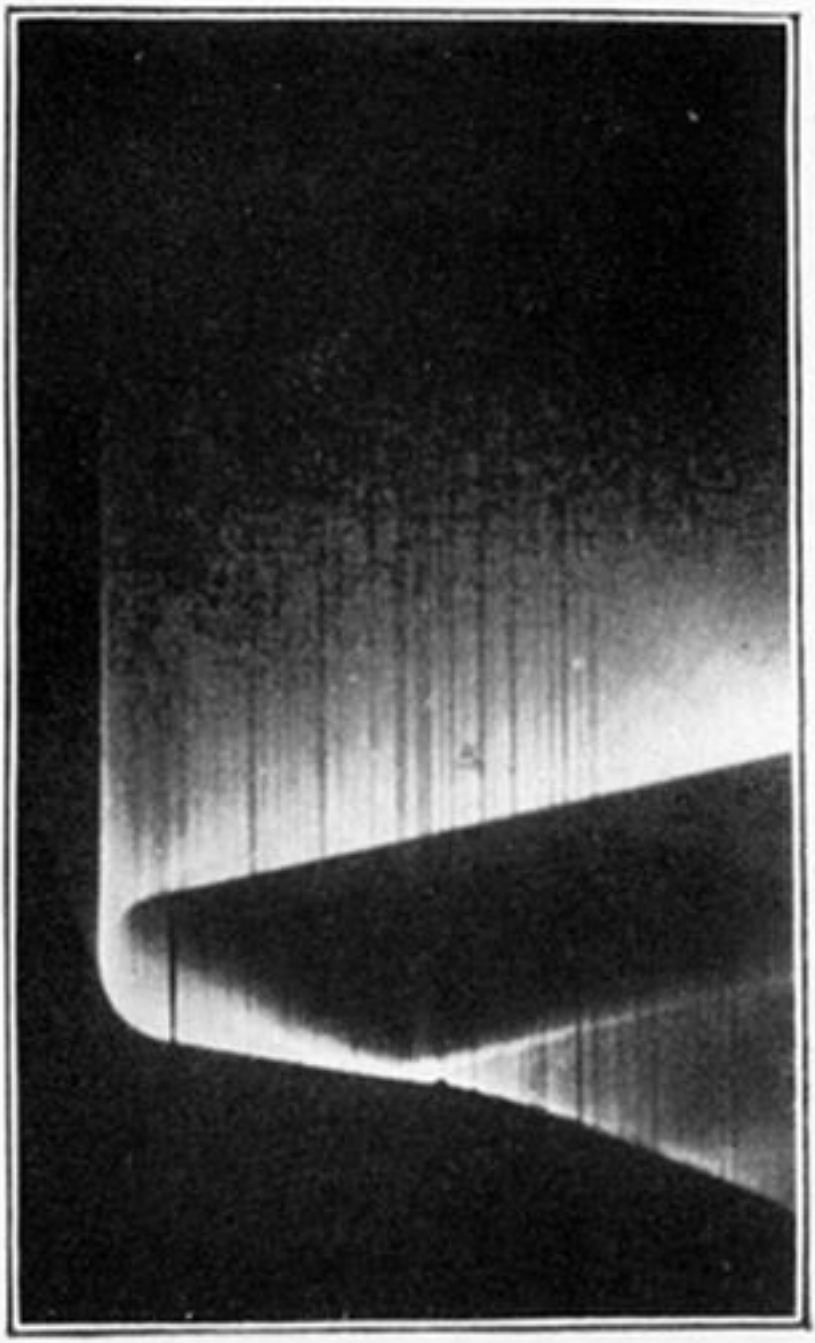

Fig. 37.—Detonation passing through glass bend.

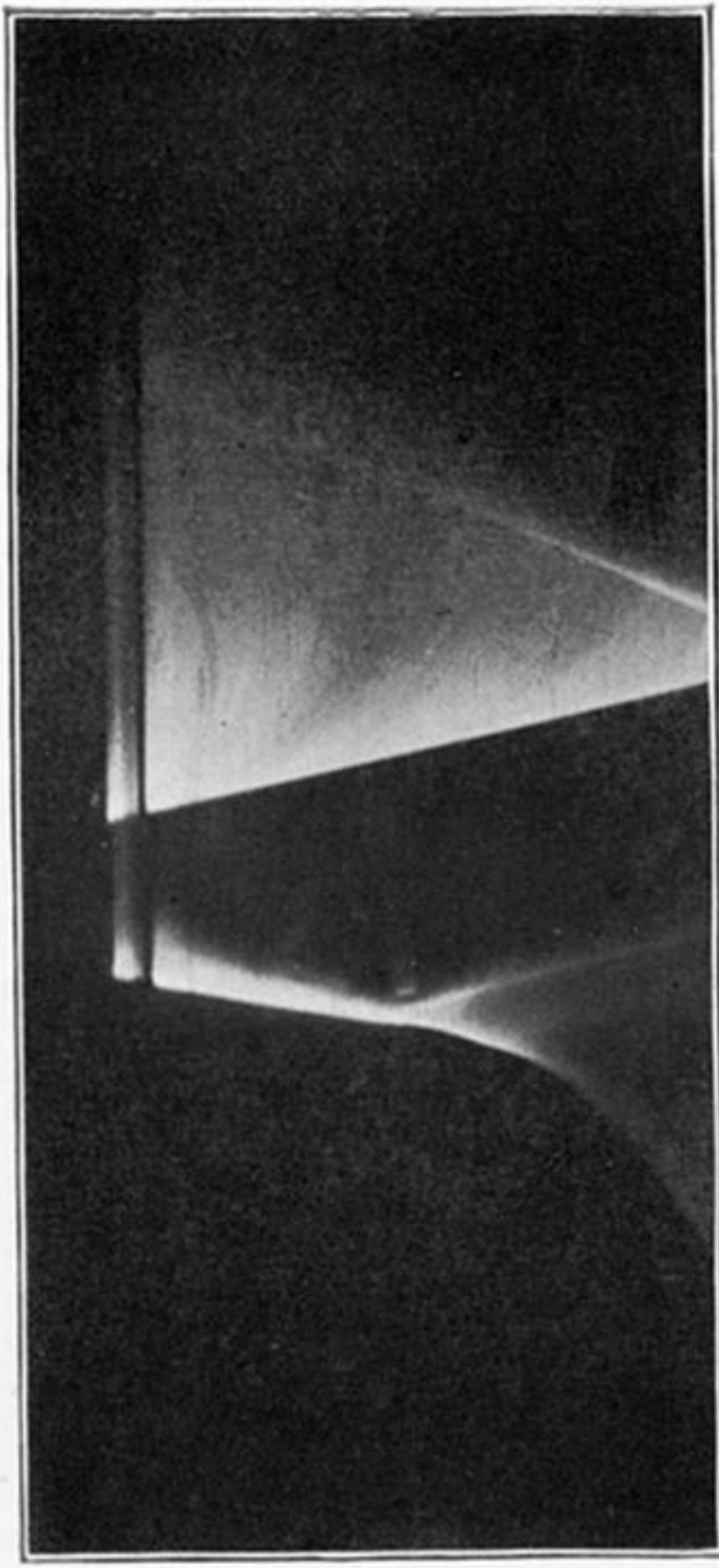

Fig. 38.—Detonation passing through flexible rubber junction without retardation.

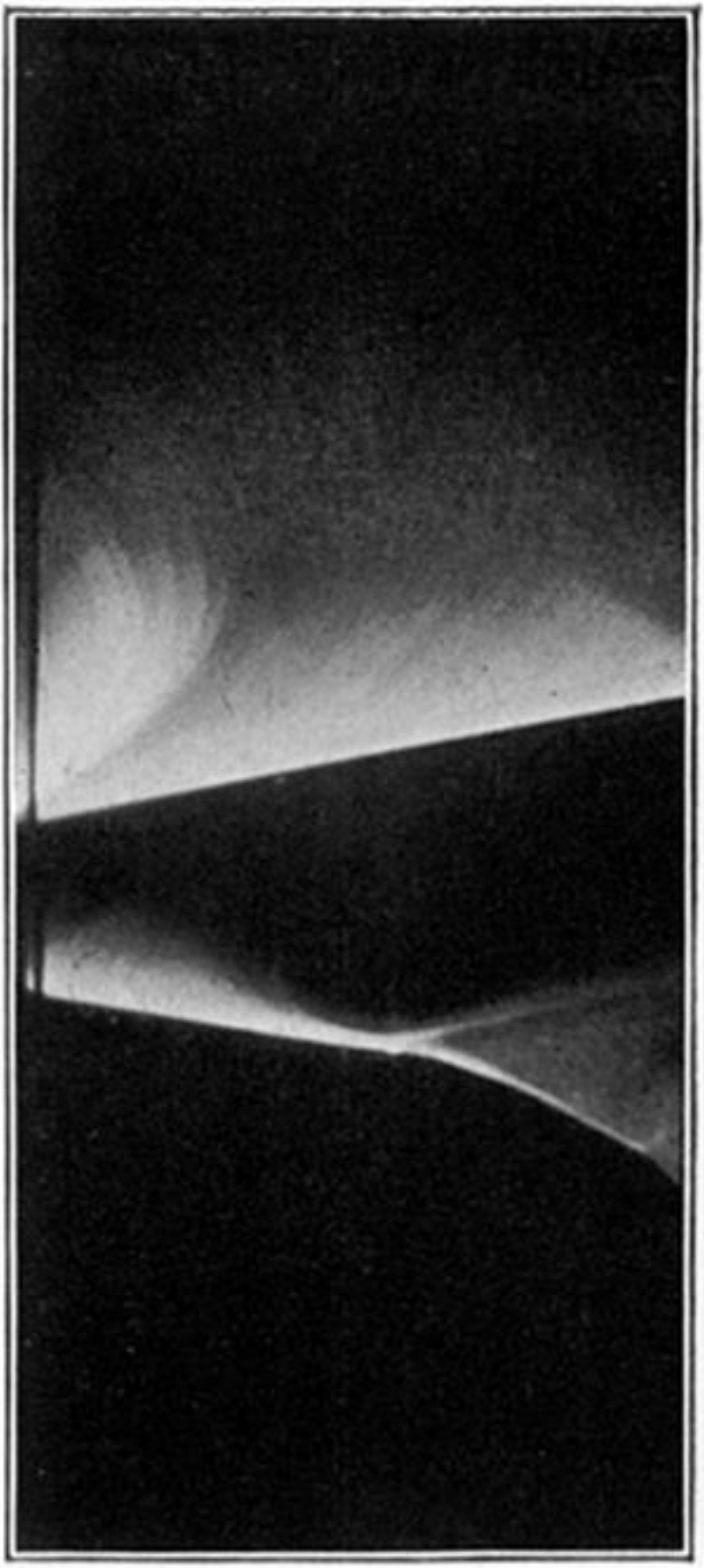

Fig. 39.—Detonation passing through rigid copper junction without retardation.

Fig. 40.—Collision of two detonation-waves.
$C_2N_2 + 2O_2$.

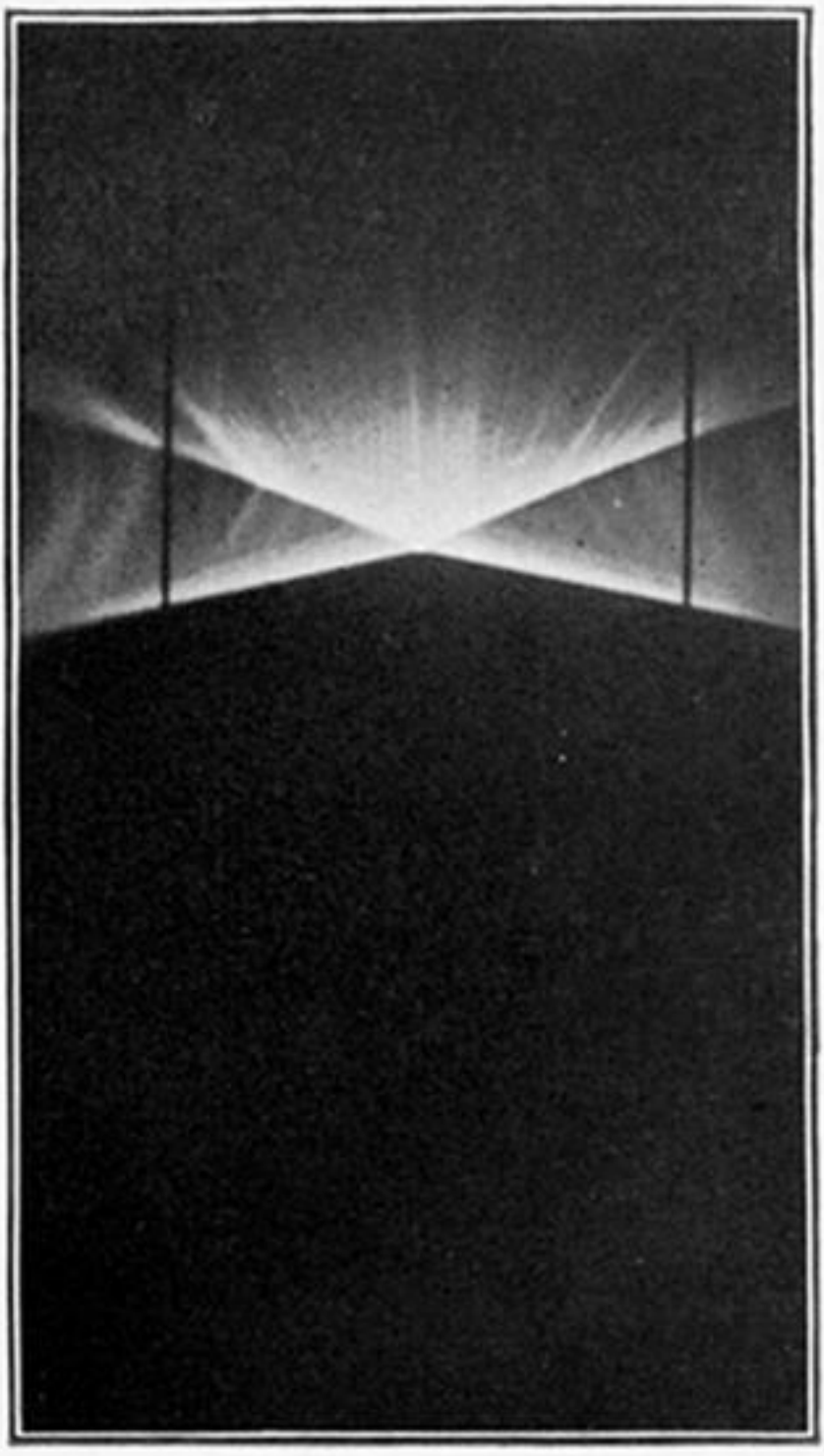

Fig. 41.—Collision of two detonation-waves.
$C_2N_2 + 2O_2$.

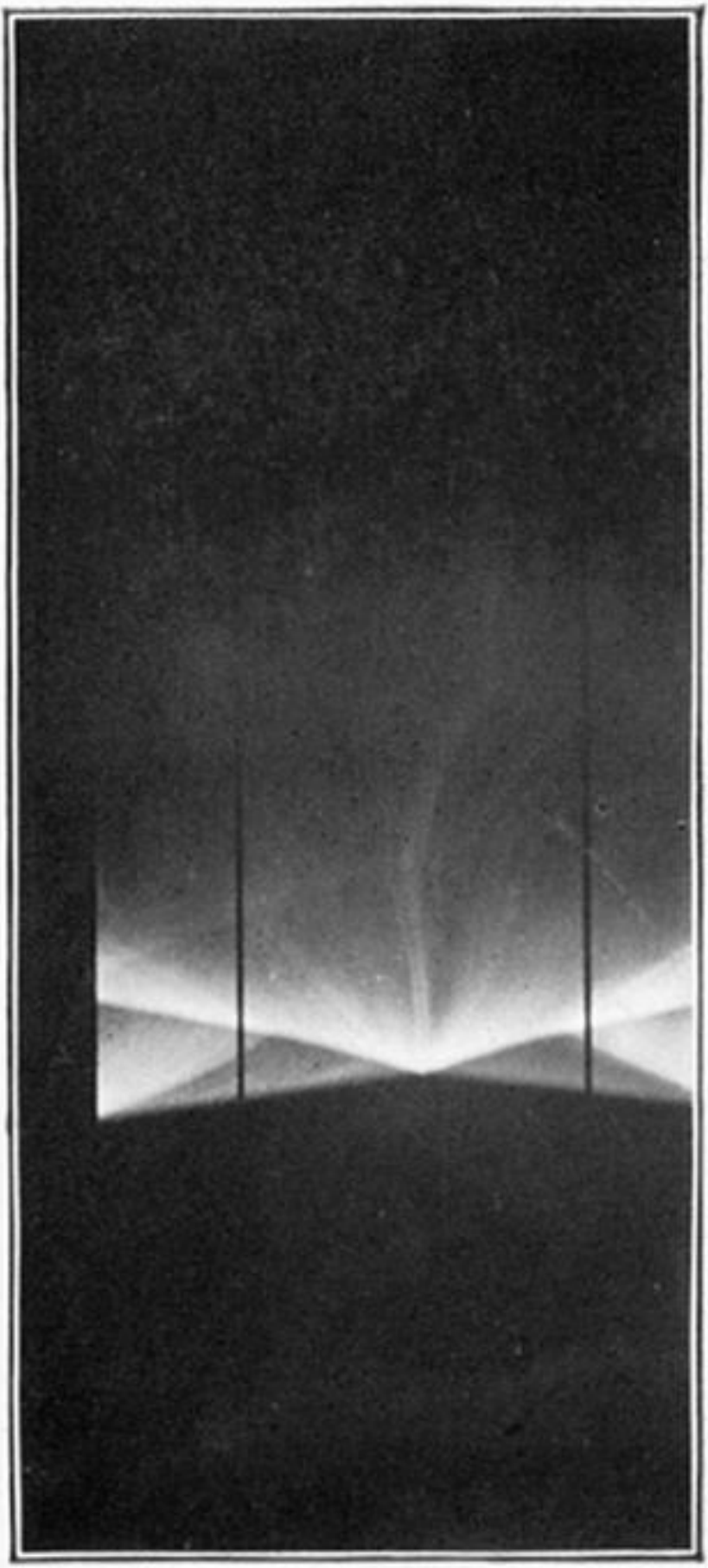

Fig. 42.—Collision of two detonation-waves.
$2H_2 + O_2$.

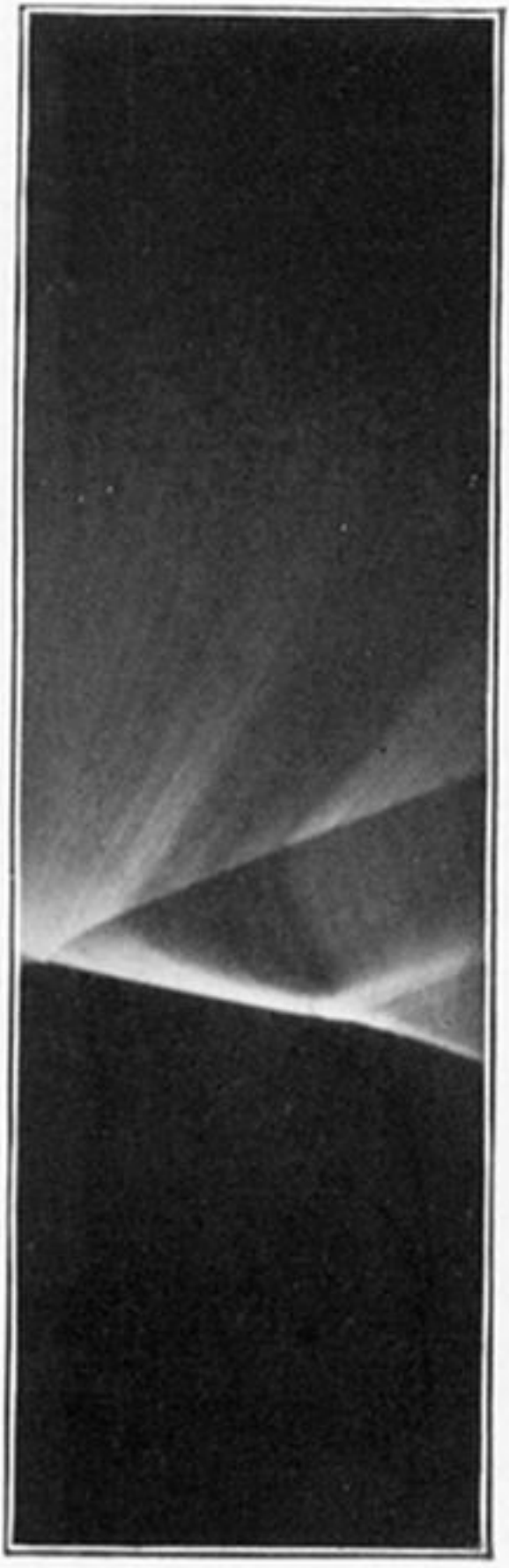

Fig. 43.—Retonation-wave running parallel with collision-wave.

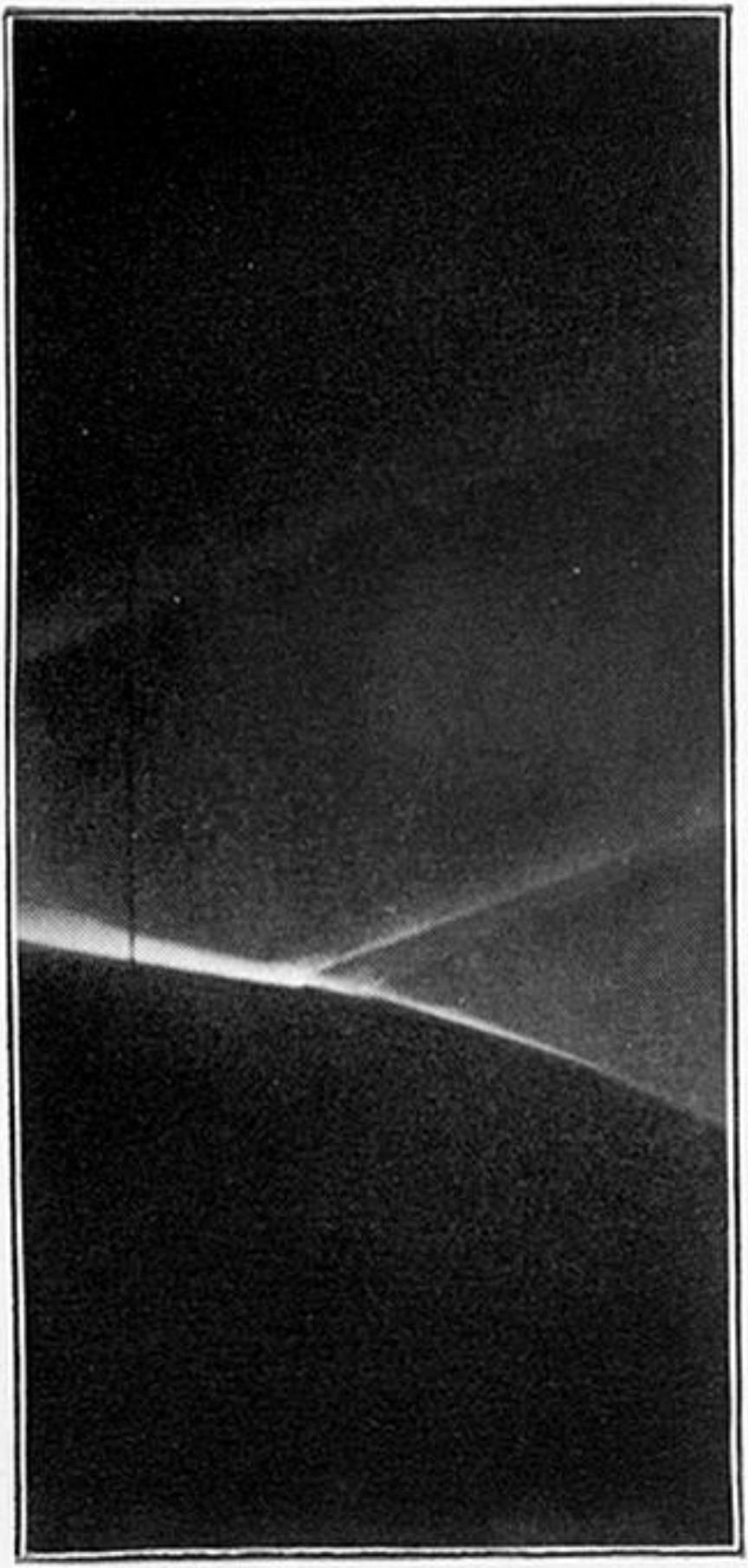

Fig. 44.—Retonation-wave and Reflexion-wave.

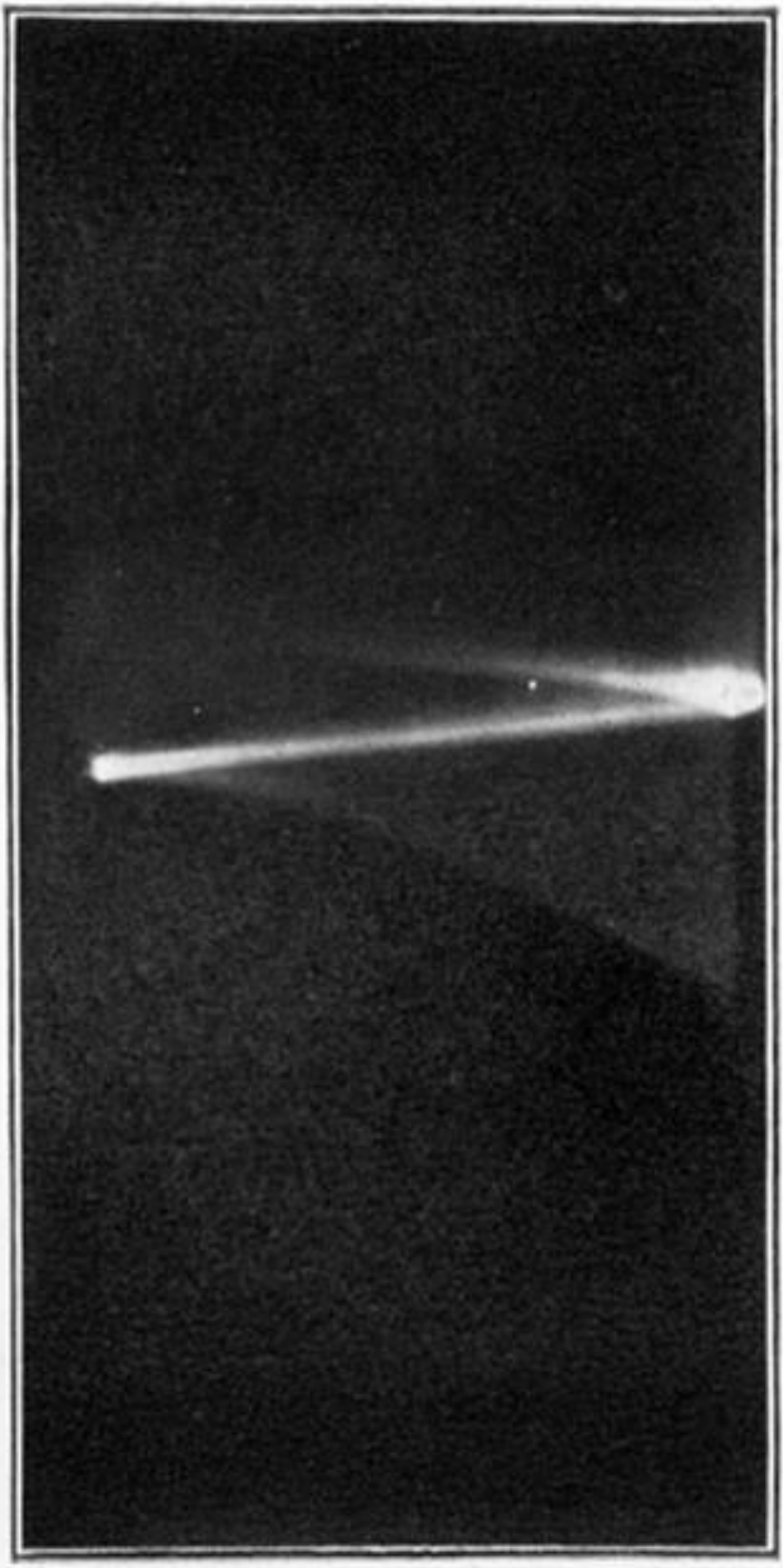

Fig. 45.—Retonation-wave started at end of tube.

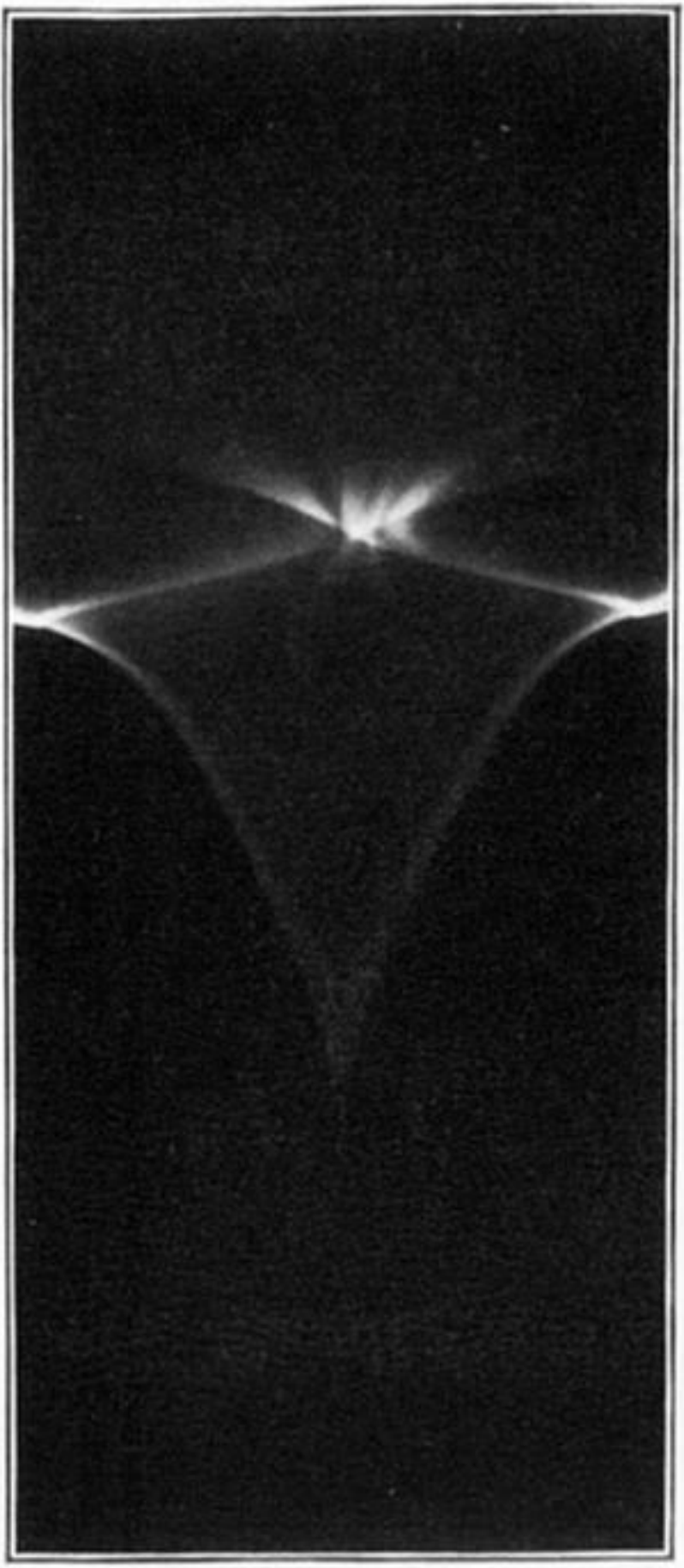

Fig. 46.—Retonation-waves formed by explosion in centre of long tube.

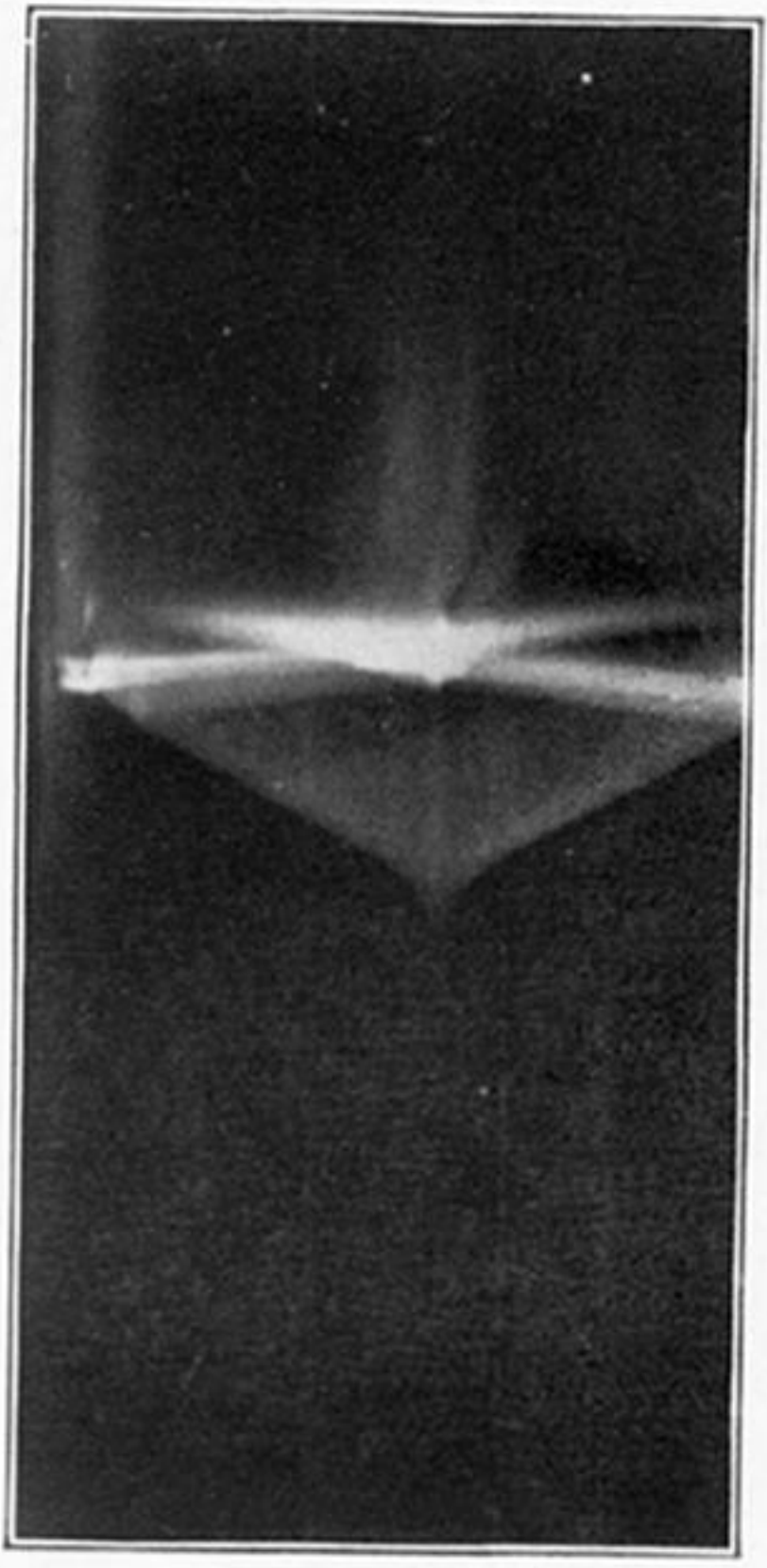

Fig. 47.—Retonation-waves formed at ends of short tube.
$C_2N_2 + O_2$.

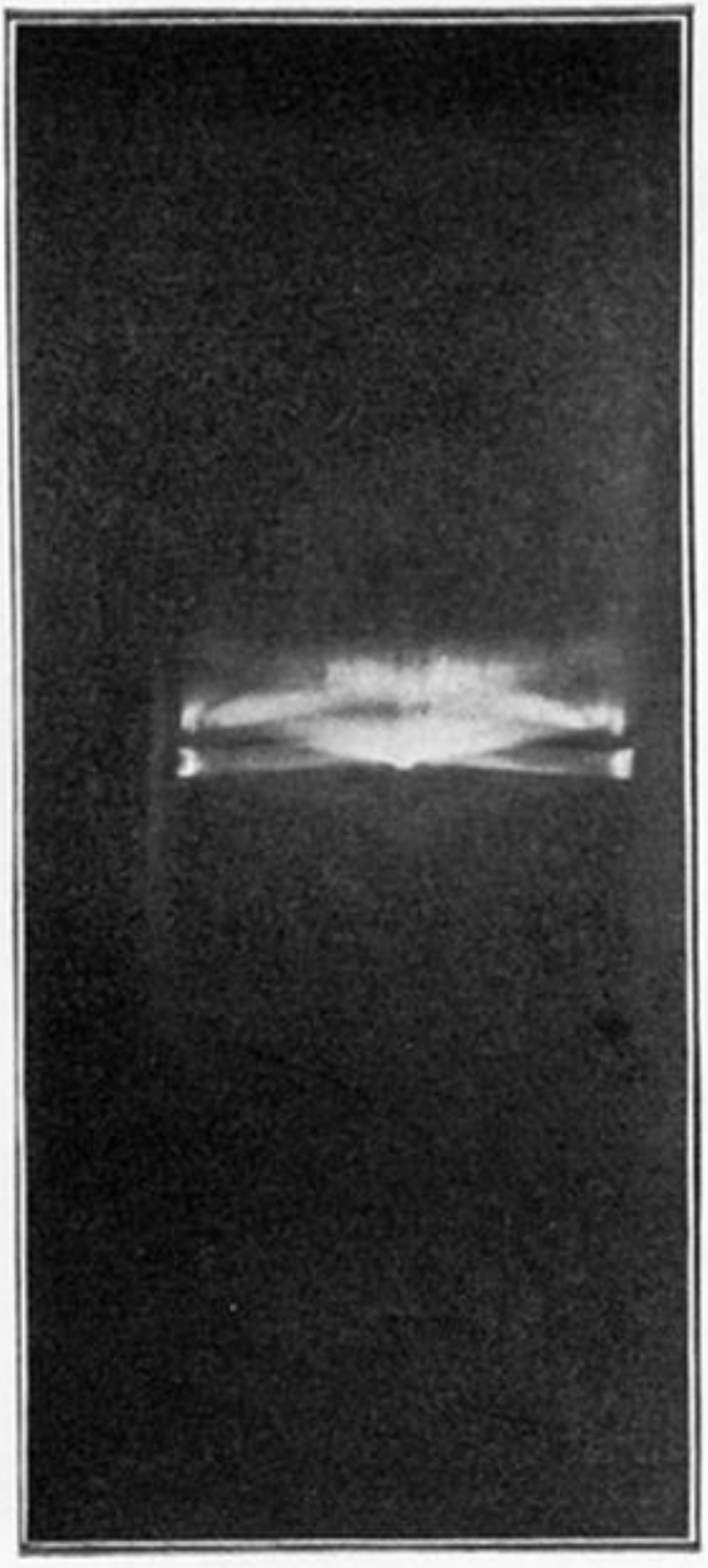

Fig. 48.—Do. $C_2H_2 + O_3$.

Fig. 49.—Retonation-wave and Reflexion-wave.

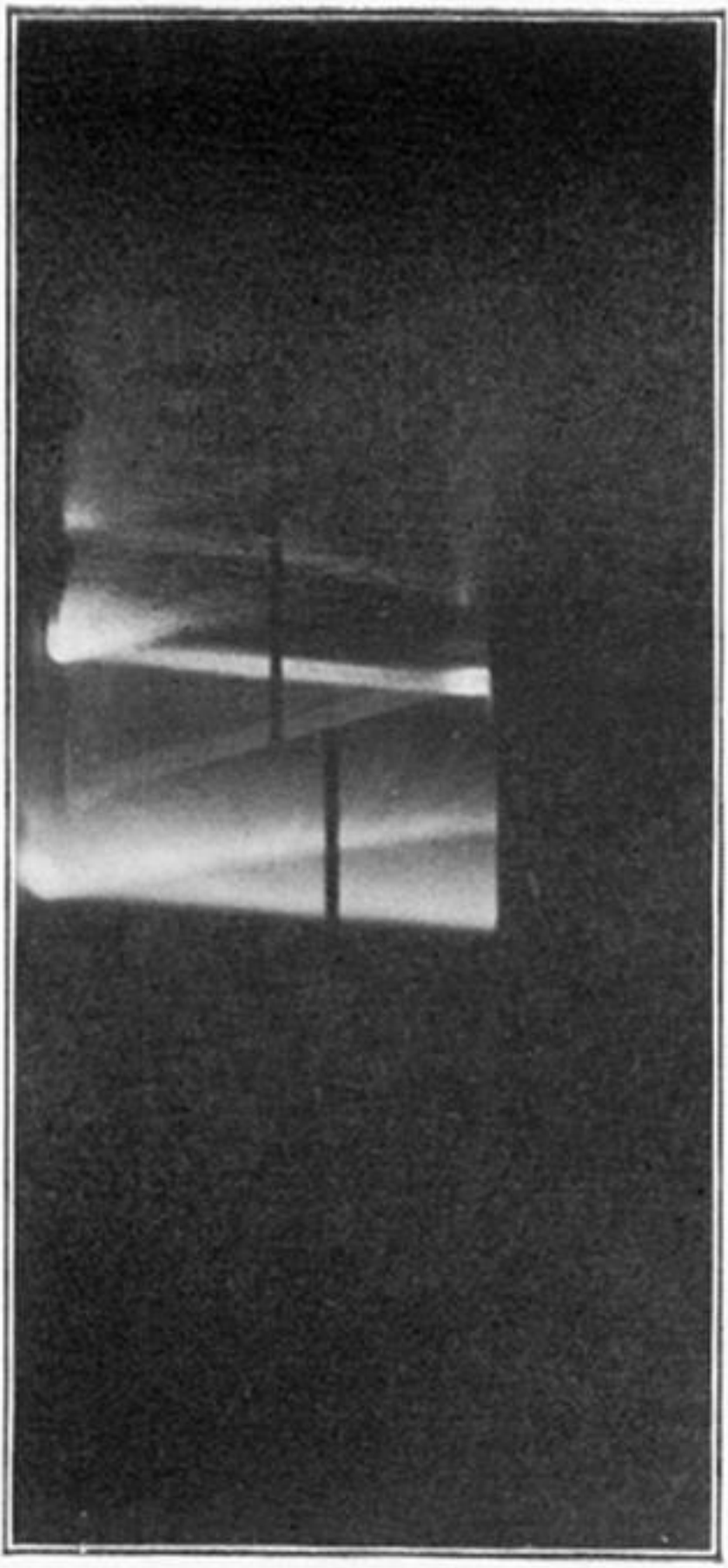

Fig. 50.—Detonation in lower tube.
Retonation in upper tube.

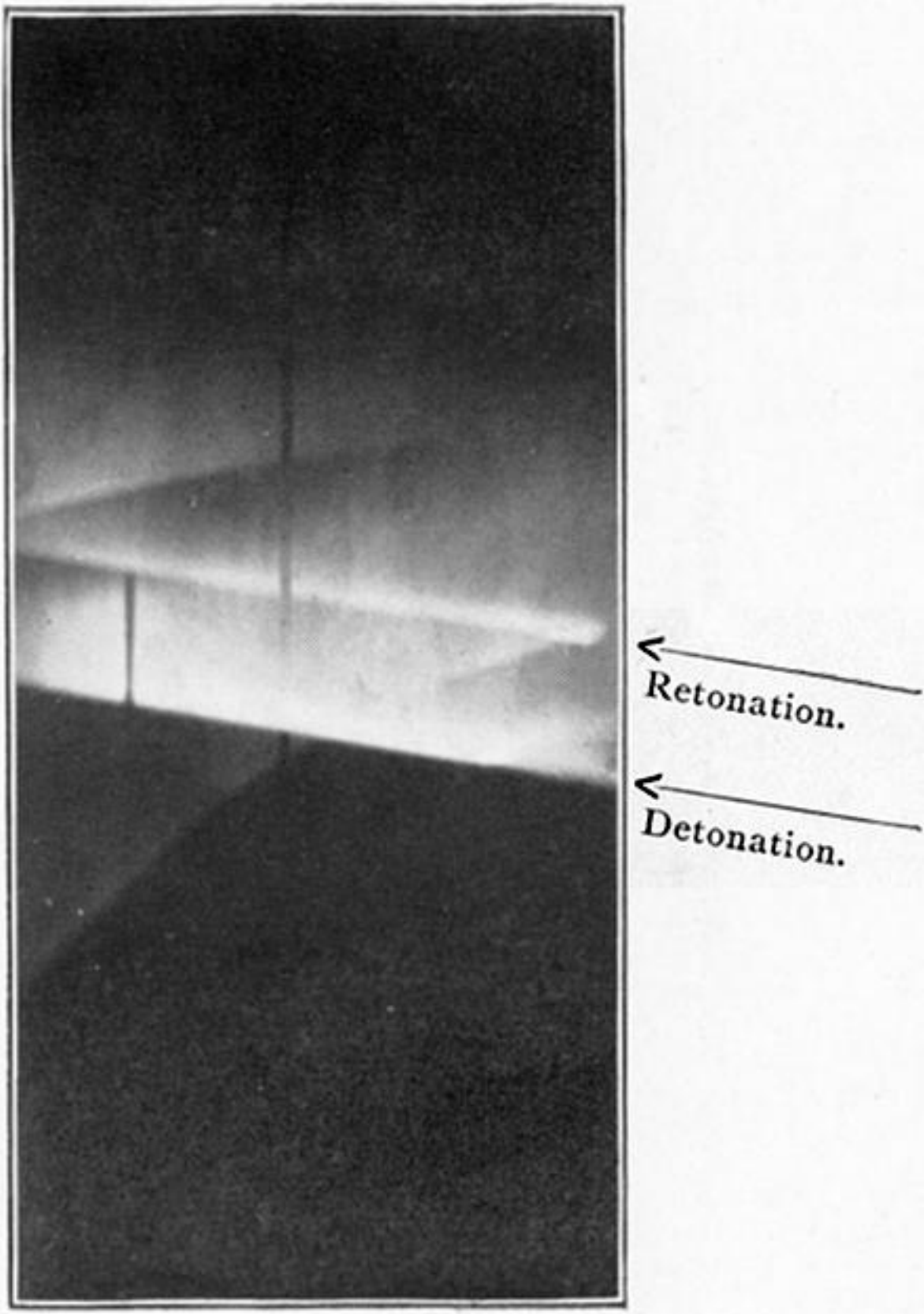

Fig. 51.—Detonation in one tube;
Retonation in other tube.

Fig. 52.—Initial wave overtaken by faster wave.

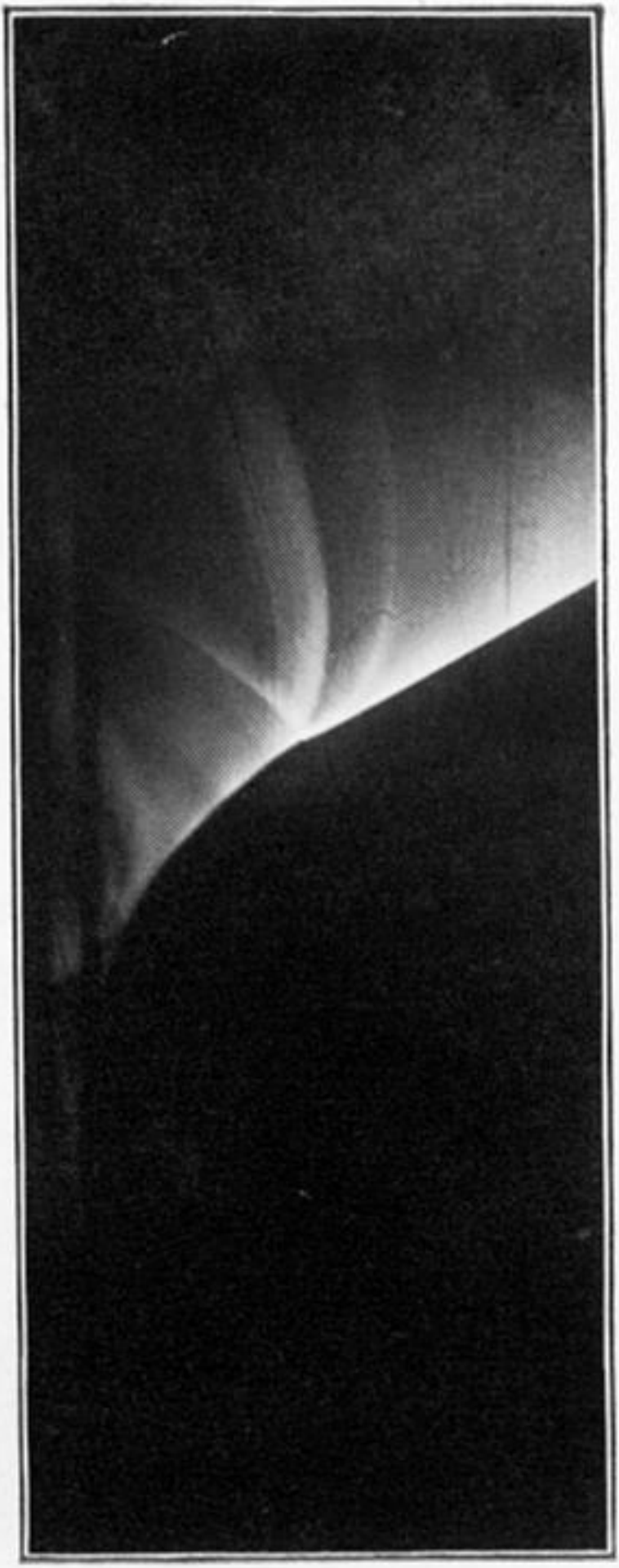

Fig. 53. $C_2N_2 + 2O_2$.

Fig. 54. $CS_2 + 3O_2$.

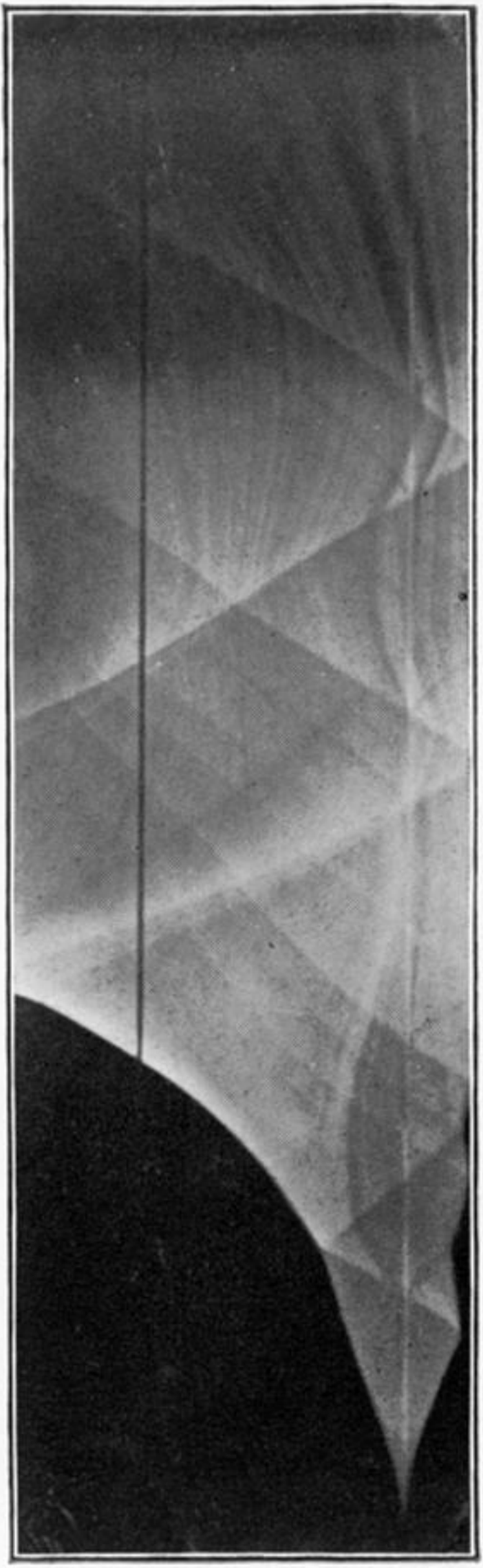

Fig. 55. $CS_2 + 5O_2$.

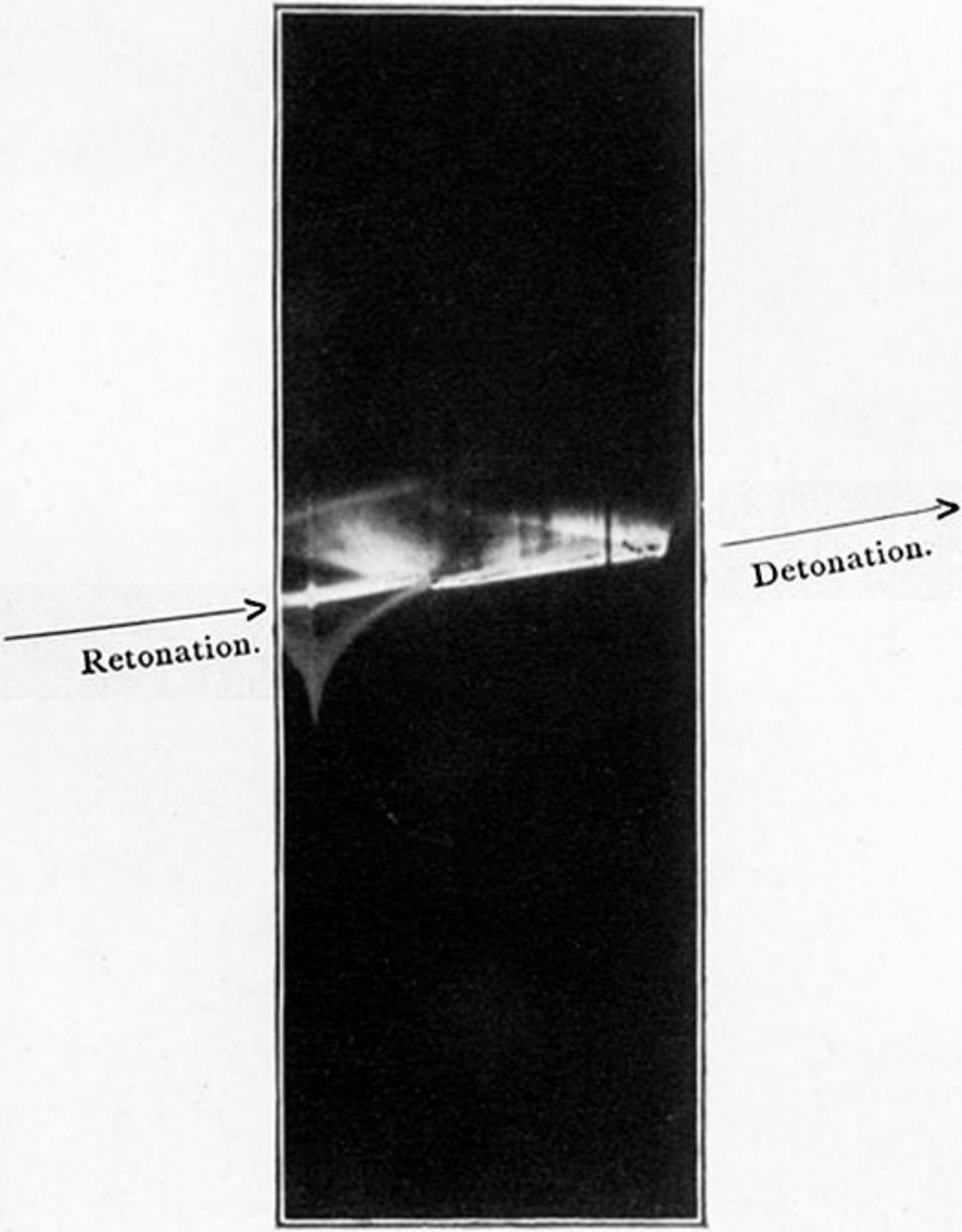

Fig. 56. $C_2N_2 + O_2$.

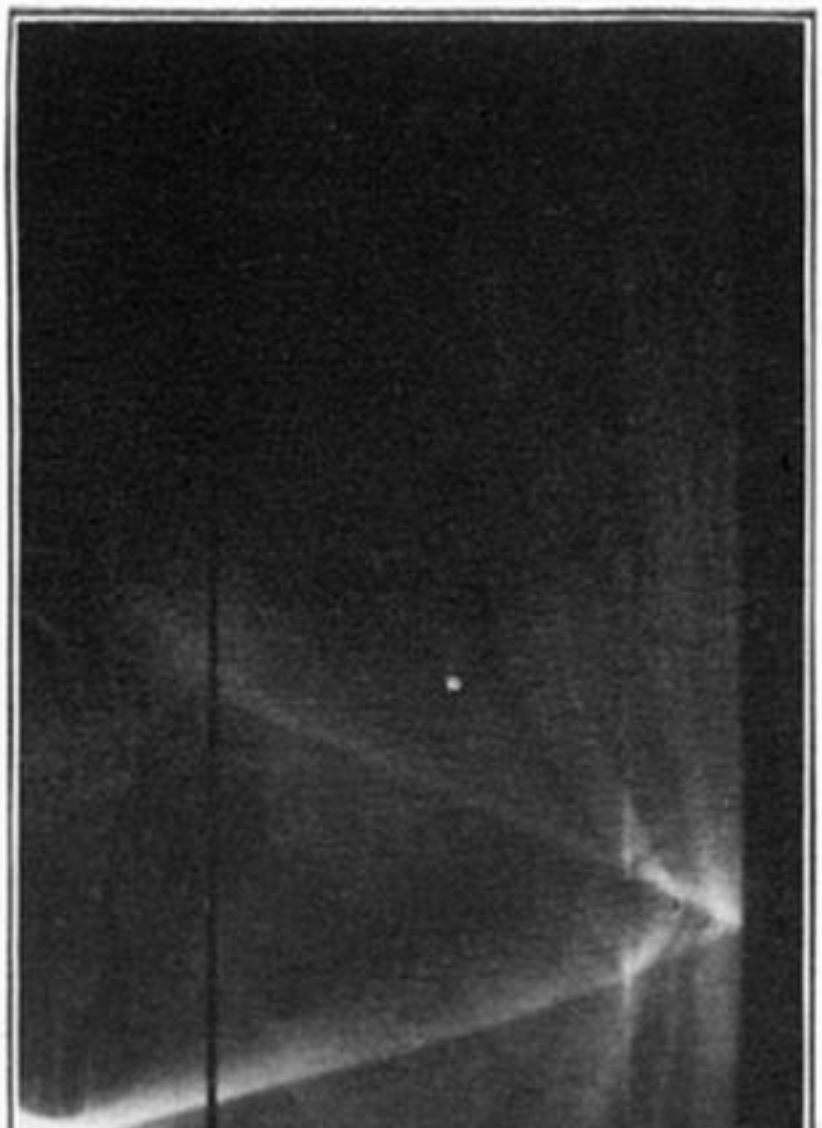

Fig. 57. $C_2N_2 + 2O_2$.

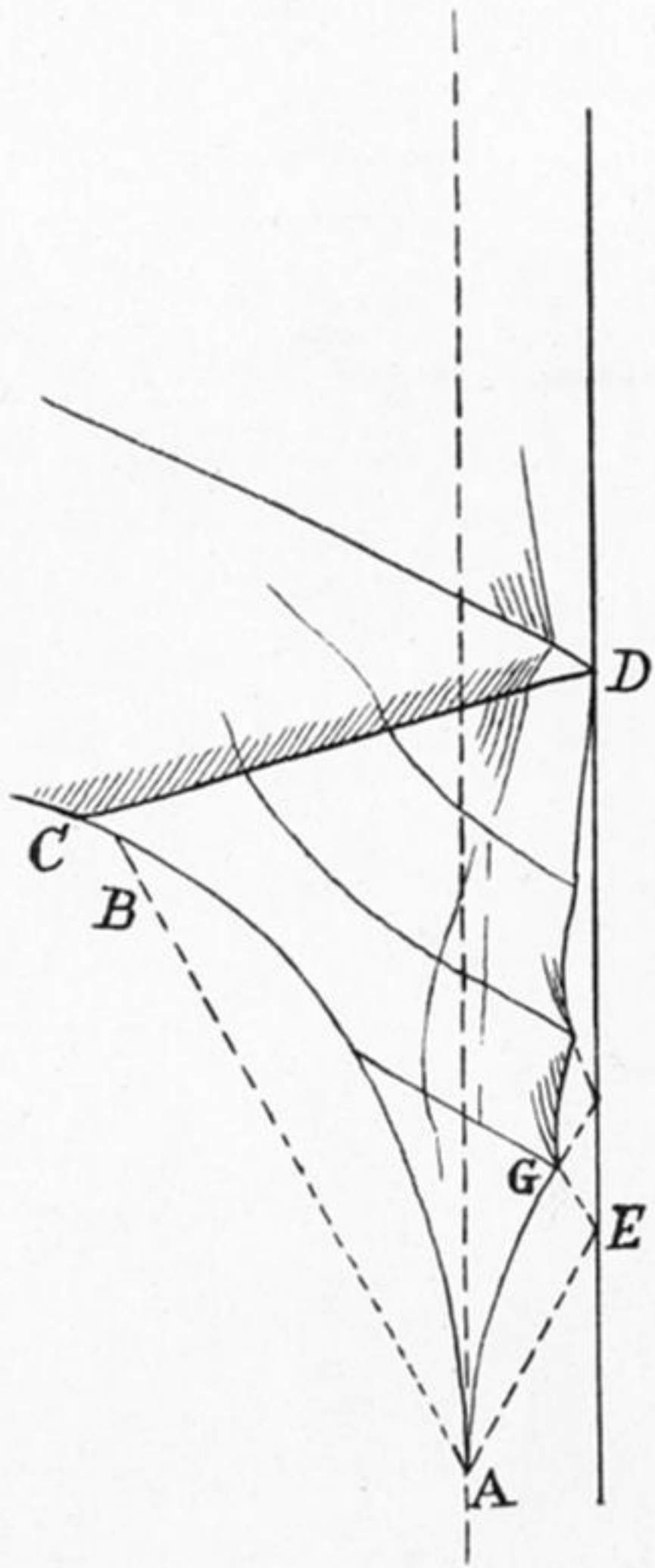

Fig. 57A.

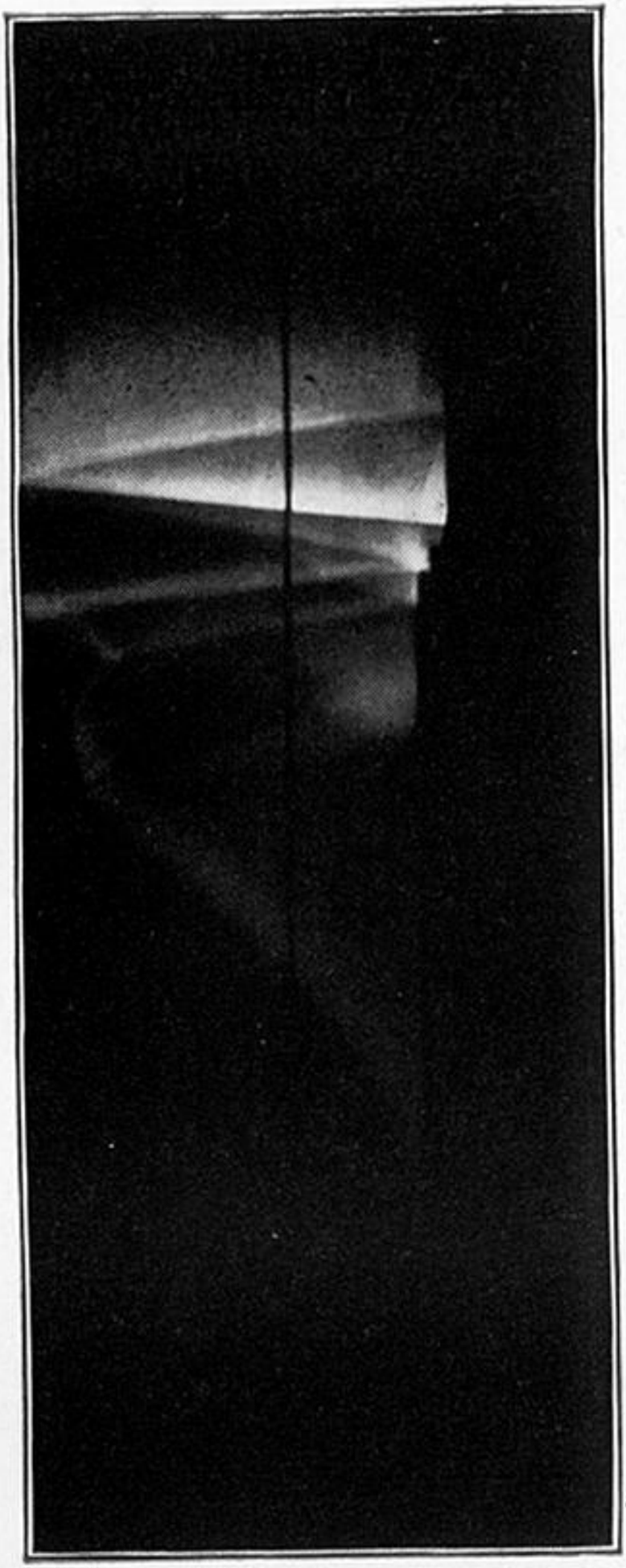

Fig. 58. $C_2N_2 + O_2$.
Detonation in upper tube.
Initial flame in lower tube.

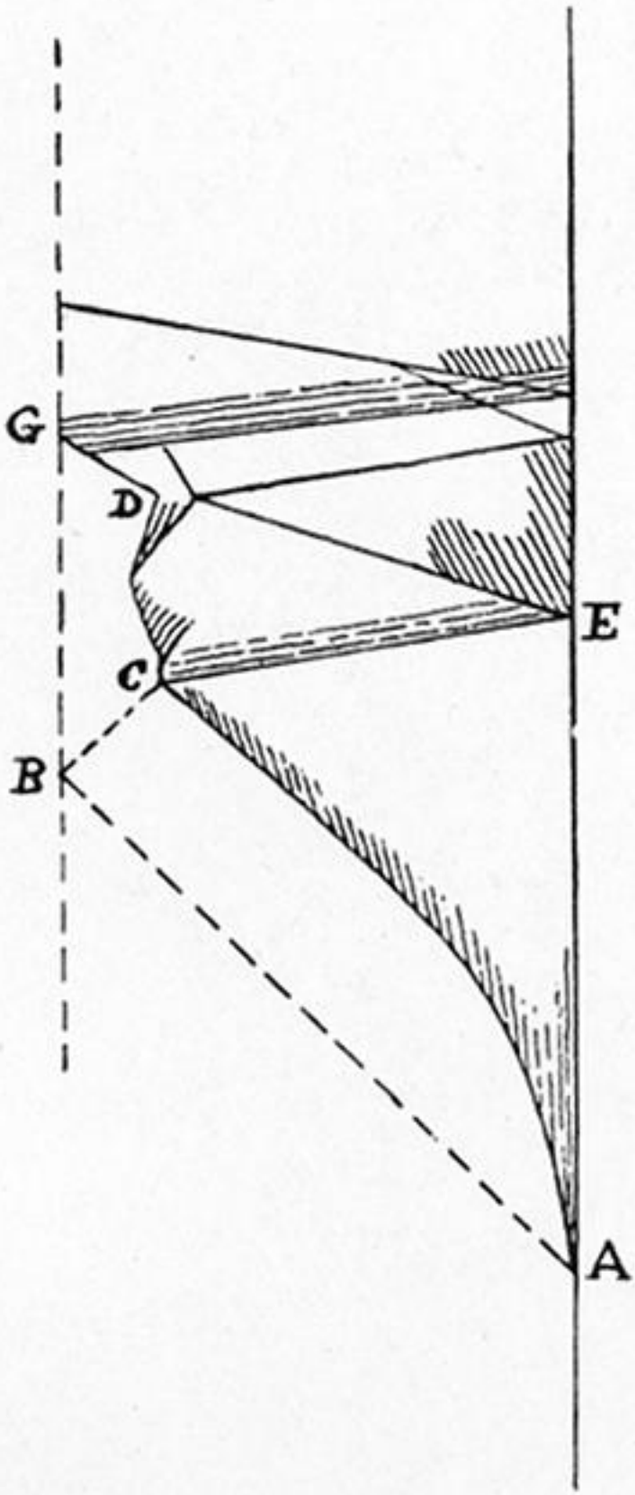

Fig. 58A.

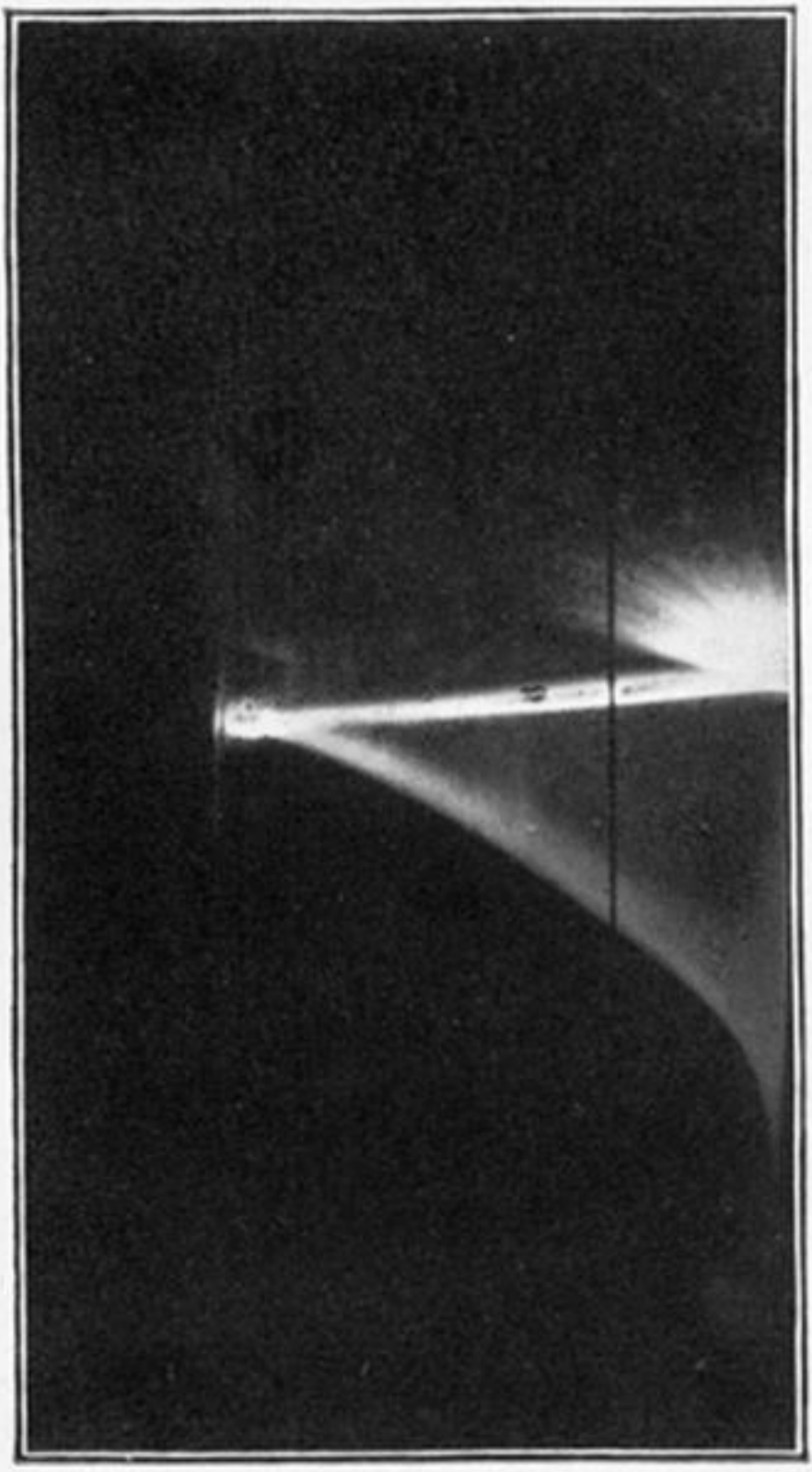

Fig. 59. $C_2N_2 + O_2$.

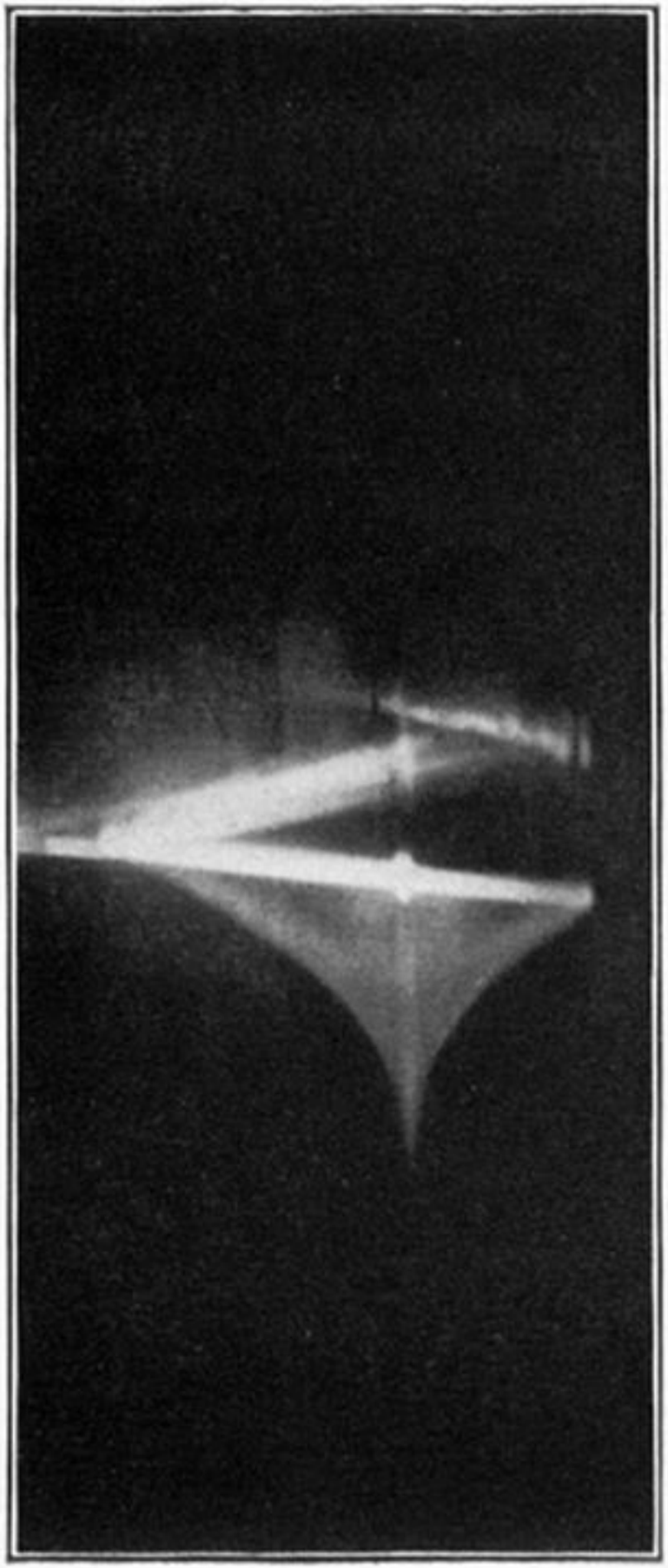

Fig. 60. $C_2N_2 + O_2$.

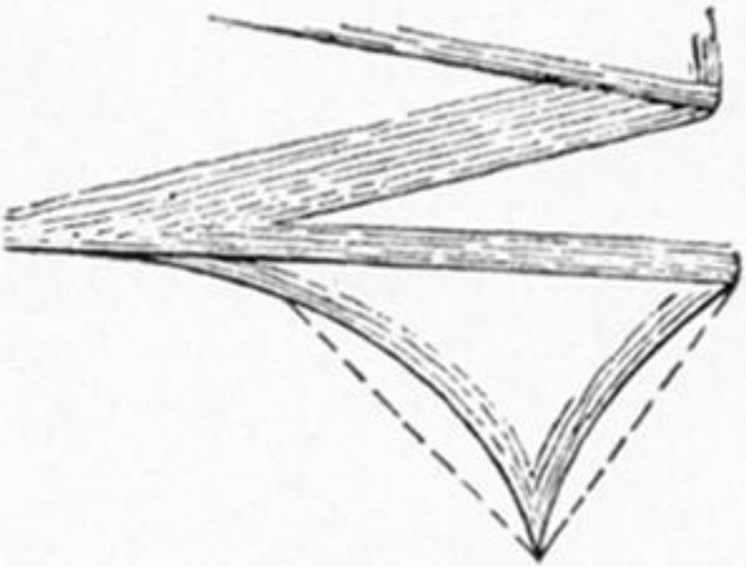

Fig. 60A.

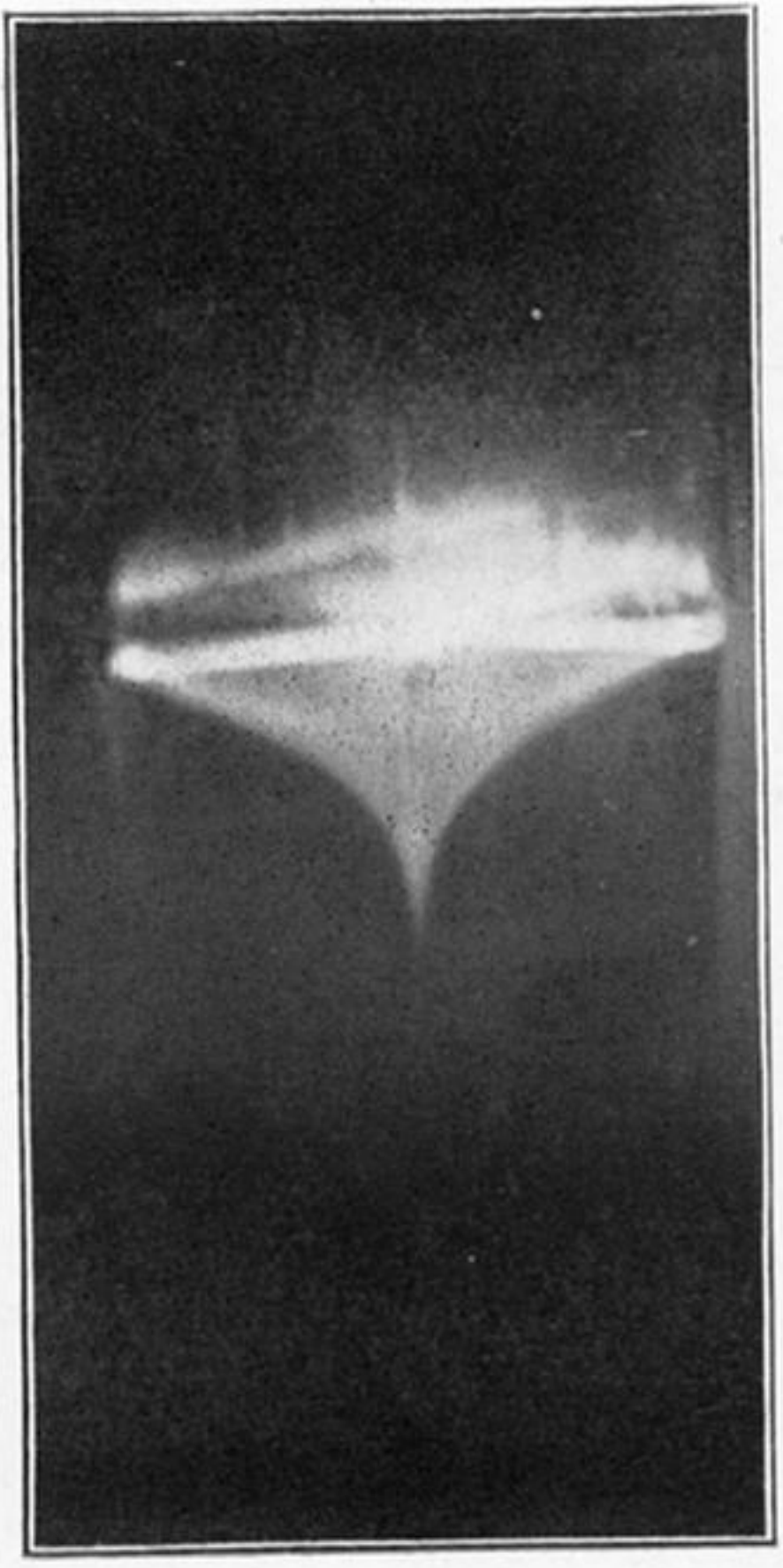

Fig. 61. $C_2N_2 + O_2$.

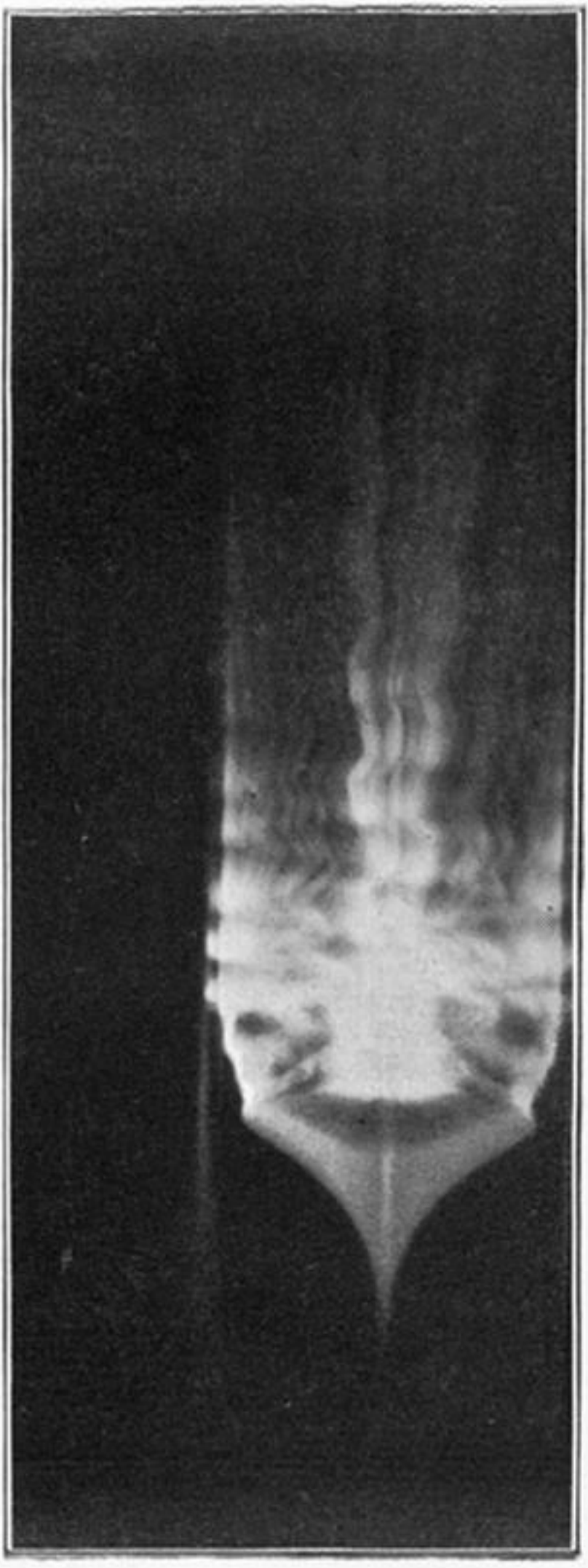

Fig. 62. $C_2N_2 + O_2$.

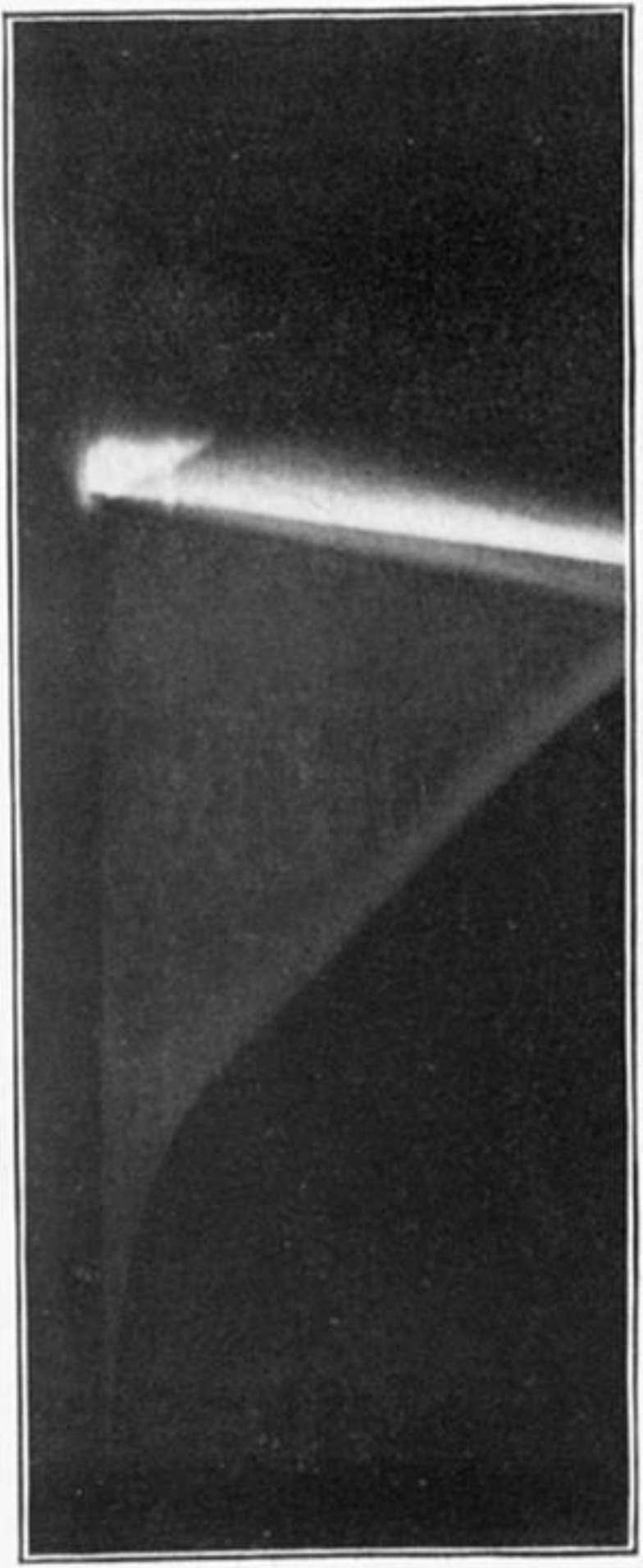

Fig. 63. $C_2N_2 + 2O_2$.

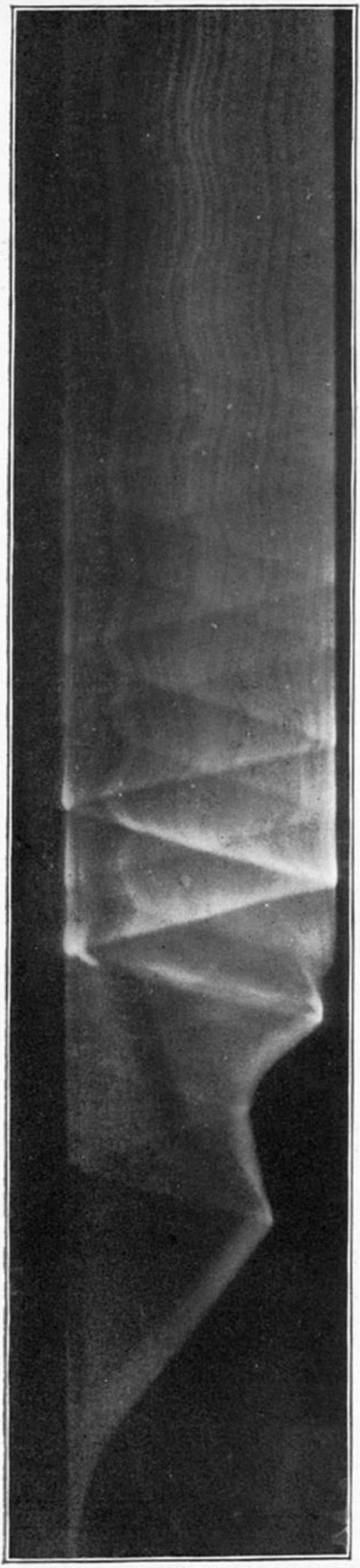

Fig. 64. $C_2N_2 + 2O_2$.
Showing sound-wave returning from right-hand end.

Fig. 65. $C_2N_2 + 2O_2$.
Showing sound-waves returning from both ends.

Fig. 66. $C_2N_2 + 2O_2$.
Fired at closed end.

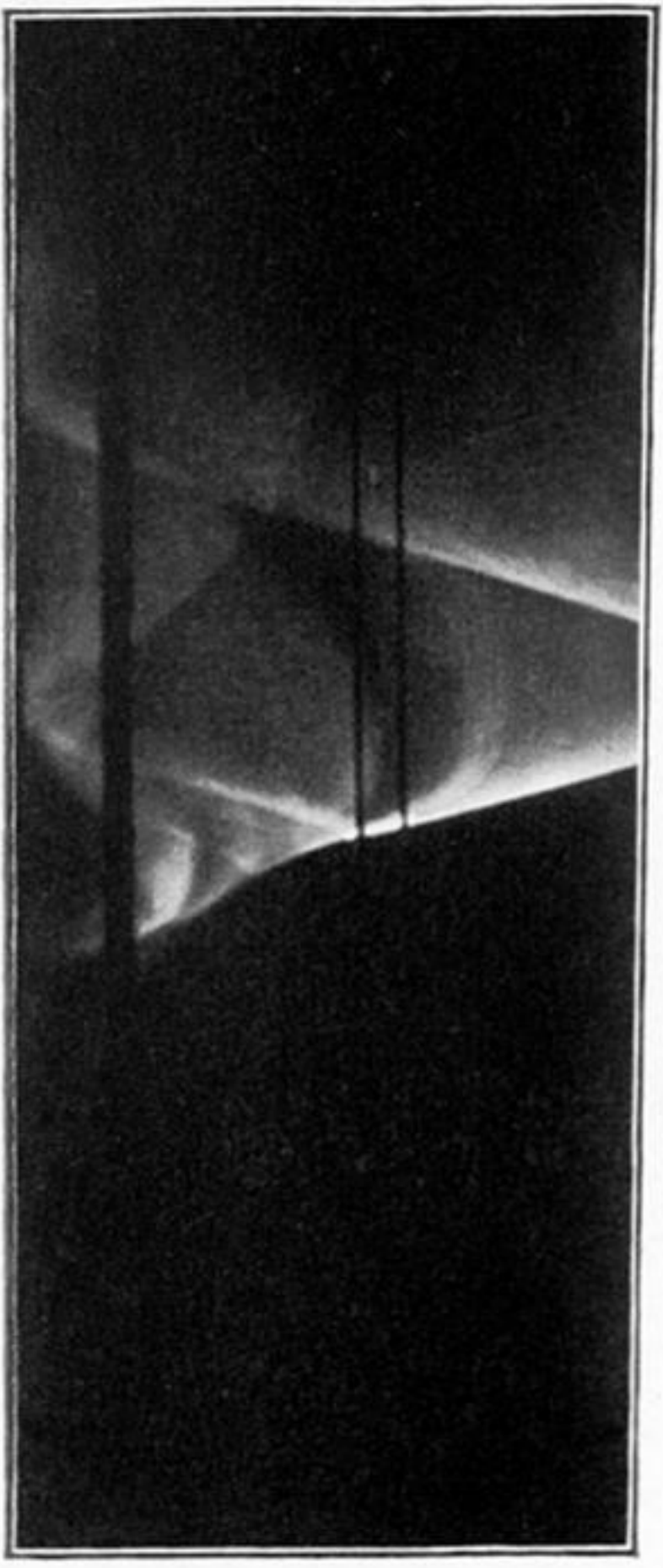

Fig. 67. $C_2N_2 + 2O_2$.
Fired 4 inches from closed end.

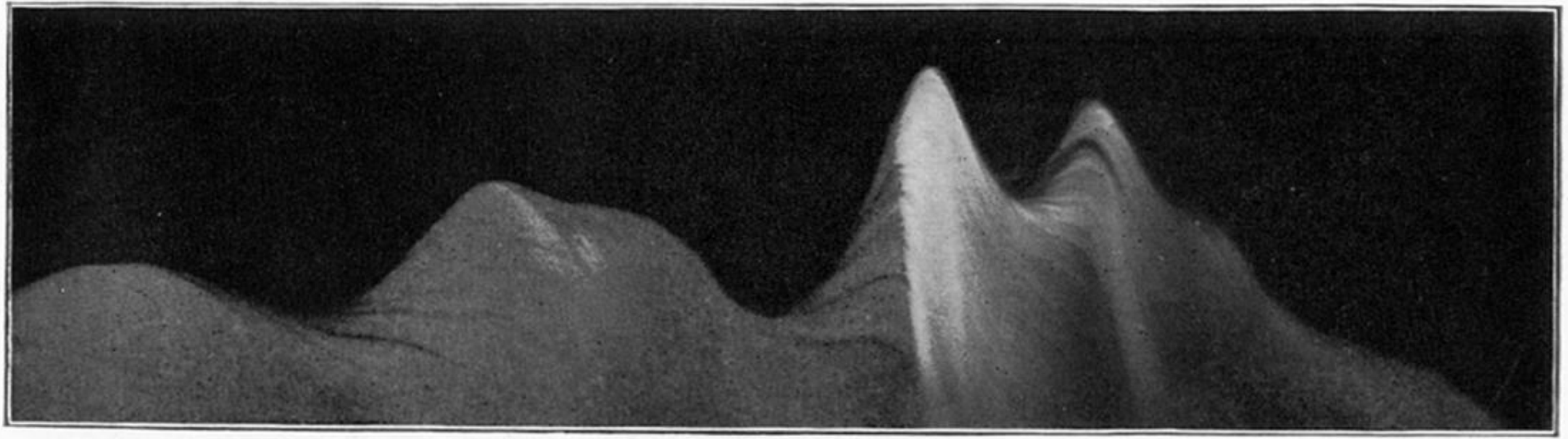

Fig. 68. $CS_2 + 8NO$.

Oscillations of flame between 4 and 5 feet from firing-point.

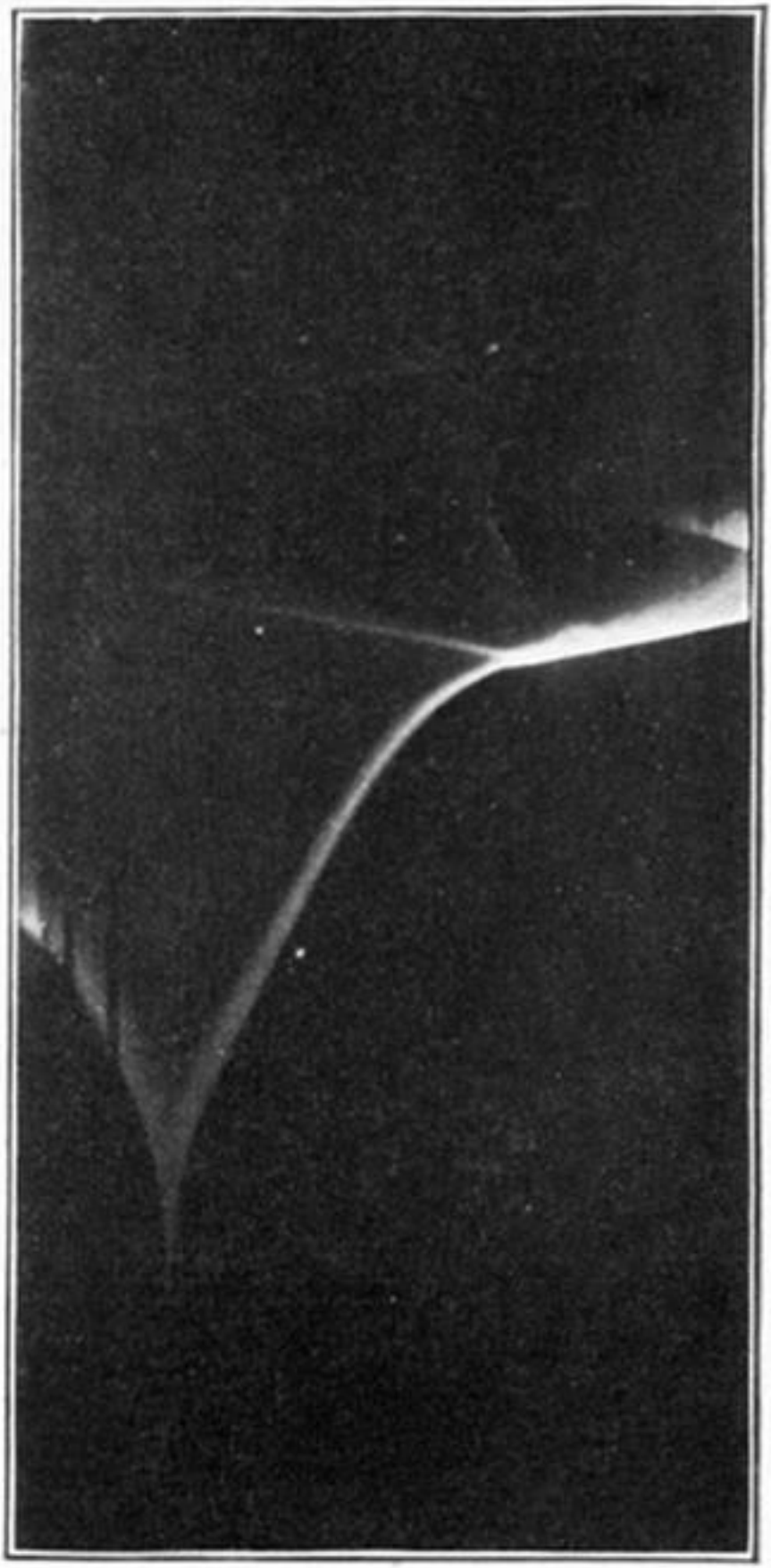

Fig. 69. $C_2N_2 + O_2$.
Fired 3 inches from open end.

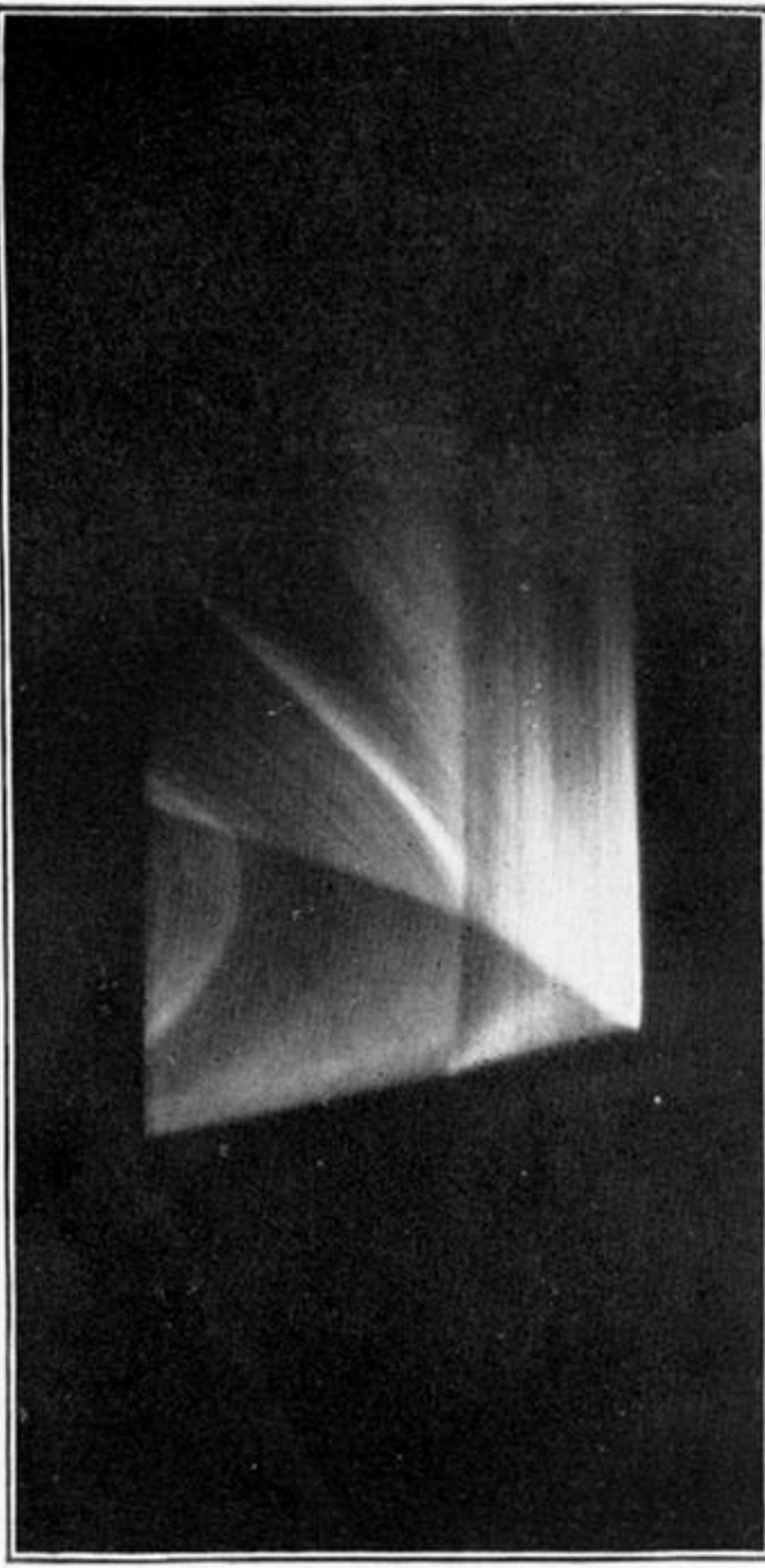

Fig. 70.—Part of tube salted.
$2H_2 + O_2$.

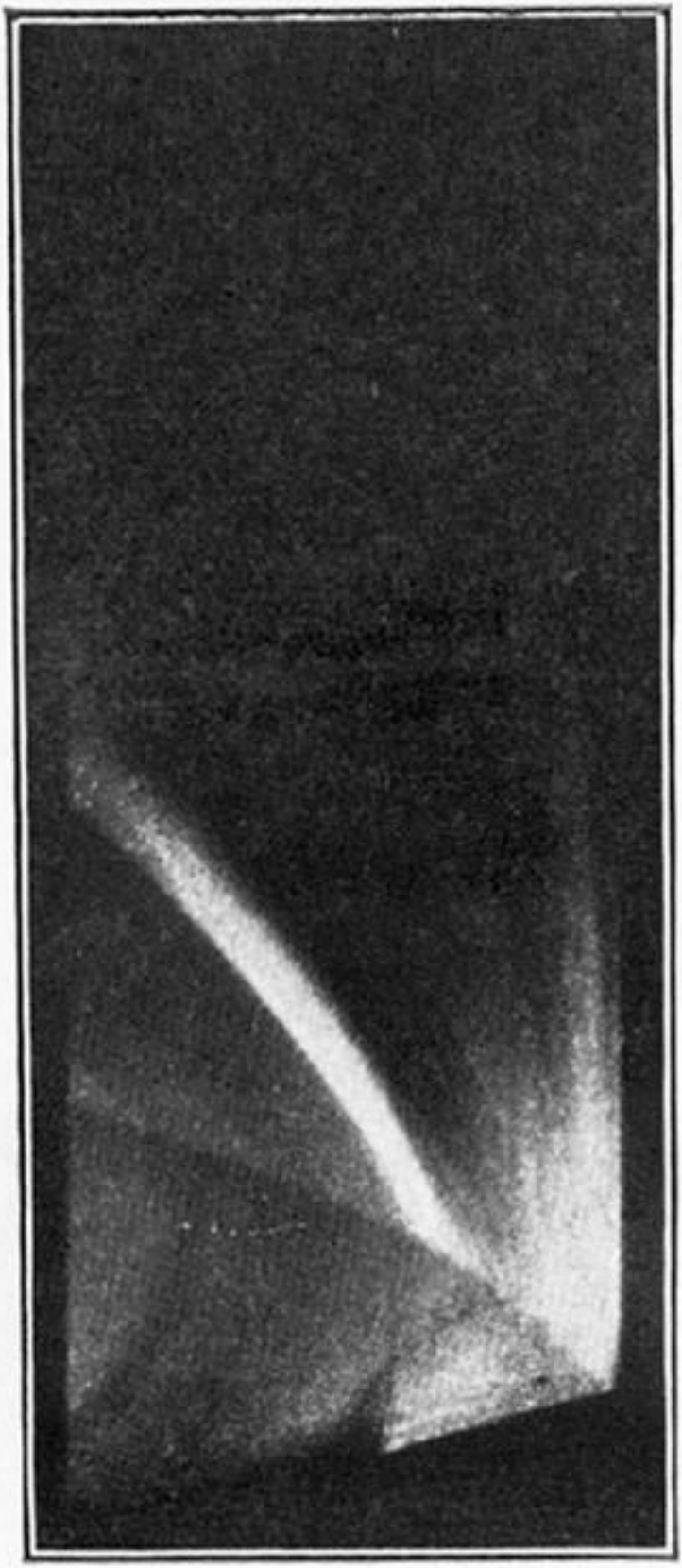

Fig. 71.—Part of tube salted.
$2H_2 + O_2$.

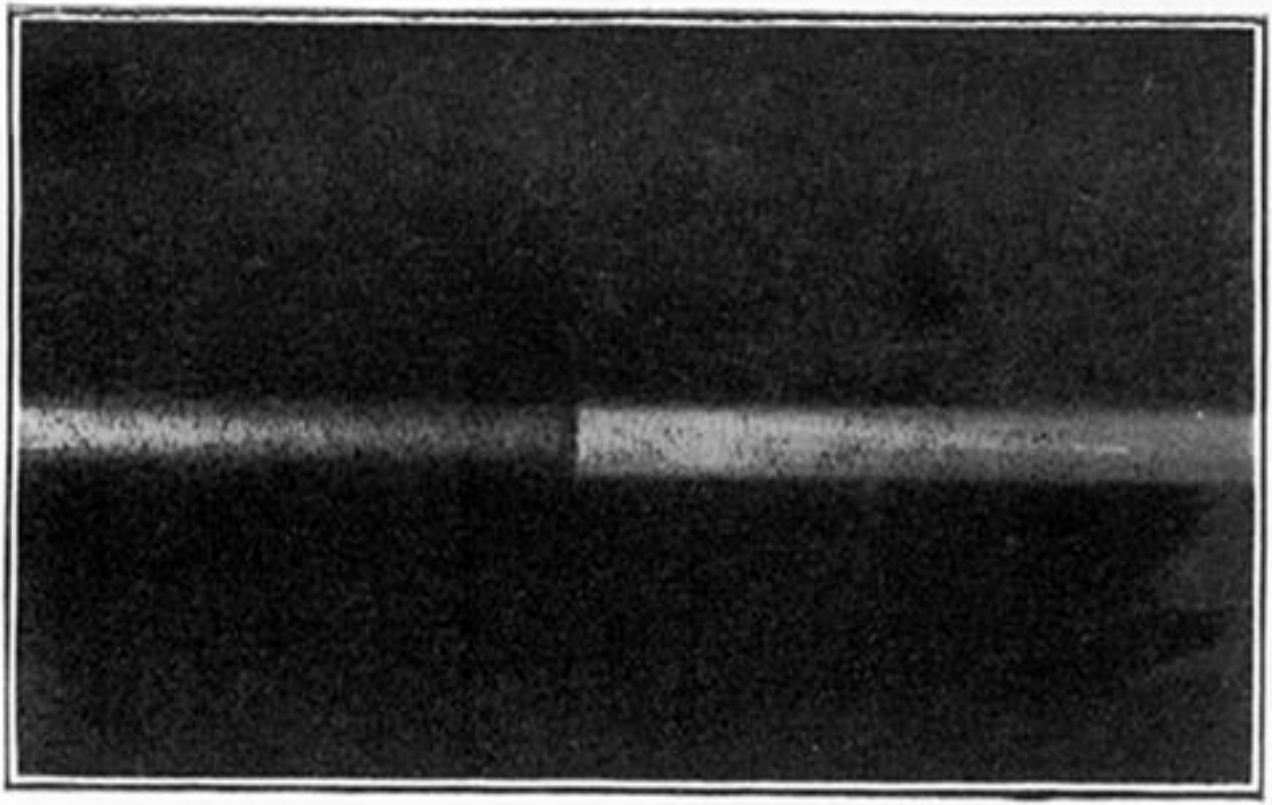

Fig. 72.—Glass tube magnified by halation.

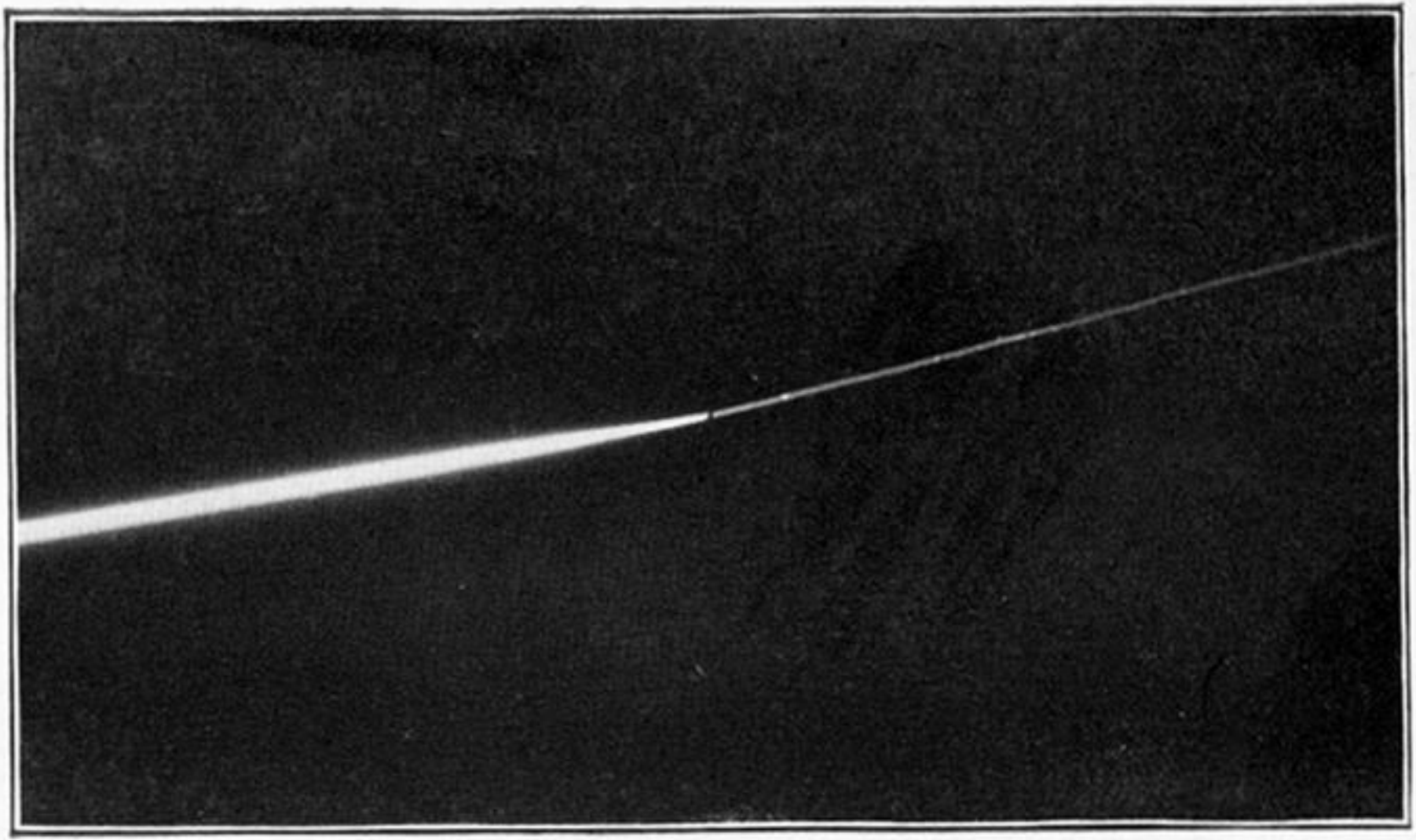

Fig. 73.—Platinum wire magnified by halation.

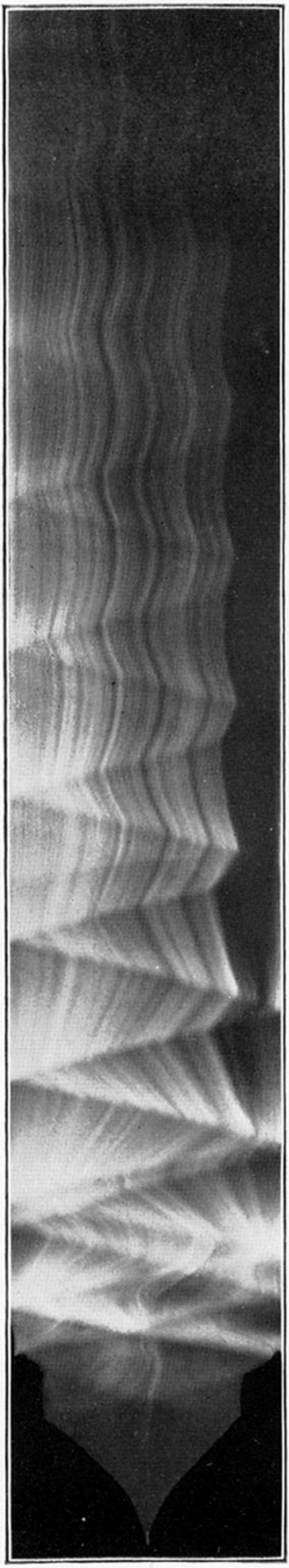

Fig. 74. $2H_2 + O_2$.

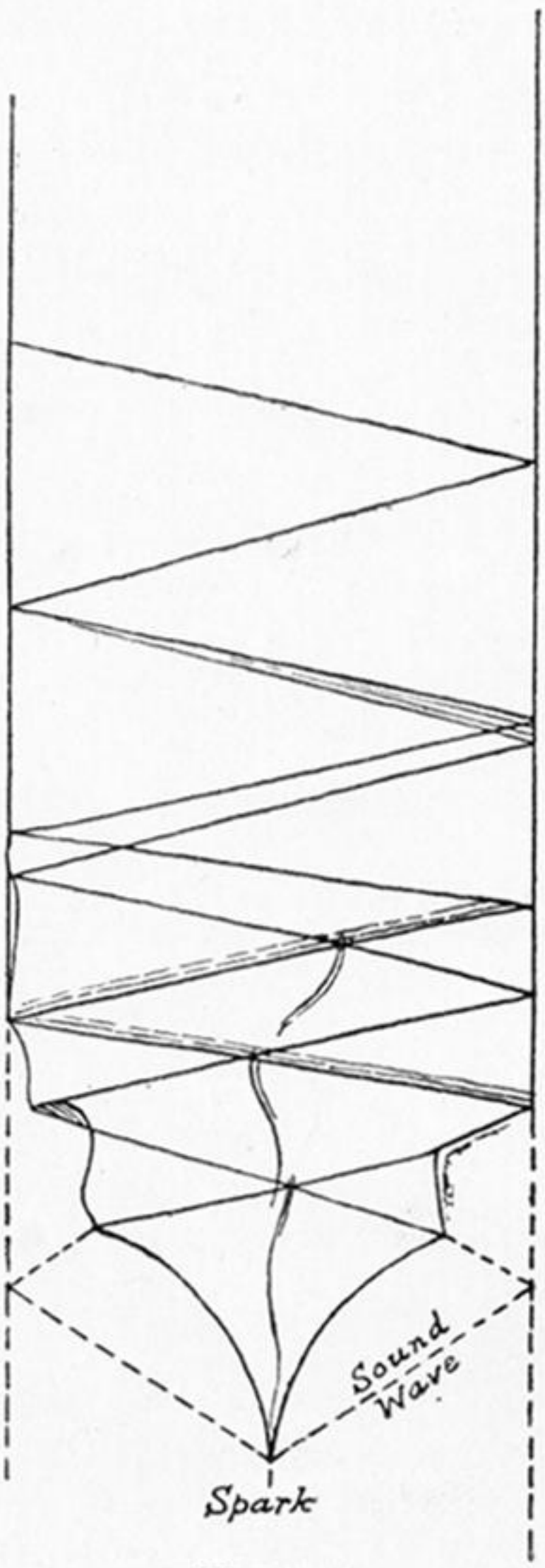

Fig. 74A.

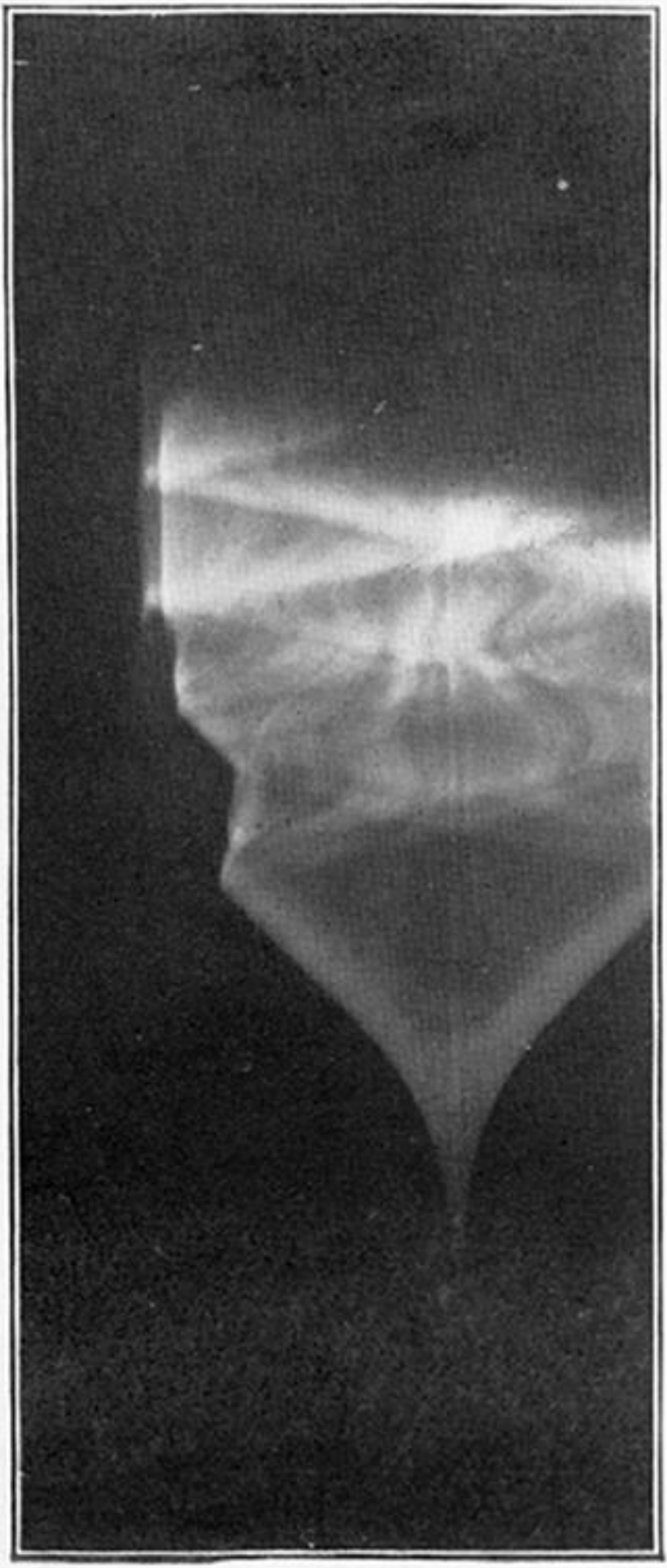

Fig. 75.

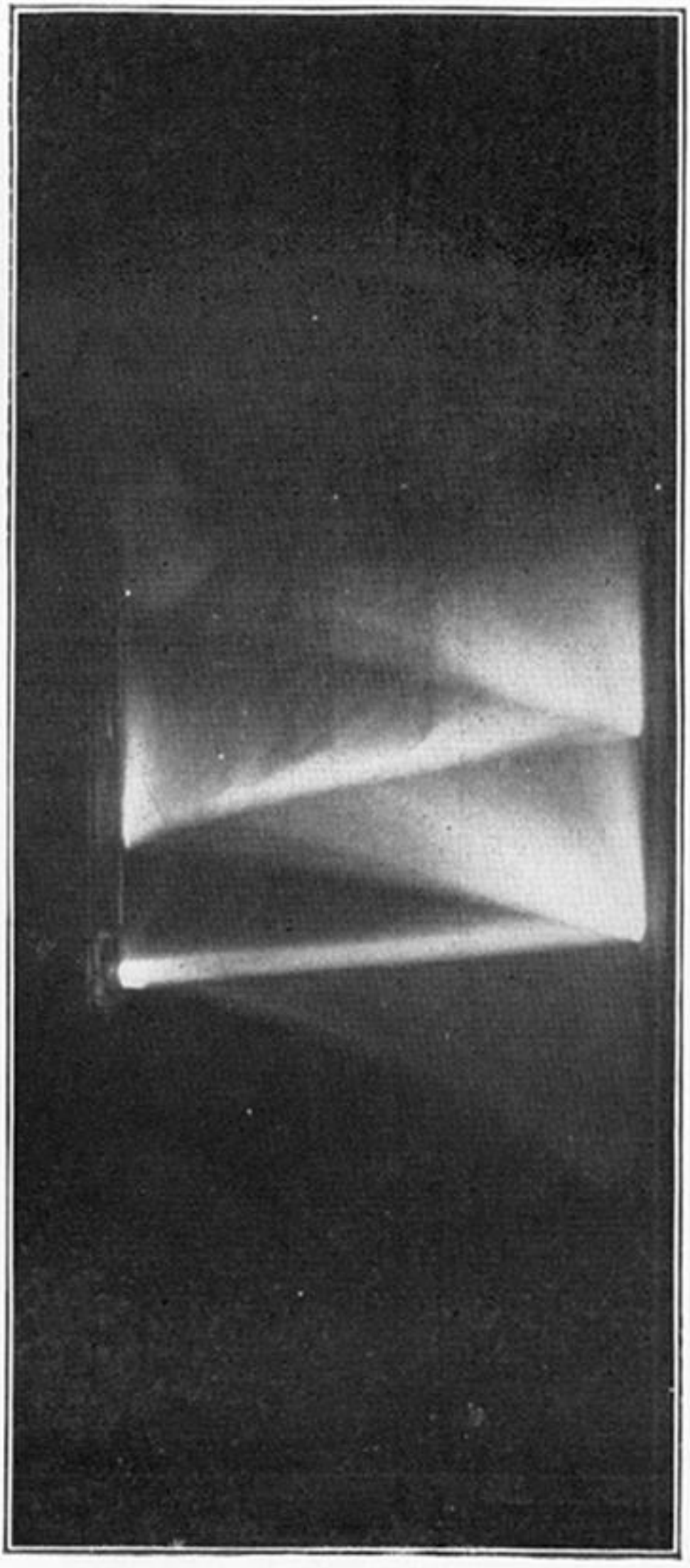

Fig. 76.

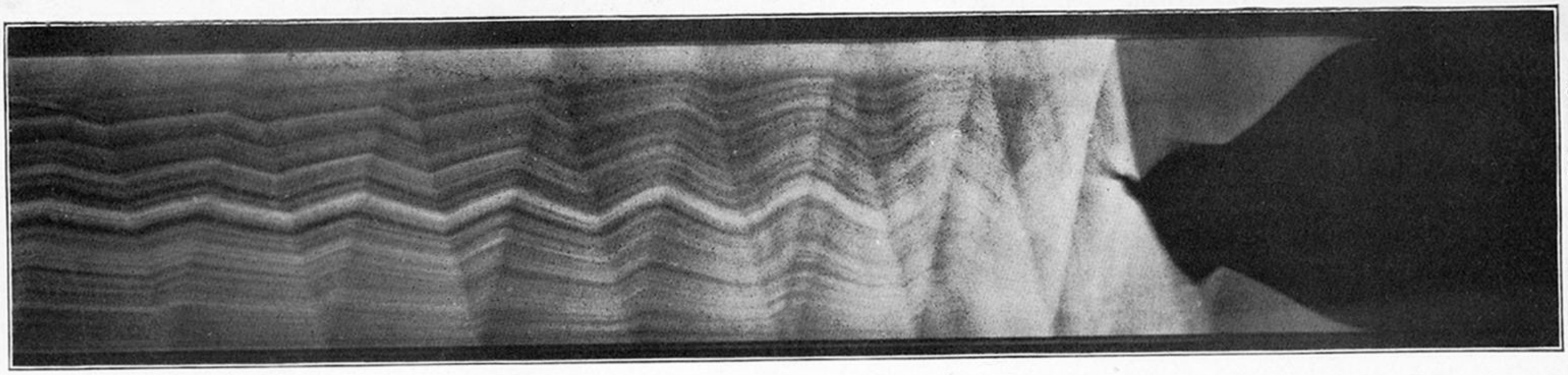

Fig. 79. $CS_2 + 3O_2$.

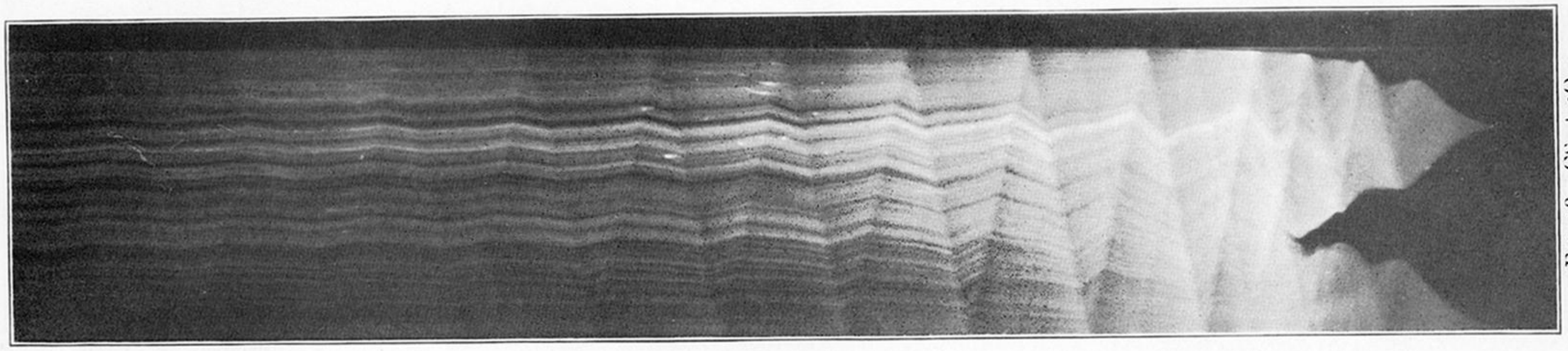

Fig. 78. $CS_2 + 3O_2$.

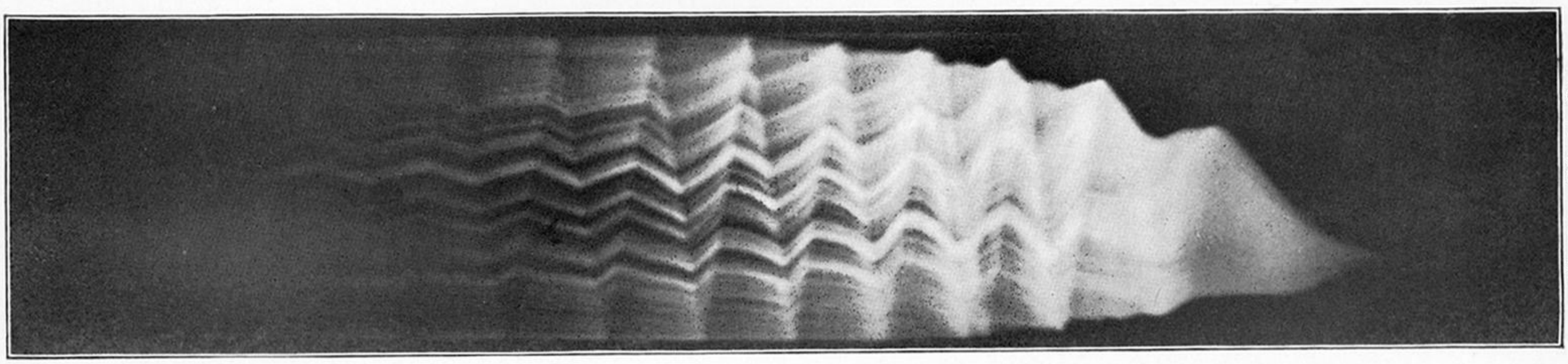

Fig. 77. $CS_2 + 3O_2$.

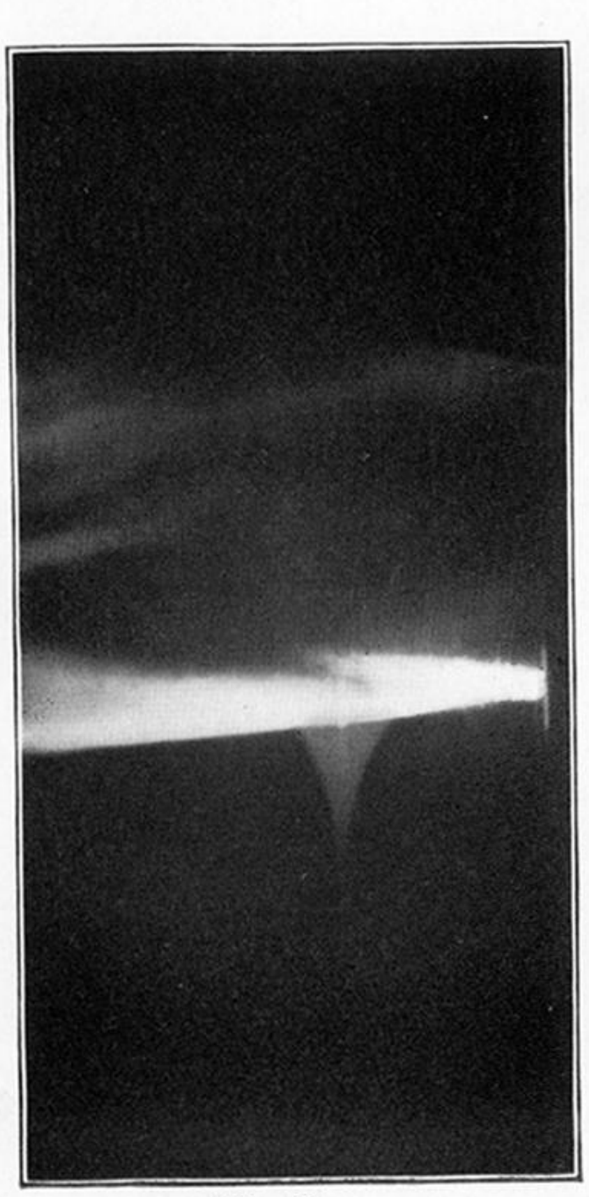

Fig. 80.

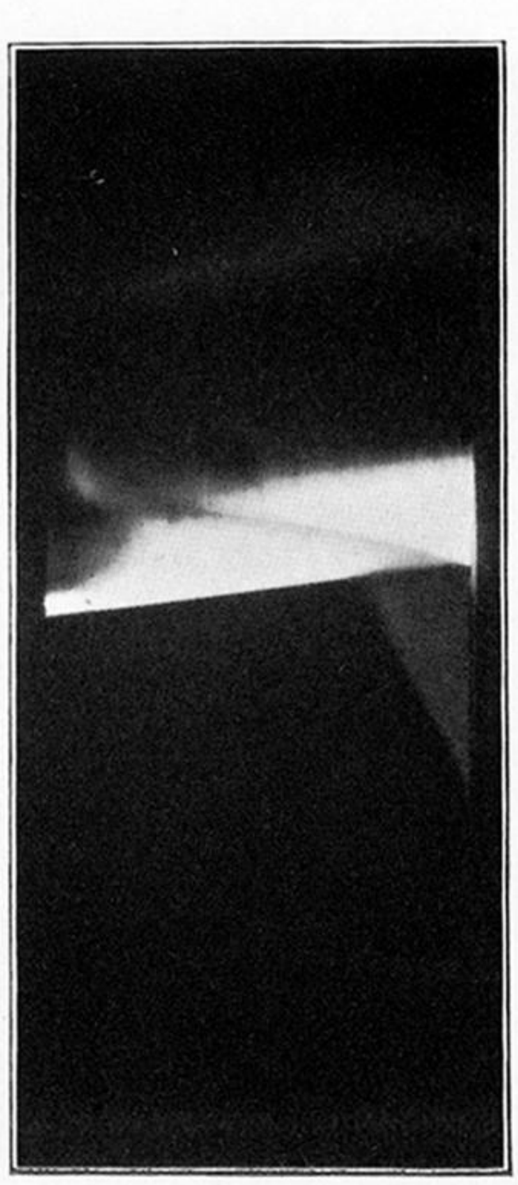

Fig. 81.

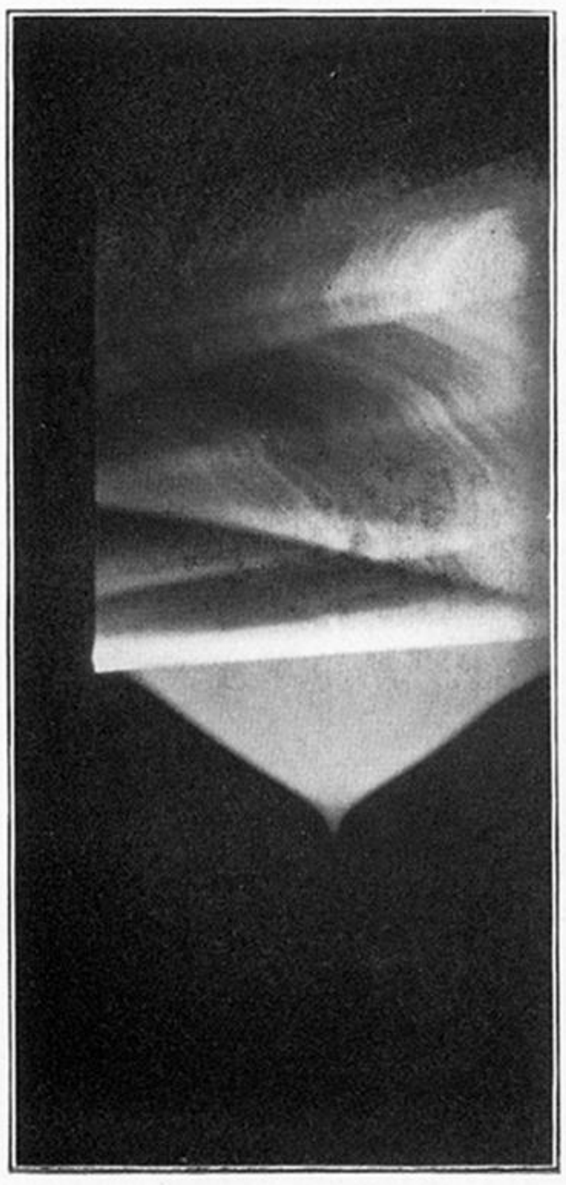

Fig. 82.

Detonation-wave passing through flames of gas ignited independently.