to a dark glow of immense proportions accompanied by a violent wind, terminating as seen.

If these violent vertical currents are not occasioned by convectional discharges of electricity, as Dr. Hare supposed them to be, what are the causes of them? Their existence is certain, and indeed it is probable, that they frequently occur, not with violence and destruction, but with gentle action and beneficent effects upon the temperature of the lower atmosphere. We shall have to classify them and give them Greek names and call it "science," according to the rule of the old peripatetic: "*Qu'il faut bien citer ce qu'on ne comprend point de tout dans la langue qu'on entend le moins.*"

THE DIFFRACTION OF SOUND.

BY W. LE CONTE STEVENS.

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The conception that sound is due to wave motion in an elastic material medium seems to have been entertained before the beginning of the seventeenth century by Lord Bacon. To Sir Isaac Newton, however, is due the credit of formulating it distinctly, and establishing it firmly on a mathematical basis. The application of the same theory to light was most natural, but Newton's clear understanding of certain necessary consequences, which, to his mind, did not seem to be realized in the case of light, caused him to reject the wave theory and to substitute for it his well-known emission theory, which for more than a century held undisputed sway. The phenomena of diffraction, which constituted Newton's stumbling-block, became afterward the strongest evidence in favor of the wave theory of light as developed by Young and Fresnel. The elementary experiments had been repeated by Grimaldi, Hooke, Huygens and Newton, but the true explanation of them did not occur to a single one of these acute observers. Waves of

of quiescence. To find the distance, x , between two successive points of maximum motion, we have

$$d'^2 = d^2 + (x + \frac{1}{2}c)^2$$

$$d''^2 = d^2 + (x - \frac{1}{2}c)^2$$

Extracting the square root and discarding powers of c , since this is small in comparison with d , as is x also, we have, approximately,

$$d' = d + \frac{(x + \frac{1}{2}c)^2}{2d}$$

$$d'' = d + \frac{(x - \frac{1}{2}c)^2}{2d}$$

whence,

$$d' - d'' = \frac{c}{d} x$$

but

$$d' - d'' = \lambda$$

hence,

$$x = \frac{d}{c} \lambda$$

From this well-known formula it is seen that $x \propto \lambda$. If c be the element of a diffraction grating for light, and d be the distance from grating to screen, x is at once determined if λ be known. Assuming a coarse transmission grating in which $c = \frac{1}{1250}$ inch, taking λ for red light $= \frac{1}{40000}$ inch, and $d = 300$ inches, we have the value of x a little over nine inches.

Now assuming the waves to be those of sound, the pitch being that of a high soprano tone, 1,024 vibrations per second, if diffraction could be produced and measured from such a grating, the corresponding value of x would be not far from eighty miles. Increasing the element of the grating to an inch, x is reduced to about 10 drays. It is obvious, therefore, that the diffraction of sound waves is, under ordinary conditions, so great as to defeat all efforts directed toward its actual measurement or even qualitative demonstration. Sound shadows, instead of being nearly geometric like those of light, are usually too ill-defined to be traceable at all, if the propagation is through air.

In 1826, Colladon's classic experiments were made in the Lake of Geneva for the determination of the velocity of sound in water. Incidentally he noticed quite well-defined sound shadows behind the edge of a stone wall projecting into the lake. A peculiar phenomenon, which was observed but not explained by him, was that the sound of the distant bell reached the membrane of the submerged hearing trumpet as a sharp click, without definite musical character. This was due to the quick and violent initial stroke of the hammer upon the bell, while the energy of the slower vibrations, due to the bell's elasticity, was absorbed by the aqueous medium.

In 1874, much more remarkable experiments on the production of sound shadows in water were made in the Bay of San Francisco, by Prof. John Le Conte and his son, Mr. Julian Le Conte. In the process of deepening the harbor, dynamite was used for the purpose of blasting away a submerged reef of sandstone. Glass bottles hung in the water were shattered by the impulse propagated through the elastic medium from a distance of forty feet, but perfectly protected if placed within the geometric shadow of a pile. When the cartridge was aligned with two piles twelve feet apart, forty feet from the nearer one, the well-defined shadow of the first pile covered the second one, so that bottles placed anywhere between the two were protected. Thick glass tubes, placed across the shadow, were shattered in all parts exposed beyond it, and protected in the middle parts that were within it.

To account for the comparative absence of diffractive effects in these experiments it is necessary to assume that the waves were exceedingly short. It was pointed out by Dr. Le Conte that a sufficient cause for this is found in the instantaneous character of the dynamite explosion. The wave length is equal to the product of the velocity of propagation and the time consumed in generating the wave. This form of statement is only a modification of the familiar formula,

$$\lambda = \frac{v}{n}$$

since the time of a single vibration and the number of

vibrations per second bear a reciprocal relation. The quickness of action manifested in the explosion of dynamite is such that the duration of the generating impulse is almost infinitesimal. Assuming it to be a millionth of a second, and taking $v = 4,700$ feet for water, the resulting wave length would be only about one-seventeenth of an inch.

In 1880, the explosion of a dynamite factory near the University of California resulted in the production of two sounds at a distance, one conducted by the ground, the other by the air. The university building cast an acoustic shadow, at least three hundred yards long, within which the aerial impulse was imperceptible. The velocity of sound in air being less than a fourth of that in water, the wave length under similar conditions must be correspondingly short.

Prior to the dynamite explosion just mentioned, Lord Rayleigh, in England, had achieved some remarkable results in diffraction of sound, without resorting to so dangerous a source as an explosive. A whistle of very high pitch was employed as a producer of sound. The difficulty in using it consists in the fact that when the intensity is very slight a high pitch becomes inaudible. Something else than the human ear has to be used, therefore, as an appreciator or indicator. Dr. Le Conte discovered in 1857 that, under appropriate conditions, a common gas flame is delicately sensitive to sound. In the hands of Barrett and Tyndall the sensitive flame was improved; and Lord Rayleigh has employed it in exploring the regions of the air, where, according to theory, sound shadows ought to be produced when short waves are propagated from a source, such as the whistle just described. I have repeated successfully all the experiments described by Lord Rayleigh, many of which have been but recently devised, and I have used the sensitive flame in establishing still further analogies between light and sound.

The value of a good sensitive flame may be illustrated in a variety of ways. In producing it the cylindrical steatite burner is best fitted into the end of a metal pipe, which is connected by rubber tubing with a cylinder of compressed coal gas. From this the supply of gas is care-

fully regulated with the aid of a water manometer gauge. A good burner gives a tall quiet flame, twenty inches or more in height, which does not begin to flare until the pressure is in the neighborhood of ten inches of water. When just ready to flare, but still quiescent, such a flame indicates very beautifully the ticking of a watch held near it, every tick producing a momentary disturbance of the flame which is visible across a large audience room. It is, moreover, unequally sensitive in two directions at right angles to each other, as first pointed out by Lord Rayleigh. If the pressure be adjusted so that the flame just flares when its sensitive side is turned toward the high pitched whistle, it will cease to flare when turned round on its own axis through a right angle, so that its "deaf" side is toward the whistle. Let a mirror now be placed a foot away on the sensitive side, and equally inclined to flame and whistle. The flaring is at once renewed, but ceases the moment the angle of incidence is changed by rotating the mirror slightly about a vertical axis. Restoring the flame so that its sensitive side is again toward the whistle, if the mirror is put on the further side squarely across the line of direction of the whistle, the flame is seen alternately to flare and become quiescent according to the distance at which the mirror is held. Reflected waves meet advancing waves, producing loops and nodes. If the mirror is at such a distance that the flame is in a loop, it flares with much violence; if in a node, it becomes quiescent. Lord Rayleigh made the remarkable observation that the effect on the ear is just the reverse. The sound seems most intense when the ear is at a node rather than a loop. A convenient method is at once suggested for measuring the pitch of the whistle, even though the note it yields may be too faint and too high to be distinctly audible. By carefully measuring the distance between two successive positions of the mirror which cause the flame to be in a node, the half-wave length is obtained. The pitch thus becomes known from the formula,

$$n = \frac{v}{\lambda}$$

where v is the known velocity of sound, and n is the number

of double vibrations per second. For these experiments the whistle should yield from 12,000 to 24,000 as its pitch.

The most interesting application of the sensitive flame is in relation to the phenomena of sound shadows and diffraction. The whistle may be held in a fixed position, and supplied with a constant blast by connecting it with a cylinder of compressed air, the supply being regulated with a water manometer gauge. When the sensitiveness of the flame is so adjusted that it flares distinctly though not very violently, the interposition of the hand is enough to restore it to quiescence by protecting it with a sound shadow. A circular disk of card-board may be substituted for the hand. In one position it may serve as a protector. In another it may cause the flame to flare as strongly as if no obstacle existed. This is caused by the meeting of waves diffracted at the edges of the disk so as to meet at a point behind the middle of this. The experiment was first performed by Lord Rayleigh about 1878; it is the acoustic analogue of the celebrated experiment in diffraction of light, skeptically suggested by Poisson and performed by Arago immediately after the French Academy had received Poisson's adverse criticism of Fresnel's paper on diffraction, written in 1819.

This principle is conveniently applied to the construction of a diffraction grating for sound, such as was first made by Lord Rayleigh. Let A (*Fig. 2*) be the radiant point, the mouth of the whistle. Let B be the sensitive point, the opening of the steatite burner at the end of the nozzle. Let a plane be passed perpendicularly across the line AB at some point, O . Every point in this plane may, according to Huygens' principle, be regarded as a diffractive centre from which secondary waves are sent forth. Let P be one of these points so selected that the sum of the distances AP and PB shall exceed AB by a half wave length; or using symbolic notation,

$$(a' + b') - (a + b) = \frac{1}{2} \lambda \quad (1)$$

Then the diffractive effect of P is to produce at B complete interference with waves proceeding from A directly to B .

In like manner there exist other points, Q , R , etc., so placed that

$$(a'' + b'') - (a + b) = \frac{2}{3} \lambda \quad (2)$$

$$(a''' + b''') - (a + b) = \frac{4}{3} \lambda, \text{ etc.} \quad (3)$$

From this it is seen that if OP , OQ , OR , etc., be taken as radii, and circumferences be drawn in the transverse plane, we will have a central circle and concentric rings around it so related that for every point in the circle whose radius is OP there is a point in the adjacent ring whose width is PQ , the effect of which is to produce complete interference; and one in the alternate ring whose width is QR , the effect of which is to produce complete accordance.

$OP = r'$; $OQ = r''$; $OR = r'''$; $\lambda = \text{wave length.}$

FIG. 2.

Let the radii OP , OQ , OR , etc., be called r' , r'' , r''' , etc. Then

$$a'^2 = a^2 + r'^2, \therefore a' = (a^2 + r'^2)^{\frac{1}{2}} \quad (4)$$

$$b'^2 = b^2 + r'^2, \therefore b' = (b^2 + r'^2)^{\frac{1}{2}} \quad (5)$$

Expanding (4) and (5) by the binominal theorem, and rejecting all after the second term, since r' is small in comparison with a or b , we have, approximately,

$$a' = a + \frac{r'}{2a}$$

$$b' = b + \frac{r'}{2b}$$

In like manner,

$$a'' = a + \frac{r''}{2a}$$

$$b'' = b + \frac{r''}{2b}, \text{ etc.}$$

Substituting these values of a' and b' in equation (1), also of a'' and b'' in equation (2), etc., and reducing, we have

$$r'^2 = \frac{ab}{a+b} \lambda$$

$$r''^2 = \frac{ab}{a+b} 2\lambda$$

$$r'''^2 = \frac{ab}{a+b} 3\lambda$$

Or, if n represent the order of any zone whatever,

$$r_n^2 = \frac{ab}{a+b} n\lambda$$

If the position of the plane of zones be midway between A and B , this formula becomes

$$r_n^2 = \frac{1}{2} a n \lambda$$

The value of λ for any given whistle having been determined by the method of stationary waves just described, and that of a being selected at will, the successive values of r are found, and the corresponding circles drawn on cardboard or zinc. Leaving the central circle intact, the first, third, fifth, etc., rings are cut out. The diffractive effects of all the remaining alternate zones are therefore conjoined, and a flame at B flares now far more violently when the whistle is sounded than if no obstacle had been interposed. If the grating be slightly lifted so as to throw the axial line AB above the nozzle of the burner, the flame becomes quiescent. It was previously in a region of noise; it is now in a ring of silence that surrounds it. Lifting the grating a little higher, the flame flares again slightly; it is in a ring of noise. This is roughly shown in *Fig. 3*, which is an amplification of the left half of *Fig. 2*. It is seen that there are other points, C , D , etc., at which sound rays from the

diffractive centres P, Q, R , etc., may meet, though the conjoint effect may not be so strong as at B . The locus of C is obviously a circle around B as centre. The relative intensities of disturbance are shown by the black areas, as determined by the German physicist, Lommel. I have at times succeeded in tracing out four or five of these successive rings of noise and silence by the aid of the sensitive flame.

When light is transmitted through a pair of adjacent small apertures, diffraction fringes are produced. According to theory, as shown by Young and Fresnel,⁵ the locus of

FIG. 3.

At 1, 3 and 5, meeting of like phases.

At 2 and 4, etc., meeting of unlike phases.

1, central area of noise; 2 and 4, first two rings of silence; 3 and 5, first two rings of noise.

interference in space between aperture and screen is a hyperbola. By very delicate micrometric measurements Fresnel found the results of experiment to justify the prevision of theory. I have applied the sensitive flame in exploring for these hyperbolas when short sound waves were transmitted through a pair of openings in a screen of cardboard. The whistle, whose pitch was about 13,000, sent forth waves, therefore, of about 1.05 inch in length. It was placed thirty-four inches from the screen, whose width was two feet. Near the middle of this were cut two vertical

slits, three inches apart and one-quarter inch wide. The screen being at right angles to the line of direction of the whistle, and this line passing midway between the two slits, the position required by theory for the hyperbolic bands was determined. There was no difficulty in detecting the middle line of maximum motion behind the screen. The nearest hyperbolas on the two sides of this were then found and traced back about a foot. The definition of these was inferior to that of the middle line, as might naturally be expected. The next pair of hyperbolas was also found, but with poor definition.

Perhaps the most important experiment employed by Fresnel in the establishment of the wave theory of light was that of producing interference bands, independently of all diffracting edges, by reflecting the light from a pair

FIG. 4.

of mirrors making with each other an angle of very nearly 180° . The acoustic analogue of this has been performed by Prof. A. M. Mayer and myself together. Six interference bands were detected by means of the sensitive flame. Their distance apart was measured, and the result was found to accord very closely with that demanded by theory. On account of the trouble resulting from waves proceeding directly from the source of sound, or diffracted around the edges of a screen interposed to cut them off, this method of experiment was abandoned. A modification of the experiment was repeatedly tried by me, and with quite uniformly satisfactory results. A single mirror was placed horizontally on the table, so that waves reflected from it might interfere with those proceeding directly from whistle to flame. The effect of the reflected waves was the same as

if they had come from a virtual source, S' (Fig. 4), and the theory becomes then the same practically as that given on a previous page for the diffraction grating for light. Knowing λ , AM , and SM , and the distances AB , AC , AD , etc., at B , C , D , etc., there is complete accordance; or, the distance of the points of complete interference may be measured and the results of experiment compared with those of theory.

In the following table the results of some experiments are given. The height, MS , of whistle above table is ten inches; the distance AM , thirty-six inches; the wave length λ , 1.05 inch. Then

$$AB = \frac{AM}{SS'} \lambda$$

The successive measurements are of distances above the table at which the flame became quiescent. The first column is calculated from the formula; the others are the records from five sets of experiments.

THEORY.	I.	II.	III.	IV.	V.
.945	.9	1.0	.9	1.0	1.0
2.835	2.8	2.7	2.7	2.8	2.9
4.725	4.7	4.6	4.7	4.9	4.7
6.615	6.7	6.7	6.7	6.9	6.7
8.505	8.9	9.0	8.8	9.0	9.1
10.395	11.0	11.3	11.0	11.2	11.3
12.285	—	13.6	—	13.6	13.6

These results are sufficient to show that the sensitive flame makes it possible to exhibit before large audiences the demonstration of principles hitherto accepted as the result of calculation, or verified only by individual experiment. If not applicable for purposes of refined and exact measurement, it comes nearer to the fulfilment of these conditions than any other means that has hitherto been applied for these purposes in acoustics.