The very small difference between the two is of course accidental, as the measurements of the displacement of the images on which the experimental value of v was founded could not be trusted to anything like 5 per cent.

The action of a magnetic force in deflecting these rays shows, assuming that the deflexion is due to the action of a magnet on a moving electrified body, that the velocity of the atom must be at least of the order we have found.

Consider an atom projected parallel to the axis of the tube which is situated in a uniform field of magnetic force, the lines of magnetic force being at right angles to the axis of the tube. Let H be the intensity of the magnetic force. Then, if m is the mass of the atom, v its velocity, and ρ the radius of curvature of its path, we have

$$\frac{mv^2}{\rho} = \mathrm{H}ev,$$

where e is the charge on the atom; since e/m for hydrogen is 10^4, we have

$$v = \rho \mathrm{H} \times 10^4.$$

I cannot find any quantitative experiments on the deflexion of these rays by a magnet; but ordinary observation shows that it would require a strong magnetic field to make ρ as small as 10 centim., which would mean clearing the tube of phosphorescence except within about 10 centim. of the cathode. If v were 2×10^7, this would give $\mathrm{H} = 200$, which is not extravagant.

XLI. *On the Amplitude of Aerial Waves which are but just Audible.* *By* Lord Rayleigh, *Sec. R.S.**

THE problem of determining the absolute value of the amplitude, or particle velocity, of a sound which is but just audible to the ear, is one of considerable difficulty. In a short paper published seventeen years ago† I explained a method by which it was easy to demonstrate a superior limit. A whistle, blown under given conditions, consumes a known amount of energy per second. Upon the assumption that the whole of this energy is converted into sound, that the sound is conveyed without loss, and that it is uniformly distributed over the surface of a hemisphere, it is easy to calculate the amplitude at any distance; and the result is necessarily a superior limit to the actual amplitude. In the case

* Read at the Oxford Meeting of the British Association. Communicated by the Author.

† Proc. Roy. Soc. vol. xxvi. p. 248 (1878).

of the whistle experimented on, of frequency 2730, the superior limit so arrived at for a sound just easily audible was $8{\cdot}1\times10^{-8}$ cm. The maximum particle velocity v and the maximum condensation s are the quantities more immediately determined by the observations, and they are related by the well-known equation $v=as$, in which a denotes the velocity of propagation. In the experiment above referred to the superior limit for v was ·0014 cm. per second, and that for s was $4{\cdot}1\times10^{-8}$. I estimated that on a still night an amplitude, or velocity, one tenth of the above would probably be audible. A very similar number has been arrived at by Wien*, who used an entirely different method†.

In connexion with calculations respecting the sensitiveness of telephones, I was desirous of checking the above estimates, and made some attempts to do so by the former method. In order to avoid possible complications of atmospheric refraction which may occur when large distances are in question, I sought to construct pipes which should generate sound of given pitch upon a much smaller scale, but with the usual economy of wind. In this I did not succeed, and it seems as if there is some obstacle to the desired reduction of scale.

The experiments here to be recorded were conducted with tuning-forks. A fork of known dimensions, vibrating with a known amplitude, may be regarded as a store of energy of which the amount may readily be calculated. This energy is gradually consumed by internal friction and by generation of sound. When a resonator is employed the latter element is the more important, and in some cases we may regard the dying down of the amplitude as sufficiently accounted for by the emission of sound. Adopting this view for the present, we may deduce the rate of emission of sonorous energy from the observed amplitude of the fork at the moment in question and from the rate at which the amplitude decreases. Thus if the law of decrease be $e^{-\frac{1}{2}kt}$ for the amplitude of the fork, or e^{-kt} for the energy, and if E be the total energy at time t, the rate at which energy is emitted at that time is $-d\mathrm{E}/dt$, or $k\mathrm{E}$. The value of k is deducible from observations of the rate of decay, *e. g.* of the time during which the amplitude is halved. With these arrangements there is no

* Wied. *Ann.* xxxvi. p. 834 (1889).

† The first estimate of the amplitude of but just audible sounds, with which I have only recently become acquainted, is that of Toepler and Boltzmann (Pogg. *Ann.* cxli. p. 321 (1870)). It depends upon an ingenious application of v. Helmholtz's theory of the open organ-pipe to data relating to the maximum condensation within the pipe as obtained by the authors experimentally. The value of s was found to be $6{\cdot}5\times10^{-8}$ for a pitch of 181.—August 21.

difficulty in converting energy into sound upon a small scale, and thus in reducing the distance of audibility to such a figure as 30 metres. Under these circumstances the observations are much more manageable than when the operators are separated by half a mile, and there is no reason to fear disturbance from atmospheric refraction.

The fork is mounted upon a stand to which is also firmly attached the observing-microscope. Suitable points of light are obtained from starch grains, and the line of light into which each point is extended by the vibration is determined with the aid of an eyepiece-micrometer. Each division of the micrometer-scale represents ·001 centim. The resonator, when in use, is situated in the position of maximum effect, with its mouth under the free ends of the vibrating prongs.

The course of an experiment was as follows :—In the first place the rates of dying down were observed, with and without the resonator, the stand being situated upon the ground in the middle of a lawn. The fork was set in vibration with a bow, and the time required for the double amplitude to fall to half its original value was determined. Thus in the case of a fork of frequency 256, the time during which the vibration fell from 20 micrometer-divisions to 10 micrometer-divisions was 16^s without the resonator, and 9^s when the resonator was in position. These times of halving were, as far as could be observed, independent of the initial amplitude. To determine the minimum audible, one observer (myself) took up a position 30 yards (27·4 metres) from the fork, and a second (Mr. Gordon) communicated a large vibration to the fork. At the moment when the double amplitude measured 20 micrometer-divisions the second observer gave a signal, and immediately afterwards withdrew to a distance. The business of the first observer was to estimate for how many seconds after the signal the sound still remained audible. In the case referred to the time was 12^s. When the distance was reduced to 15 yards (13·7 metres), an initial double amplitude of 10 micrometer-divisions was audible for almost exactly the same time.

These estimates of audibility are not made without some difficulty. There are usually 2 or 3 seconds during which the observer is in doubt whether he hears or only imagines, and different individuals decide the question in opposite ways. There is also of course room for a real difference of hearing, but this has not obtruded itself much. A given observer on a given day will often agree with himself surprisingly well, but the accuracy thus suggested is, I think, illusory. Much depends upon freedom from disturbing noises. The wind

in the trees or the twittering of birds embarrasses the observer, and interferes more or less with the accuracy of results.

The equality of emission of sound in various horizontal directions was tested, but no difference could be found. The sound issues almost entirely from the resonator, and this may be expected to act as a simple source.

When the time of audibility is regarded as known, it is easy to deduce the amplitude of the vibration of the fork at the moment when the sound ceases to impress the observer. From this the rate of emission of sonorous energy and the amplitude of the aerial vibration as it reaches the observer are to be calculated.

The first step in the calculation is the expression of the total energy of the fork as a function of the amplitude of vibration measured at the extremity of one of the prongs. This problem is considered in § 164 of my 'Theory of Sound.' If l be the length, ρ the density, and ω the sectional area of a rod damped at one end and free at the other, the kinetic energy T is connected with the displacement η at the free end by the equation (10)

$$T = \tfrac{1}{8}\rho l\omega(d\eta/dt)^2.$$

At the moment of passage through the position of equilibrium $\eta = 0$ and $d\eta/dt$ has its maximum value, the whole energy being then kinetic. The maximum value of $d\eta/dt$ is connected with the maximum value of η by the equation

$$(d\eta/dt)_{\text{max.}} = 2\pi/\tau \,.\, (\eta)_{\text{max.}};$$

so that if we now denote the double amplitude by 2η, the whole energy of the vibrating bar is

$$\tfrac{1}{8}\rho\omega l\pi^2/\tau^2 \,.\, (2\eta)^2,$$

or for the two bars composing the fork

$$E = \tfrac{1}{4}\rho\omega l\pi^2/\tau^2 \,.\, (2\eta)^2, \quad . \quad . \quad . \quad . \quad . \quad (A)$$

where $\rho\omega l$ is the mass of each prong.

The application of (A) to the 256-fork, vibrating with a double amplitude of 20 micrometer-divisions, is as follows. We have

$$l = 14{\cdot}0 \text{ cm.}, \qquad \omega = {\cdot}6 \times 1{\cdot}1 = {\cdot}66 \text{ sq. cm.},$$

$$1/\tau = 256, \qquad \rho = 7{\cdot}8, \qquad 2\eta = {\cdot}050 \text{ cm.};$$

and thus

$$E = 4{\cdot}06 \times 10^3 \text{ ergs.}$$

This is the whole energy of the fork when the actual double amplitude at the ends of the prongs is ·050 centim.

As has already been shown, the energy lost per second is kE, if the amplitude vary as $e^{-\frac{1}{2}kt}$. For the present purpose k must be regarded as made up of two parts, one k_1 representing the dissipation which occurs in the absence of the resonator, the other k_2 due to the resonator. It is the latter part only which is effective towards the production of sound. For when the resonator is out of use the fork is practically silent; and, indeed, even if it were worth while to make a correction on account of the residual sound, its phase would only accidentally agree with that of the sound issuing from the resonator.

The values of k_1 and k are conveniently derived from the times, t_1 and t, during which the amplitude falls to *one half*. Thus

$$k=2\log_e 2\,./t, \quad k_1=2\log_e 2\,./t_1\,;$$

so that

$$k_2=2\log_e 2\,.\,(1/t-1/t_1)=1{\cdot}386\,(1/t-1/t_1).$$

And the energy converted into sound per second is k_2E.

We may now apply these formulæ to the case, already quoted, of the 256-fork, for which $t=9$, $t_1=16$. Thus t_2, the time which would be occupied in halving the amplitude were the dissipation due entirely to the resonator, is 20·6; and $k_2=$·0674. Accordingly,

$$k_2\mathrm{E}=267 \text{ ergs per second,}$$

corresponding to a double amplitude represented by 20 micrometer-divisions. In the experiment quoted the duration of audibility was 12 seconds, during which the amplitude would fall in the ratio $2^{12/9}:1$, and the energy in the ratio $4^{12/9}:1$. Hence at the moment when the sound was just becoming inaudible the energy emitted as sound was 42·1 ergs per second*.

The question now remains, What is the corresponding amplitude or condensation in the progressive aerial waves at 27·4 metres from the source? If we suppose, as in my former

* It is of interest to compare with the energy-emission of a source of light. An incandescent electric-lamp of 200 candles absorbs about a horse-power, or say 10^{10} ergs per second. Of the total radiation only about $\frac{1}{100}$ part acts effectively upon the eye; so that radiation of suitable quality consuming 5×10^5 ergs per second corresponds to a candle-power. This is about 10^4 times that emitted as sound by the fork in the experiment described above. At a distance of $10^2\times30$, or 3000 metres the stream of energy from the ideal candle would be about equal to the stream of energy just audible to the ear. It appears that the streams of energy required to influence the eye and the ear are of the same order of magnitude, a conclusion already drawn by Toepler and Boltzmann. —August 21.

calculations, that the ground reflects well, we are to treat the waves as hemispherical. On the whole this seems to be the best supposition to make, although the reflexion is doubtless imperfect. The area S covered at the distance of the observer is thus $2\pi \times 2740^2$ sq. centim., and since *

$$S \cdot \tfrac{1}{2}a\rho v^2 = S \cdot \tfrac{1}{2}\rho a^3 s^2 = 42{\cdot}1,$$

we find

$$s^2 = \frac{42{\cdot}1}{\pi \times 2740^2 \times {\cdot}00125 \times 34100^3},$$

and

$$s = 6{\cdot}0 \times 10^{-9}.$$

The condensation s is here reckoned in atmospheres; and the result shows that the ear is able to recognize the addition and subtraction of densities far less than those to be found in our highest vacua.

The amplitude of aerial vibration is given by $as\tau/2\pi$, where $1/\tau = 256$, and is thus equal to $1{\cdot}27 \times 10^{-7}$ cm.

It is to be observed that the numbers thus obtained are still somewhat of the nature of superior limits, for they depend upon the assumption that all the dissipation *due to the resonator* represents production of sound. This may not be strictly the case even with the moderate amplitudes here in question, but the uncertainty under this head is far less than in the case of resonators or organ-pipes caused to speak by wind. From the nature of the calculation by which the amplitude or condensation in the aerial waves is deduced, a considerable loss of energy does not largely influence the final numbers.

Similar experiments have been tried at various times with forks of pitch 384 and 512. The results were not quite so accordant as was at first hoped might be the case, but they suffice to fix with some approximation the condensation necessary for audibility. The mean results are as follows :—

c', frequency $= 256$, $s = 6{\cdot}0 \times 10^{-9}$,

g', „ $= 384$, $s = 4{\cdot}6 \times 10^{-9}$,

c'', „ $= 512$, $s = 4{\cdot}6 \times 10^{-9}$,

no reliable distinction appearing between the two last numbers. Even the distinction between 6·0 and 4·6 should be accepted with reserve; so that the comparison must not be taken to prove much more than that the condensation necessary for audibility varies but slowly in the singly dashed octave.

* 'Theory of Sound,' § 245.

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"Nec aranearum sane textus ideo melior quia ex se fila gignunt, nec noster vilior quia ex alienis libamus ut apes." JUST. LIPS. *Polit.* lib. i. cap. 1. Not.

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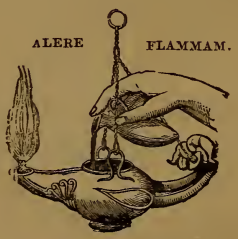
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"Meditationis est perscrutari occulta; contemplationis est admirari perspicua .... Admiratio generat quæstionem, quæstio investigationem, investigatio inventionem."—*Hugo de S. Victore.*

——"Cur spirent venti, cur terra dehiscat,
Cur mare turgescat, pelago cur tantus amaror,
Cur caput obscura Phœbus ferrugine condat,
Quid toties diros cogat flagrare cometas,
Quid pariat nubes, veniant cur fulmina cœlo,
Quo micet igne Iris, superos quis conciat orbes
Tam vario motu."

J. B. Pinelli ad Mazonium.



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