XV. *Aberration Problems.—A Discussion concerning the Motion of the Ether near the Earth, and concerning the Connexion between Ether and Gross Matter; with some new Experiments.*

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Received and Read March 31, 1892.—Revised July 17, 1893.

[PLATES 31, 32.]

TABLE OF CONTENTS.

25.10.93

Experimental Portion.

More detailed consideration of Aberrational Effects in Moving Medium.

More detailed consideration of Doppler Effects.

More detailed consideration of Michelson Experiment or Interference Effects in Moving Medium.

The Laws of Reflexion and Refraction in a Moving Medium.

1. THE nature of the connexion between ether and gross matter is one of the most striking physical problems which now appear ripe for solution, and as a preliminary to the undertaking of fresh experiments I propose to review the subject in order to realize our present position in connexion with it.

The subject may be attacked either optically or electrically. It first prominently presented itself historically in connexion with the earth's motion through space and the finite velocity of light; and it will be convenient to consider the matter first on this side, and to realize precisely what ought to be expected to happen on any simple hypothesis concerning the ether; working it out, however, in most cases with accuracy,* and by no means ignoring as negligible small quantities of the second order (hundred-millionths), which MICHELSON has practically shown to be nowadays within the limits of highly-refined observation.

Necessary Hypotheses or Postulates.

2. There are one or two hypotheses regarding the ether so elementally obvious that they may be regarded as almost axiomatic, such as the following :—

(i.) *In interstellar space the ether is free;* that is, its properties in no way depend on the existence or motion of gross matter. It may, therefore, be called at rest. Whether it is in absolute rest or not appears to be a question which can hardly be put into an intelligible shape. If it be moving relatively to itself, we have in those regions no obvious means of ascertaining the fact. But just as it is natural to assume that its properties in free space are uniform, so it is natural to assume that its motion there, whatever it is, is perfectly uniform, and it may be *defined* as absolute rest. When I speak of the ether anywhere as "stationary," I mean stationary with respect

* Whenever equations are approximate only, the symbol $\approx$ is used instead of the symbol $=$.

to interstellar or free ether. When I speak of the ether anywhere as "free," I mean that its properties are identical with the interstellar ether enormously distant from all gross matter. And this is the condition of ordinary space, except for the presence of meteoric particles, whose influence, if any, we at present legitimately ignore.

The only hypothesis which at first sight *appears* to assume infinitely distant ether to be affected by the motion of, say, the earth, is that of Sir GEORGE STOKES, in 1845, where an irrotational motion, zero with respect to the earth, was postulated for it. But he must have seen some way in which so impossible an assumption could be avoided ; and the question how far any kind of irrotational motion can be conceived of as allowing rest at infinity, and yet no slip at the earth's surface, will be discussed later, § 31.

(ii.) *Inside material bodies the ether is modified.*—We learn this by direct experiment and observation.

For transparent bodies we learn it by optical experiments, which proves that light travels more slowly through their modified ether than it does in free ether ; while at the same time there is no doubt but that the ether inter-penetrates them, because material substance itself is wholly incompetent to transmit anything possessing the properties and the speed of radiation.

In metallic bodies we find great opacity combined with anomalous dispersion and other complex effects. In them evidently the ether is intensely modified, if it exists at all.

I shall call the ether inside gross matter of any kind "modified ether," but as to the particular way it is modified I make no assumption. [Electrostatic experiments *suggest* that inside transparent bodies, something which may be called its "virtual elasticity" is diminished. Magnetic experiments suggest that inside several opaque substances it is loaded, so as to increase what may be called its "virtual density ;" and there is a temptation to identify $4\pi/K$ with the one, and $4\pi\mu$ with the other, of these two ethereal constants. Further, electrokinetic experiments suggest that inside metallic conductors the ether has a virtual viscosity, whereby its motion through matter is resisted precisely as the first power of the velocity. But none of these doubtful hypotheses shall here be obtruded.]

Rate of Travel of "Modified" Ether.

3. Defined in this way it is quite obvious that "modified ether" travels at the same steady pace as its material encasement. For lift a lump of glass or of copper from one side of a table to the other, the modified ether which was in one place is now in another, and has necessarily accompanied the material body. If the modification of ether by matter requires time, there would be some lag during epochs of acceleration ; but during steady velocity there would even so be no difference in speed between modified ether and matter, only a slight lag in space.

Ignoring this possible finite speed of affection of ether by matter, unless circumstances make us revert to it, the question faces us, what is meant by the travelling of the modified ether?

It is not a question easy to state without some looseness of language, but we may ask:

(*a*) Does it mean that the identical stuff inside the matter travels from one place to the other? If so, the free ether which it has displaced must stream back round the body in the same way as a material fluid would have to do.

(*b*) Or does it mean that no ether travels at all, that the mere presence of the matter causes the modification wherever it is, so that it is only the modification or affection which travels? If so, the ether abandoned by the matter becomes free *in situ*, while the ether encroached on by the matter becomes modified *in situ*, and there is no question as to its motion.

On hypothesis (*b*) the whole ether is fixed and imperturbable by the motion of matter. The portion enshrouded by matter at any instant has properties differing from those of free ether, but the modification is only connected with the matter causing it in the same sort of way as a shadow is connected with the object casting it.

Of the two hypotheses, there can be no question but that the second is the simpler and considered as a hypothesis is preferable, but we must enquire whether it is competent to sustain the weight of all known facts.

FRESNEL'S *Hypothesis.*

4. It is notorious that the hypothesis at present holding the field is not exactly either of these, but is some form of the bold and picturesque idea of FRESNEL; viz., that in addition to the free and undisturbed ether of space existing equally everywhere and flowing through the pores of gross matter, there is an extra quantity of bound ether fixed to the matter and travelling with it; this additional quantity being $(1 - 1/n^2)^{\text{th}}$ of the whole.

This idea of FRESNEL'S seems, at first sight, essentially to involve the condensation of ether by matter, so that its density inside bodies is n^2; for the fixed ether is superposed upon the normal ether of space. (Certainly the converse is true; viz., that extra ethereal density involves FRESNEL'S law, as will be shortly shown.)

Now the facts of gravitation, and many electrostatic experiments, suggest that the ether is practically incompressible; hence the notion of any actual increase of density inside gross matter is repugnant.

FRESNEL, however, himself pointed out, in a subsequently written postscript to his original letter to ARAGO* promulgating his famous hypothesis, that the extra density need not be taken too literally. (As this postscript seems rather to have been overlooked it may be worth while to quote it).

"*Note additionnelle à la lettre de* M. FRESNEL *à* M. ARAGO, *insérée dans le dernier Cahier des Annales.*

En calculant la réfraction de la lumière dans un prisme entraîné par le mouvement terrestre, j'ai supposé, pour simplifier les raisonnements, que la différence entre les vitesses de la lumière dans le prisme

* 'Ann de Chim. et de Phys.' (2), vol. 9, p. 56.

et dans l'éther environnant provenait uniquement d'une différence de densité, l'élasticité étant la même de part et d'autre ; mais il est très possible que les deux milieux diffèrent en élasticité comme en densité. On conçoit même que l'élasticité d'un corps solide peut varier avec le sens suivant lequel on le considère ; et c'est très probablement ce qui occasionne la double réfraction, comme l'a observé le Dr. YOUNG. Mais quelle que soit l'hypothèse que l'on fasse sur les causes du ralentissement de la marche de lumière dans les corps transparents, on peut toujours, pour résoudre le problème qui m'était proposé, substituer par la pensée, au milieu réel du prisme, un fluide élastique en équilibre de tension avec l'éther environnant, et d'une densité telle que la vitesse de la lumière soit précisément la même dans ce fluide et dans le prisme supposés en repos ; cette égalité devra subsister encore dans les deux milieux entraînés par le mouvement terrestre : or, telles sont les bases sur lesquelles repose mon calcul."—('Ann. de Chim. et de Phys.,' 1818, t. 9, p. 128 or 286.)

And Mr. GLAZEBROOK ('Phil. Mag.,' December, 1888) shows that in the interaction of ether and matter, a term depending on relative acceleration is sufficient to sustain the results achieved by FRESNEL's hypothesis. In other words, that a *virtual* density, or loading of the ether by matter, is quite enough without true condensation.

It is, however, still appropriate to speak of the extra ethereal density inside matter; meaning the coefficient of this acceleration term.

5. A plausible mode of exhibiting the naturalness of FRESNEL's law is as follows :—

The constant which determines the speed of electromagnetic waves through any medium is μK ; by the differential equation to wave motion.

In a dense body the value of this constant is $\mu' K'$.

Shift a lump of this body from one place to another. Its constant $\mu' K'$ has been shifted in position too, but the ordinary space-value μK remains behind ; so the resultant shift of the property determining the velocity of light (the effective medium) is a fraction $(\mu' K' - \mu K)/\mu' K'$, of the shift of the body.

So, if the lump moves with velocity u, the property of it concerned with the velocity of light shifts with velocity $(\mu' K' - \mu K)/(\mu' K').u$; that is with speed $(1 - 1/n^2)u$.

And, as in all probability the velocity of wave motion *relative to its medium* is unaltered, this may be taken as the extra speed of the light caused by the motion of the matter.

6. It is here assumed that the medium simply carries the wave motion with it as air carries sound. It is not customary to doubt that wave motion must be affected by any motion of its medium in that simple manner. But a singular investigation by Professor J. J. THOMSON ('Phil. Mag.,' April, 1880) seems to show that on electromagnetic principles the speed of ether waves is affected with only *half* the velocity of the medium conveying them.

This extraordinary result is not at present positively contradicted by the FIZEAU experiment, even as repeated by MICHELSON, because the value of $1 - 1/n^2$ for water is not sufficiently different from $\frac{1}{2}$ to afford a certain criterion ; and water is the only substance for which a positive result has as yet been obtained. Certainly the negative result obtained for *air* by both FIZEAU and MICHELSON is in accord with FRESNEL's theory and not in accord with J. J. THOMSON's. But a definition of what is meant by "moving medium" seems necessary before we can adequately test the question whether electromagnetic waves in it move with it or lag behind.

I suppose that it must be desirable to examine substances other than water, especially those with a much higher refractive index. I hope to do this, though it may be noted that the value of n which would make FRESNEL'S and THOMSON'S theories *exactly* agree, is 1·4142, and that the available range of refractive indices of liquids and solids affords but a narrow margin for discrimination between the two hypotheses.

The balance of evidence is at present strongly in favour of FRESNEL'S hypothesis, and I propose ordinarily to assume its truth. I cannot, indeed, understand the possibility of THOMSON'S theory, though I detect no flaw in his work, for it seems to require a distinction between the case of source or receiver moving through a medium, and the case of medium flowing past source or receiver; that is, it seems to demand a knowledge of *absolute* velocity.

FRESNEL'S *Law*.

7. The statement of FRESNEL'S law can be thrown almost into the form of hypothesis (b), § 3, and at the same time its apparent licence of language about "free" and "bound" ether can be lessened, by supposing that the "modification" induced by the encroachment of matter on the ether is really a condensation, in the ratio $1 : n^2$; no motion in the ether other than what is necessarily involved in that act being postulated. On this method of statement the ether outside a moving body is absolutely stationary, but, as the body advances, ether is continually condensing in front, and, as it were, evaporating behind, while inside it is streaming through the body in its condensed condition at a pace such that what is equivalent to the normal quantity of ether in space may remain absolutely stationary. To this end its speed relatively to the body must be v/n^2, and accordingly its speed in space must be $v(1 - 1/n^2)$.

Thus, instead of saying that a portion of the ether is moving with the full velocity of the body while the rest is stationary, it is probably preferable to say that the whole internal ether is moving with a fraction of the velocity of the body.

One or other form of statement is absolutely involved in the Fresnellian idea of increased ethereal density, as may be rigorously shown (*vide* Lord RAYLEIGH, 'Nature,' March, 1892; *vide* also EISENLOHR), thus:—

Consider a slab moving forward flatways with velocity v, let its internal ethereal density be n^2, and let the external ether, of density 1, be stationary. Let the speed of the internal ether *through space* be xv, and consider that the amount of ether enclosed between two planes moving with the slab, one outside and one inside, must be constant; it follows at once that

$$v = n^2 (v - xv)$$

whence

$$x = 1 - \frac{1}{n^2}.$$

Now whatever may be the inner meaning of this statement concerning the velocity of the internal ether, it certainly agrees with, and is at once suggested by, the fact, thoroughly established by both negative and positive experiments, that light travels down a running stream of matter at a pace

$$\frac{V}{n} + v\left(1 - \frac{1}{n^2}\right).$$

The negative experiments supporting this are such as the achromatic prism experiment suggested and tried by ARAGO, repeated more elaborately by MAXWELL and by MASCART; the water-telescope observations suggested by BOSCOVICH, tried by AIRY and by HOEK; interference experiments of BABINET and of HOEK; and several other experiments by MASCART. The positive experiment establishing it is the very beautiful and well-known one of FIZEAU, now repeated and confirmed beyond the reach of any but quantitative cavil by MICHELSON.*

Whether any ether is moved by moving matter may still be an open question, but that the speed of light is affected in a fairly ascertained way by the motion of transparent matter through which it is passing, is certain.

8. But the specific motion of the internal ether is not the whole of FRESNEL's hypothesis; there is the fixity of the external ether to be verified too. And that has not yet been done. In fact, one important experiment, to be discussed later on, throws grave doubt upon it, at least for large moving bodies like the earth.

But unless the fixity of external ether be granted, our argument from density concerning the value of the internal velocity breaks down. Consider again two planes moving with a slab of matter, one inside and one outside the mass, and let the space motion of the outside ether at the position of outside plane be affected by the motion of the slab to the extent yv, then all we can say is that

$$v - yv = n^2 (v - xv),$$

or,

$$x = 1 - \frac{1 - y}{n^2},$$

wherefore it is possible for x and y to be unity together.

We may take it, however, that the quantitative accuracy of the FIZEAU experiment renders anything of this sort very unlikely, and that we are bound to suppose the ether immediately outside moving matter to be stationary, *i.e.*, to be completely unaffected by its motion, unless we are directly forced by facts to admit the contrary.

* 'Amer. J. Sci.,' vol. 31, p. 377.

The two parts of FRESNEL's law, the motion of internal ether, and the fixity of external ether, can and ought to be verified separately. The FIZEAU experiment has verified the one. I propose to attempt the other. To this end I am passing a beam of light, split into two equal halves, very near a rapidly rotating disk (in fact between a pair of rotating disks clamped together), so that one half the light travels with the mechanical motion and the other half travels against it. The two half beams, after several journeys round and round, are united, with interference effects, and the observation consists in watching the system of bands for any shift caused by the motion. For description of this experiment see §§ 33–47 below.

Phenomena Resulting from Motion of Source, Receiver, or Medium.

9. The phenomena which can be appealed to as evidence of a state of motion, and which necessarily result from that motion if of a suitable kind, are four, viz.:—

(1) Changes or apparent changes in direction of ray, as observed by telescope with cross-wires; the change commonly called "aberration" proper.

(2) Changes or apparent changes in frequency of vibration, as observed by the pitch or colour appreciated by an observer, or by the shifted position of lines in a spectroscope; a change which may be referred to as the Doppler effect.

(3) Changes or apparent changes in the time taken over a fixed journey, as observed by the relative lag in phase between two portions of a split beam and the consequent shift of interference fringes when they are re-united.

(4) Changes or apparent changes in the intensity of radiation in different directions, as observed by the amount of energy received by a given area exposed normal to the rays at a given distance from a source, but having different aspects with respect to the line of motion.

Or, briefly summarizing them, the possible phenomena caused by motion are changes in direction, in period, in phase, and in amplitude.

Apparent Direction as Affected by Motion in General.

10. Consider the subject first from a corpuscular or projectile point of view, first ignoring the medium. A gun travelling broadside on must be aimed behind the object, and its shot will travel in a skew direction (keeping always straight in front of the muzzle, but not travelling along the axis of the gun) with a velocity compounded of the speed of projection and the speed of the gun. The apparent position of the source, as recognized through a hole in the target, will therefore be its true position at time of firing, but not its position at time of hit.

Whether we choose to call this an aberration or not is a matter of nomenclature merely.

If the gun is fixed, with the target moving across the line of fire, the gun must be aimed in front of the object. The shot will go straight along the barrel produced, but the hole in the target will indicate a gun in front of its true position; this error being aberration proper.

Fig. 1.

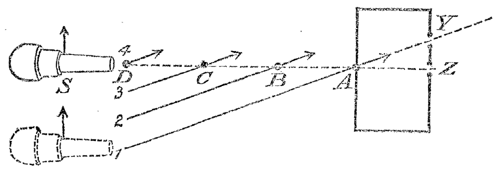


Diagram of shot fired from a moving cannon; piercing a target, at Y if stationary, at Z if moving at same pace as gun. ABCD is the locus of successive shots, but is not the line of fire.

If both gun and target are travelling at the same speed everything occurs as if they were at rest, unless a stagnant medium has to be taken into account. Relative motion of the medium causes windage, as is well known.

Since motion of the medium causes a shift of the line of fire, it may be expected to produce a miss, but this is not a true aberration, it only appears to be such because of the fire being limited to one line; suppose instead of a single gun a broadside of guns or a number of guns firing from a turret, then the effect of a cross-wind is, indeed, to displace all the shots, but not to prevent the target being hit by one which would otherwise have missed it, and the hole in the target will indicate the position of the gun really firing the shot.* Hence, even on a corpuscular theory, a wind across the line joining source and receiver, will not cause any effective aberration. Neither can a steady tail wind deliver a stream of bullets from a machine-gun more frequently than they are emitted.

If guns are fired from a revolving turret, the paths of the shot will not be radial, but will be skewed by an amount depending upon the peripheral velocity.

Watching the beams of a revolving lighthouse, tracking their way to a distance and brandished rapidly round, it is not at once quite evident whether the shape of those beams is not a spiral of enormous pitch (see below). We see, however, that on the corpuscular view the paths will be straight, though not radiating from the precise centre; for instance, the rays from the Sun, whose peripheral velocity is nearly 5000 miles an hour, would if regarded as projectiles, be inclined to their radius at an angle of $\frac{5}{186 \times 3600}$ radian, or about $1\frac{1}{2}$ seconds of arc; and the Sun's centre would be, apparently displaced through a fraction of this angle, equal to Sun's radius/Sun's distance; *i.e.*, through about the $\frac{1}{150}$th part of a second.

11. But now, proceeding to look at the matter from the point of view of waves, there are many differences; principally depending on the fact that there is no question of initial velocity of projection about a wave: it crawls through the medium,

* As these projectile examples are only used for illustration, I simplify matters artificially by omitting all curvatures of path. The subject of aberration in general is illustrated more fully in a Royal Institution Lecture, 'Proc. R. I.,' April 1, 1892; also reported in 'Nature,' vol. 46, p. 497.

self-propelled, at its own definite velocity. No aberrational effect can be produced by any cause which does not act on a wave-front for a finite time.

Fig. 2.

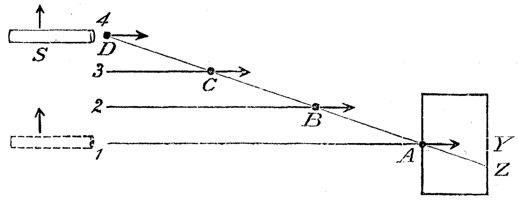


Diagram of disturbances or waves emitted without momentum from a moving source; leaving target or telescope, at Y if stationary, at Z if moving. The line ABCD is the locus of successive disturbances, but is not the ray or real path. The diagram may also be taken to represent the effect of a cross stream of medium, with source stationary.

Hence waves emitted by a revolving source advance just as they would if it were stationary; any peculiarity on the surface, say a Sun spot, is depicted in a precisely radial direction, and there will be no displacement of the Sun's centre. So also with light from a flying star: the star will be seen in its position at time of emission, just as it is seen in the physical state corresponding to that instant, not to the instant of vision.

Fig. 3.

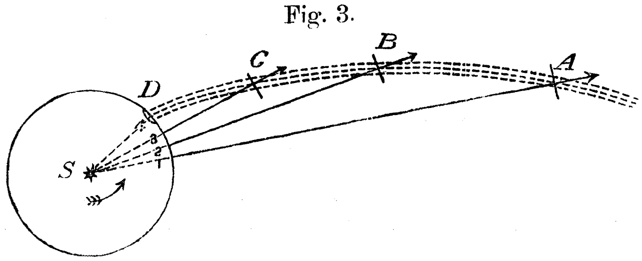


Diagram of parallel beams emitted from a revolving lighthouse. ABCD is the apparent beam, but AS, BS, &c., are the lines of vision or true rays.

As to a beam from a revolving lighthouse, it is not the path of a labelled disturbance, or true ray, which displays itself by illuminating dust particles, but it is the locus of successive disturbances sent out from a given moving point; so if the source has revolved through an angle θ while the light travels a distance r, $\theta = (\omega/V)\,r$, and their shape *is* a spiral of ARCHIMEDES as suspected above; though the direction of vision is not tangential to them, but is truly radial as already stated.

The analogy between rays of light and lines of force is fairly close, and just as it is convenient to say that a rotating source revolves its rays, so it is convenient to say that a rotating magnet revolves its lines of force. The induction phenomena obtained from a magnet spinning on its own axis are a sufficient justification of this statement.*

In an old note-book of date 1876, I find a suggestion for measuring the speed of magnetic propagation, by rotating a long bar magnet on its axis and observing its action on a distant magnetic needle;

* See also Mr. TOLVER PRESTON, 'Phil. Mag.,' February and March, 1885.

the idea being that with a finite speed of propagation the lines of force would lag, and thereby acquire a curvature out of the magnet's meridian; so that a distant needle instead of pointing straight at the magnet would be tangential to these lines, and would therefore be slightly deflected during the spin.

We now see, however, that no such aberrational effect is to be expected, except on a corpuscular view of magnetic propagation.

Concerning the effect of motion of other kinds, certain things are experimentally known; *e.g.*, motion of the receiver is known to cause aberration, however the fact be precisely accounted for; and motion of the medium alone is known not to cause aberration of any perceptible magnitude, else would terrestrial surveying operations be inaccurate. But no experimental data as yet obtained are evidence concerning small quantities of the second order, and it will be well to examine critically and geometrically the whole subject of wave motion from a moving point to a moving telescope through a uniformly moving medium, all the velocities being possibly different in magnitude and direction. So far as steady and uniform motion is concerned this may be considered the most general case.

Convenience of attributing Relative Motion to Medium.

12. Before considering separately the phenomena mentioned in § 9, it may be convenient to consider what it is which must be in motion in order to produce one or other of them. And, first, which of them a motion of the medium alone causes.

Nothing can be more certain than that relative motion is all we are concerned with, so that whether a source travels through a medium, or the medium drifts past the source, comes to precisely the same thing. Sometimes one mode of expression is convenient, sometimes the other. It may be most natural to contemplate the medium as stationary, and to throw all motion on source and receiver, but I find that it is often very simple and helpful to invert this order, and to think of the ether of space as drifting past the earth, or other body, supposed stationary.

We shall not invariably use this device, but whenever a number of things—source, mirrors, telescope, and observer—have to be thought of as moving all precisely alike through the ether, it is simpler to think of the ether as streaming past them.

Case of Fixed Source in Moving Medium.

13. Consider now a fixed point-source in a uniformly moving medium.

Spherical wave-fronts are thrown off and immediately begin to drift, so that their centres get displaced a distance, vt, while their radii enlarge by an amount, Vt; and the distance through space which a disturbance has by that time travelled in the direction θ will be compounded of these two distances, and will be inclined to the radius, or direction of travel if all were stationary, by an angle ϵ, which may be called the aberration angle. The velocity with which light journeys over the radius vector, r, is

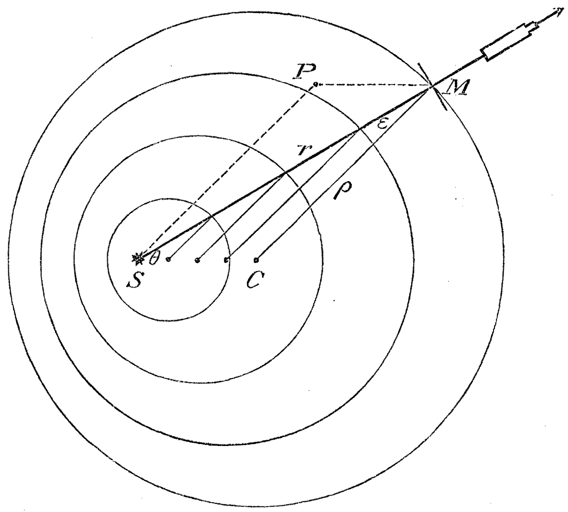
$$V \cos \epsilon + v \cos \theta, = V_1 \text{ say}:$$

the time of the journey being simply t, as before.

The angle ϵ is defined by the equally obvious geometrical relation

$$V \sin \epsilon - v \sin \theta = 0.$$

Fig. 4.



Successive waves emitted by a fixed source S into a drifting medium. The row of dots SC represent the respective wave-centres. The figure also represents waves in a stationary medium, emitted by a source moving from C to S.

Here is a picture of the source and successively-emitted and abandoned drifting wave-fronts. SM is the path of a labelled disturbance, and is to be considered as a ray; it is inclined at angle ϵ to the corresponding wave-normals.

SP is what would have been the light journey in the same time if the medium had been stationary; PM or SC represents the drift.

The result of the state of things exhibited in the diagram may or may not be appreciated by a spectator—that depends on what his own motion is,—but if he is moving simply with the medium, he perceives the following:—

(1) An aberration, ϵ, in any direction inclined at angle θ to the motion, such that

$$\sin \epsilon = \frac{v}{V} \sin \theta = \alpha \sin \theta,$$

it being convenient to denote the ratio of velocities, v/V, by a single symbol α, and to call it the aberration constant. A telescope moving with the medium and placed with its object glass tangential to the advancing wave-fronts, will focus the image on its cross wires, and will be pointing not to the object, but to the centre of the wave it is receiving; its collimation axis coincides with a radius or wave-normal, not with a ray.

(2) A Doppler alteration of wave-length in every direction; as is obvious in the figure, from the distribution of drifted wave-fronts. It is positive on one side, and negative on the other side, of a certain direction, θ_0, such that the radius vector is equal to the radius, or

$$\cos \theta_0 = \frac{v}{2V} = \tfrac{1}{2} \alpha ;$$

the aberration angle for this particular case of no Doppler effect being twice the complement of θ_0.

A spectator moving with the medium will perceive this change of wave-length as a change of pitch (or colour) of value

$$\log \frac{n}{n'} = \log \frac{\lambda'}{\lambda} = \log (\cos \epsilon + \alpha \cos \theta) \approx \alpha \cos \theta.$$

An observer travelling with the medium will not observe any modification in interference or diffraction effects, nor will he experience any change of intensity due to motion; for the waves will be brought him at the customary time periods, and be subject to the ordinary flux of energy, as if everything were stationary.

Case of moving Source in fixed Medium.

14. The same figure (fig. 4) serves to illustrate the common case of medium and observer stationary, and source alone moving.

But we must be careful to note that ϵ is only the aberration *angle*, and that whether it is to be called "aberration" or not depends on the meaning attached to that term. The source emits spherical waves in its successive positions, and leaves them to expand at their normal rate. The fixed telescope, pointing to centre of advancing wave, is therefore pointing to the source at the instant when it emitted that light; and, since it is thus seen in its true place at instant of emission, it is most natural to say that the aberration caused by moving source alone is *nil;* for that it may have moved by the time of vision, is obvious.

There is not much more to be said on this head, for the source after throwing off a wave may do what it likes, the light will convey information as to where and how it was at the time of emission. Phenomena depending on a *succession* of waves, *e.g.*, changes of pitch, are of course produced, see fig. 4.

The question arises whether the waves thrown off from a moving source are really spherical shells: whether the motion of the source does not affect its vibration? It is not easy to answer this thoroughly and accurately, but practically there can be no doubt that the emission of light cannot be affected by any feasible terrestrial motion;

for, in the time of one vibration, the earth, which is the quickest available vehicle, has only moved a distance of $\frac{1}{10000}$ of a wave-length; which is equivalent to a middle C fork sounding and creeping along at the rate of 15 inches an hour. No practical question as to imperfection in spherical form of wave from moving source is therefore likely to arise. See however § 19, for discussion of a question not of *shape* but of *intensity*.

There happen to be one or two interesting things connected with the reflexion of light from a moving source when there is some connexion established between the reflected ray and the subsequent position of the source, *e.g.*, as when a ray is reflected back upon itself, with the object of causing interference; these are specially dealt with in §§ 59, 60.

Case of Source and Receiver moving together through Stationary Medium; or, correlative case of Medium drifting past fixed Source and Receiver.

15. Consider a telescope fixed relatively to source, and medium drifting freely past both. The object-glass must be set skew to the wave front, but normal to the advancing ray or radius vector.

In fig. 4, SM is the axis of the telescope, and it points straight at the source. There is no resultant aberration, the object is seen in its true position.

It is also seen of its right colour, for the waves are carried to the receiver at their accustomed frequency: there is no Doppler effect. A steady wind alone is powerless to influence either direction or pitch.

But what about interference phenomena, depending on the *time* of a given journey? Manifestly a motion of the medium will be able to affect this, and may accordingly bring about the displacement of fringes representing hurry or lag of phase.

Consider a telescope fixed relatively to the source and placed so as to receive light along the radius vector r.

If the medium is stationary, the light journey is accomplished in the time

$$T = \frac{r}{V},$$

but if moving, the time of the journey is

$$T' = \frac{r}{V\cos\epsilon + v\cos\theta},$$

and so there is a hurrying up of phase

$$\frac{T}{T'} = \cos\epsilon + \alpha\cos\theta,$$

or

$$T - T' \approx \alpha T\cos\theta.$$

The wind therefore causes a positive or negative change of phase in every direction except that whose cosine is $\frac{1}{2}\, v/\mathrm{V}$, the same direction as that already (§ 13) indicated as possessing a zero Doppler effect.

But the *observation* of the lag of phase thus caused by motion of the entire ethereal medium is not so easy as might appear, and, in fact, it has not yet been detected; for the simple reason that it is liable to affect both the interfering rays equally: as we now show.

Devices for Observing the Lag of Phase.

16. The possible ways in which change of phase, produced by a moving medium, may be looked for, are :—to split a beam of light into two halves, and then—

(1) Make the medium flow with one half beam and against the other.

This is successful, and is the FIZEAU experiment; but it entails control over the medium, and artificial motion of it; the terrestrial orbital motion cannot be utilized in this way.

(2) Send the two beams, not parallel, but round contours in two different planes; or, say one across the line of ether motion, and the other along.

This is MICHELSON's experiment; but it only attempts an effect whose magnitude is the second order of aberration magnitudes; because, before the beams can be brought together again to interfere, a reversal or complete circuit is necessary.

(3) Make the medium flow at different rates along the two beams: as for instance, by interposing a dense substance in one of them.

But, on FRESNEL's hypothesis, this ought to fail; because the free ether, which is the only ether in motion, is unaffected by the dense substance. The only way to move either more or less than the normal quantity of ether in any given space, is to move bodily a dense substance occupying that space. So long as that is stationary, with respect to source and receiver, motion of the whole produces no effect.

To prove that on FRESNEL's law, no dense substance can cause different interference effects when moving than it causes when stationary, we can proceed to calculate the virtual thickness of a slab immersed in an ether stream, or the time retardation it causes in a beam.

Interference Effects as modified by Ether Motion through Dense Stationary Bodies.

17. The calculation of the lag in phase caused by FRESNEL's ethereal motion is a very simple matter. A dense slab of thickness z, which would naturally be traversed with the velocity V/μ, is traversed with the velocity $(\mathrm{V}/\mu)\cos\epsilon + (v/\mu^2)\cos\theta$; where v is the relative velocity of the ether in its neighbourhood; whence the time of journey through it is

$$\frac{\mu z}{V\left(\cos\epsilon + \frac{\alpha}{\mu}\cos\theta\right)}, \qquad \text{instead of } \frac{\mu z}{V},$$

or the equivalent air thickness, instead of being $(\mu - 1)z$, is

$$\frac{\mu z}{\cos\epsilon + \frac{\alpha}{\mu}\cos\theta} - z = \left(\frac{\mu\cos\epsilon - \alpha\cos\theta}{1 - \left(\frac{\alpha}{\mu}\right)^2} - 1\right)z,$$

or, to the first order of minutiæ, $(\mu - 1)z - \alpha z\cos\theta$; θ being the angle between ray and ether drift inside the medium.

So the extra equivalent air layer *due to the motion* is approximately $\pm\alpha z\cos\theta$, a quantity independent of μ.

Hence, no plan for detecting this first-order effect of motion is in any way assisted by the use of dense stationary substances; their extra ether, being stationary, does not affect the lag caused by motion, except indeed in the second order of small quantities, as shown above.

Direct experiments made by HOEK,* and by MASCART, on the effect of introducing tubes of water into the path of half beams of light, are in entire accord with this negative conclusion.

Thus, then, we find that no general motion of the entire medium can be detected by changes in direction, or in frequency, or in phase; for on none of them has it any appreciable (*i.e.*, first-order) effect even when assisted by dense matter.

The remaining possible effect that may be looked for is a change of energy.

Effect of Motion on Intensity of Radiation in Different Directions.

18. At first sight it looks as if there ought to be an unequal distribution of energy round a source past which the medium is streaming. For when the waves are drifting along, their energy moves too, and it can thus be distributed unsymmetrically round the source.

The energy emitted per second, or the *power* of the radiation, is

$$P = 4\pi\rho^2 Vq,$$

where q is the energy per unit volume at distance ρ from the wave centre; supposing that radiating power is unaffected by the motion. So at a place r, θ, reckoning from source as origin, and line of drift as initial line (as in fig. 4), since $r = \rho\,(\cos\epsilon + \alpha\cos\theta)$,

* 'Archives Néerlandaises' (1869), vol. 4, p. 443, or 'Nature,' vol. 26, p. 500.

$$q = \frac{\mathrm{P}\,(\cos\epsilon + \alpha\cos\theta)^2}{4\pi \mathrm{V} r^2}$$
$$\approx q_0\,(1 + 2\alpha\cos\theta + \alpha^2\cos 2\theta - \tfrac{1}{2}\,\alpha^3\sin\theta\sin 2\theta),$$

q_0 being the energy at the same place when there was no drift.

So the energy received per second by a given small area A at that place, facing the source, *i.e.*, normal to the rays, is

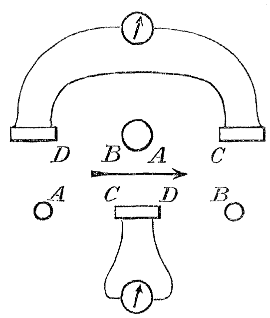
$$q\mathrm{V}\,\mathrm{A}\cos\epsilon = \frac{\mathrm{A}\cos\epsilon}{4\pi r^2}\,\mathrm{P}\,(\cos\epsilon + \alpha\cos\theta)^2.$$

The radiation at distance r from the source is, in fact, the same as what the radiation would be at distance ρ in a stationary medium; except for the small inclination ϵ.

So a pair of similar thermopiles, fore and aft, at equal distances from a source, will, on this hypothesis, receive unequal radiation; the difference being equal to $4\alpha\,(\mathrm{PA}/4\pi r^2)$, or proportional to 4α.

FIZEAU suggested this method, but I am not aware of its having been tried yet.*

Fig. 5.



Thermopile experiment suggested by FIZEAU; in two alternative forms.

19. But it is a serious question whether the reasoning establishing the effect is quite sound. It is not unlikely that motion may affect the radiating power of a source. In fact, the theory of exchanges almost necessitates something of the kind, else the two faces of an enclosure would become unequal in temperature by reason of mere motion through the ethereal medium.†

Hence, if, as in fig. 5, we consider a pair of thermopiles with a hot body half-way

* The suggestion is quoted in a comprehensive, but to me not very intelligible, treatise on the whole subject of aberration: 'Astronomische Undulationstheorie,' by Professor Dr. KETTELER, of Bonn.

† BALFOUR STEWART ('Brit. Assoc. Report,' 1871, Sects. p. 45), argued that this inequality of temperature actually occurred; and, since motion thus afforded an available heat engine, he deduced an ethereal friction, dissipating energy. But, as Lord RAYLEIGH points out (in his Article on "Aberration," 'Nature,' March 1892), it is far more likely that motion should alter radiating and absorbing powers than that it should disturb equality of temperature.

between them, or a pair of equally hot bodies with a thermopile half-way between them, all subject to an ethereal drift in the direction of the arrow, we may assert that although the radiation from A is carried down stream in undue proportion towards C, the amount actually emitted in this direction is diminished in a compensatory manner, so that the resultant flux of energy remains unaffected by the motion.

It is not necessary to suppose that motion disturbs the equality which otherwise exists between radiating and absorbing powers. It is true that if a surface like A radiates less than when the medium is stationary, a surface like C facing the stream must radiate more; but then it may absorb more also. So that in all respects the balance may be undisturbed by the motion of the medium.

It is probable, therefore, that even by this intensity method, nothing more than the second order of aberration magnitude is effective for displaying a general drift of the medium as a whole.

At the same time it seems desirable that an experiment with thermopiles, like that suggested by FIZEAU, should be tried, in order to verify the above deductions from the theory of exchanges, combined with the supposed persistent uniformity of temperature of an enclosure whether at rest or in motion; for thereby the absence of friction or dissipation of energy by motion of solids through ether would be verified.

Case of only Receiver Moving.

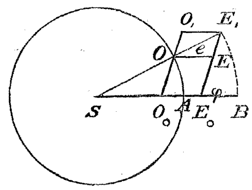
20. If the receiver be not fixed relatively to the medium, nor relatively to the source, but be moving on its own account, the effects due to this motion must be added to the preceding effects. First suppose both source and medium stationary.

The source S emits waves in spherical shells, whose radii are also rays. Any motion of the receiving telescope can be resolved tangentially and radially. Radial motion gives Doppler effect only; tangential motion gives aberration only—both of the commonplace type.

If the telescope were stationary, its object-glass must be tangential to the wave front, but directly it moves it must encounter the wave front obliquely, with the same obliquity ϵ as if it were stationary and the medium drifting (fig. 4), and the eye-piece will then be brought to the light at the right instant. Revolution of a radial telescope about the source would effect this in the simplest way, without introducing any Doppler effect or change in focal length.

Consider a telescope O_0E_0 pointing straight at a source S (fig. 6), and at the instant a given luminous disturbance starts from S, let the telescope begin moving in a direction ϕ with a velocity u. Let it thus reach the position OE by the time the light has got as far as O, *i.e.*, to the spherical wave front indicated in the diagram. Then it follows that by the time the telescope has reached the position O_1E_1 the light will have reached E_1, too, and will accordingly have passed along the collimating axis by reason of the combined motions.

Fig. 6.



A telescope receiving light from S and moving from OE to O_1E_1 while light traverses OE_1.

A stationary telescope receiving the same ray at the same instant would have had to occupy the position OE_1, and would have looked straight at the object (with a slightly greater focal length). Hence the angle O_1E_1O or OSO_0 is the angle of aberration, the amount by which the object appears to be displaced in the direction of motion. A telescope which had been revolving round the source, instead of being translated, would have gone from AB to OE_1 in the time, and have rotated through this same angle. Call it e; it is such that

$$\frac{\sin e}{\sin \phi} = \frac{EE_1}{OE_1} = \frac{u}{V} = \beta, \text{ say,}$$

the medium, remember, being stationary.

The focal length of the moving telescope differs from that necessary for a fixed one; being OE instead of OE_1, or

$$f' = f(\cos e - \beta \cos \phi);$$

but this is best regarded as part of the Doppler effect, since its principal term represents radial motion. With a non-achromatic lens the change of refrangibility due to motion tends to compensate* this effect. But whereas the change of refrangibility is produced equally by motion of source or motion of receiver, this change of focal length seems to be caused only by motion of receiver. It is a shortening of focus as a telescope recedes from the light. I suppose it is too small to observe, else it would seem able to discriminate motion of earth from motion of star, and give absolute motion of telescope through the ether.

A terrestrial source (*e.g.*, a sodium flame) might be used, and a perfectly achromatic lens; but surely no focussing could be delicate enough to discriminate such sort of difference as exists between the two sodium emissions ?

The way in which motion of receiver to or from source causes an apparent change of frequency, *i.e.*, a real change in the frequency with which waves are *received*, is too well known and simple to be more than mentioned. Its amount in any direction is

$$\log \frac{n}{n'} = \log (\cos e + \beta \cos \phi) \approx \beta \cos \phi,$$

where $\beta = u/V$, $\sin e = \beta \sin \phi$, and u is the velocity of the telescope at angle ϕ with the ray.

* This was originally written "exaggerate."

Summary.

21. Collecting these statements together, we may summarize them thus :—

Source alone moving produces—

- A real and apparent change of colour ;
- A real but not apparent error in direction ;
- No lag of phase, except that appropriate to altered wave-length ;
- A change of intensity corresponding to different wave-length.

Medium alone moving, or Source and receiver moving together } gives—

- No change of colour ;
- No change of direction ;
- A real lag of phase, but undetectable without control over the medium ;
- A change of intensity corresponding to different virtual distance, but probably compensated by change of radiating power.

Receiver alone moving gives—

- An apparent change of colour ;
- An apparent change of direction ;
- No change of phase, except that appropriate to extra virtual speed of light ;
- A change of intensity corresponding to different virtual velocity of light.

Thus the interference effect and the Doppler effect do not occur together. Motion of the medium produces one ; motion of source or of receiver produces the other.

Aberration of direction and of pitch occur simultaneously, but are complementary to each other, since one depends on motion across the line of sight, the other on motion along it. One varies as the sine, the other as the cosine, of the inclination. Further discussion of the Doppler effect is deferred to §§ 53–58.

22. It is noteworthy that not one of the methods is able to establish the existence or non-existence of a general ethereal drift near the earth ; for, as shown above, *uniform motion of the entire medium produces no observable first-order effect of any kind.* It plainly becomes the more necessary to attend minutely to possible second-order effects.

In a paper in the 'Archives Néerlandaises,' vol. 21, Professor H. A. LORENTZ discusses, with much power, the whole subject of ether movement ; the idea of the following method of treatment is derived from that paper.

Definition of Ray.

23. In § 13 we defined a ray as the path of a labelled disturbance,* for it is that which enables an eye to fix direction, it is that which determines the line of collimation of a telescope. Now in order that a disturbance from A may reach B, it is necessary that adjacent elements of a wave front at A shall arrive at B in the same phase; hence the path by which a disturbance travels must satisfy this condition from point to point, viz., that disturbances arriving at any point from a preceding point of a ray agree in phase. This condition will be satisfied if the time of journey down a ray and down all infinitesimally differing paths is the same.

The equation to a ray is therefore contained in the statement that the time taken by light to traverse it is a minimum; or

$$\int_A^B \frac{ds}{V} = \text{minimum}.$$

If the medium, instead of being stationary, is drifting with the velocity v, at angle θ to the ray, we must substitute for V the modified velocity $V \cos \epsilon + v \cos \theta$, and so the function that has to be a minimum in order to give the path of a ray in a moving medium is

$$\int_A^B \frac{ds}{V(\cos \epsilon + \alpha \cos \theta)} = \int_A^B \frac{V \cos \epsilon - v \cos \theta}{V^2 (1 - \alpha^2)}\, ds = \text{minimum}.$$

Path of Ray, and Time of Journey, through an Irrotationally Moving Medium.

24. Writing a velocity-potential ϕ in the above equation to a ray, that is putting

$$v \cos \theta = \frac{\partial \phi}{\partial s},$$

and ignoring possible variations in the minute correction factor $1 - \alpha^2$, between the points A and B, it becomes

$$\text{Time of journey} = \int_A^B \frac{\cos \epsilon}{1 - \alpha^2} \cdot \frac{ds}{V} - \frac{\phi_B - \phi_A}{V^2 (1 - \alpha^2)} = \text{minimum}.$$

Now the second term depends only on end points, and therefore has no effect on path. The first term contains only the second power of aberration magnitude; and hence it has much the same value as if everything were stationary. A ray that was

* [It has been objected that a bit of wave-front cannot be labelled, because of diffraction effects. This seems to me only a practical difficulty, and a more practical definition based upon preserved phase-connexion follows a few lines later in the text; but the meaning conveyed by the convenient phrase "labelled disturbance" can equally well and I think unobjectionably be expressed by calling a ray the path of a definite, or identical, portion of energy—the direction of energy-flux.—July, 1893.]

straight, will remain straight in spite of motion; whatever shape it had, that it will retain. Only cos ϵ, and variations in α^2, can produce any effect on path, and effects so produced must be very small, since the value of cos ϵ is $\sqrt{(1 - \alpha^2 \sin^2 \theta)}$. A second-order effect on direction may therefore be produced by irrotational motion, but not a first-order effect. A similar statement applies to the time of journey round any closed periphery.

MICHELSON'S *Experiment.*

25. We conclude, therefore, that general ethereal drift does not affect either the path of a ray or the time of its journey round a complete contour, to any important extent. But that taking second-order quantities into account, the time of going to and fro in any direction inclined at angle θ to a constant drift is, from the above expression, § 24,

$$\frac{2\,\mathrm{T} \cos \epsilon}{1 - \alpha^2} = \frac{\sqrt{(1 - \alpha^2 \sin^2 \theta)}}{1 - \alpha^2} \times 2\mathrm{T},$$

where 2T is the ordinary time of the double journey.

Hence, by this means, interference effects due to drift would seem to be possible, since the time depends subordinately on the inclination of ray to drift (*cf.* §§ 59–62)

The above expression applies to MICHELSON'S* remarkable experiment of sending a split beam to and fro, half along and half across the line of earth motion; and is, in fact, the theory of it. There ought to be an effect due to the difference between $\theta = 0$ and $\theta = 90°$, but he does not observe any. Hence, either something else happens, or the ether near the earth is dragged with it, so as not to stream through our instruments. When α is constant I see no way out of this conclusion, except hypothetical disturbance at reflexion of some minute kind, one of the mirrors being normal and the other tangential to the drift; but I perceive no adequate reason for this suggestion (see § 60). It is true that if the earth is carrying the ether with it, α will *not* be constant, at different distances from its surface; but, then, the plane of MICHELSON'S experiment was horizontal.

If the ether is dragged along near moving matter it behaves like a viscous fluid, and a velocity-potential must (save by some exceptional theory, § 31) be abandoned; but, as this would involve the curvature of rays striking the earth and much complication, it seems a pity to abandon it until compelled by direct experimental evidence to recognize ethereal viscosity.

The experiment of MICHELSON'S raises a strong presumption in favour of such viscosity, nevertheless his negative result is conceivably explicable in other ways; one of which has been ingeniously suggested by Professor FITZGERALD, viz., that the cohesion force between molecules, and, therefore, the size of bodies, may be a

* 'Phil. Mag.,' Dec., 1887.

function of their direction of motion through the ether; and accordingly that the length and breadth of MICHELSON's stone supporting block were differently affected, in what happened to be, either accidentally or for some unknown reason, a compensatory manner.

26. There is already one experiment, which I have never seen criticised either way, tending in a sense precisely contrary to MICHELSON's. FIZEAU* observed the polarization produced by a pile of plates, and considered that he had proved that the azimuth of the plane of polarization varied with the direction of orbital motion of the Earth, and hence that the ether was streaming past them. If so, polarization by reflexion is the only phenomenon known which is capable of showing a first-order effect of the general ethereal drift. The experiment seems to me extremely difficult, but to be well worthy of repetition by other observers. [I believe that Lord RAYLEIGH's objection to the experiment as performed by FIZEAU is that the effect was unseen until an illegitimate or unsafe magnifying device was employed.]

Meanwhile I shall hope to examine the question of ether motion near moving matter in a simpler fashion (§ 33).

Assuming for the present that the ether is not disturbed in a viscous manner by the motion of gross matter through it, we can make the following assertions :—

General Statements Concerning Aberration.

27. A ray is straight whatever the motion of the medium, unless there are eddies, and accordingly no irrotational currents of ether can divert a ray. But, if the observer is moving, the apparent ray will not be the true ray, and accordingly the line of vision will not be the true direction of object.

In a stationary ether, wave-normal and ray coincide, but the line of vision of a moving observer slants across both (§ 20).

In a moving ether, wave-normal and ray enclose an angle, and line of vision depends upon motion of observer. If the observer is stationary his line of vision is the ray; if he moves at the same rate as the ether his line of vision is the wave-normal (§ 13).

The line of vision, in fact, always depends on the motion of the observer, not at all on the motion of the ether so long as it has a velocity-potential. Hence nothing can be simpler than the theory of aberration if this condition is satisfied.

A similar but more general condition (to be obtained in the next section) suffices to secure the straightness of a ray whatever happens, or more generally that whatever the path of a ray may be by reason of reflexion or refraction in a stationary ether, the same it shall be in a moving one; and readily accounts for the absence of all effect on direction due to the general relative drift of the medium, whether in the

* 'Ann. de Chim. et de Phys.,' 1859, vol. 57, p. 129.

presence of dense matter (water-filled telescopes) or otherwise (*cf.* 'Nature,' vol. 46, p. 498).

However matter affects or loads the ether inside it, it cannot on this theory be said to hold it still, or carry it with it. The general ether stream must remain unaffected, not only near, but inside matter, if rays are to retain precisely the same course as if it were relatively stationary.

But it must be understood that the ethereal motion here contemplated is the *general drift of the entire medium,* or its correlative the uniform motion of all the matter concerned. There is nothing to be said against aberration effect being producible or modifiable by motion of *parts* of the medium, as, for instance, by sliding one portion of the ether past another portion, as by the artificial motion of slabs and other partitioned-off regions. These matters are to some extent mixed up with the law of refraction, which we consider later, but the general ideas concerning them have been already given. Artificial motion of matter may readily alter both the time of journey and the path of a ray (*cf.* §§ 7 and 52).

Effect of placing Ordinary Matter in the path of a ray in a Drifting Medium. FRESNEL'S *Law a special case of a universal Potential-function.*

28. Inside a transparent body light travels at a speed V/μ; and the ether, which outside drifts at velocity v making an angle θ with the ray, inside may be drifting with velocity v' and angle θ'.

Hence the equation to a ray inside such matter is

$$T' = \int \frac{ds}{(V/\mu)\cos\epsilon' + v'\cos\theta'} = \text{min.,} \quad \text{where } \frac{\sin\epsilon'}{\sin\theta'} = \frac{v'}{V/\mu} = \alpha'.$$

This may be written

$$T' = \int \frac{\cos\epsilon'\, ds}{V/\mu\,(1-\alpha'^2)} - \int \frac{v'\cos\theta'\, ds}{V^2/\mu^2\,(1-\alpha'^2)};$$

the second term alone involves the first power of the motion, and assuming that $\mu^2 v' \cos\theta' = d\phi'/ds$, and treating α'^2 as a quantity too small for its possible variations to need attention, the expression becomes

$$T' = \mu T \frac{\cos\epsilon'}{1-\alpha'^2} - \frac{\phi'_B - \phi'_A}{V^2(1-\alpha'^2)},$$

T being the time of travel through the same space when empty. Now, if the time of journey and course of ray, however they be affected by the dense body, are not to be more affected by reason of ethereal drift through it than if it were so much empty space, it is necessary* that the difference of potential between two points A and B should be the same whether the space between is filled with dense matter or not (or, say, whether the ray-path is taken through or outside a portion of dense medium); in other words (calling ϕ the outside and ϕ' the inside potential-function), in order to secure that T′ shall not differ from μT by anything depending on the first power of motion, it is necessary that $\phi'_B - \phi'_A$ shall equal $\phi_B - \phi_A$, *i.e.*, that the potential inside and outside matter shall be the same up to a constant, or that $\mu^2 v' \cos\theta' = v\cos\theta$; which for the case of drift along a ray is precisely FRESNEL's hypothesis.

Another way of putting the matter is to say that to the first power of drift velocity

$$T' = \mu T - \int(\mu^2 v' \cos\theta - v\cos\theta)\ ds/V^2,$$

and that the second or disturbing term must vanish.

29. Hence FRESNEL's hypothesis as to the behaviour of ether inside matter is equivalent to the assumption that a potential-function, $\int \mu^2 v \cos\theta\, ds$, exists throughout all transparent space, so far as motion of ether alone is concerned.

Given that condition, no first-order interference effect due to drift can be obtained from stationary matter by sending rays round any kind of closed contour, nor can the path of a ray be altered by ethereal drift through any stationary matter.

As soon as matter is locally moved, however, its motion may readily produce an effect, for it has no potential conditions to satisfy; it may easily be moved in a closed contour. Suppose it moves with velocity u, always with the light, the relative drift of ether thereby caused in it must, as above, be u/μ^2, and so it may be said to virtually carry the ether inside it forward with velocity $u - u/\mu^2$; for that is the amount by which it affects the time of journey of a ray. This does not mean that it carries with it any ether of space; in fact, it definitely means that it does *not* appreciably disturb the ether of space (*cf.* § 3, *b*).

The equation to a ray in *moving* matter, subject to an independent ether drift, is

$$\int \frac{ds}{V/\mu\cos\epsilon + v/\mu^2\cos\theta + u[1-(1/\mu^2)]\cos\phi} = \text{const.}$$

30. It is noteworthy that almost all the observations which have been made with negative results as to the effect of the Earth's orbital motion on the ether are equally consistent with complete connexion and complete independence between ether and

* [The argument has here been slightly expanded since the MS. was sent in to meet a suggestion of inadequacy made by Dr. SCHUSTER, to whom I am also indebted for an objection to the term "velocity-potential" at first applied to this function ϕ'. As Professor FITZGERALD has observed, it is more general than a velocity-potential, though it reduces to that when the medium is homogeneous, or when $\mu = 1$. The text has been altered accordingly.—July, 1893.]

matter. If there is complete connexion, the ether near the earth is relatively stagnant, and negative results are natural. If there is complete independence, the ether is either absolutely stationary or has a velocity-potential, and the negative results are thereby explained.

Ordinary astronomical aberration, and all other phenomena concerned with vision through strata high above the earth, so far as they have been accurately observed, are consistent with complete independence, but not with a viscous drag.

On the other hand, the negative result of Mr. MICHELSON'S attempt to detect a second-order effect appears only to be consistent with relative stagnation.

A doubtful positive result, supposed to be obtained by FIZEAU (§ 26), on a change in the azimuth of the plane of polarization effected by transmission through oblique plates, would, if established, support relative motion between earth and ether.

31. Is it possible for a sphere to move through a fluid without disturbing it rotationally and propagating rotary motion into space?

It is not possible for an ordinary solid moving through an ordinary fluid. Diffusion of motion, or viscosity, is bound to occur.

It is possible for a vortex ring or assemblage of vortex rings, because at their surface there is no slip. It is possible also if the sphere be a solidified portion of the fluid, which condenses in front and evaporates behind (as already mentioned).

Professor STOKES seems to say, that though not possible to retain a velocity-potential with any *viscosity*, yet with some kind of *rigidity* it may be possible, because deviations from irrotational motion go off into space with the speed of light. If so, the earth might possibly carry some ether with it, and yet a ray be straight.

I do not see any way in which it can abstain from rotationally disturbing the fluid if at the same time it has to carry some with it. Neither, I think, do Mr. HICKS or Mr. LARMOR, to whom I wrote.

Lord KELVIN, however ('Papers,' vol. iii., p. 436), has invented an "ether," or kinematically rigid incompressible ideal substance, which satisfies electromagnetic equations and magnetic boundary conditions, whose equations of motion are like those of an elastic solid, and which yet permits locomotion of smooth solids filling vesicular hollows in it, and which in general "takes precisely the same motion for any given motion of the boundary as does a frictionless incompressible liquid in the same space showing the same boundary."

The experiment now to be described proves, I think, that by the motion of ordinary masses of matter the ether is appreciably undisturbed, and raises a presumption in favour of the earth's motion being equally impotent.

The one thing in the way of the simple doctrine of an ether undisturbed by motion is MICHELSON'S experiment, viz., the absence of a second-order effect due to terrestrial movement through free ether. This experiment may have to be explained away; perhaps as suggested above (end of § 25).