

CHRISTIAAN HUYGHENS AND THE WAVE THEORY OF LIGHT: Part II

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5. THE WAVE-OPTICS OF HUYGHENS

BEFORE proceeding to comment on the writings of later authors on the work of Huyghens, we may usefully here summarise the basic concepts of his theory. Huyghens put forward and sought to establish the proposition that when a wave of light diverges from its source, every small portion of the wave is capable of propagating itself independently with the same velocity as the rest of it; in an isotropic medium, the direction of such propagation is the wave-normal and hence this is also the direction of the ray in the sense of geometrical optics. The same idea forms the basis of Huyghens' explanation of the reflection and refraction of light. When the elements of area of an advancing wave-front reach the boundary between two media, each such element gives rise, respectively in the two media, to the elements of area in the reflected and refracted waves. These latter advance normally to themselves in such a direction that they can join up and form continuous wave-fronts. The geometric constructions employed by Huyghens enable these requirements to be satisfied. The propagation of light in an inhomogeneous medium considered in the fourth chapter of Huyghens' treatise can also be very simply dealt with on the same basis. The elements of area of the wave-front in such a medium advance normally to themselves with the velocity appropriate to their positions in the medium. As they advance, they join up to form new wave-fronts which are orthogonal to the path of the light-rays in the medium.

Later writers have criticised the arguments employed by Huyghens in his treatise. One remark which is often made is that the theory of Huyghens would result in his wave-fronts moving backwards as well as forwards and that he had given no explanation for the absence of backward propagation. But this criticism is not justified and is itself based on a misunderstanding. Huyghens was concerned with the behaviour of an *advancing* wave-front in a homogeneous medium. The partial waves which in his theory give the observed light intensity by their superposition are those which diverge from points lying on the straight line between the source and the observer; in order to reach the observer simultaneously they should all move *away* from the source and *towards* the point of observation, in other words move

forwards towards the observer. The possibility of backward propagation is thus ruled out completely.

Another criticism which has frequently been advanced is that the theory of Huyghens is based on an arbitrary assumption, *viz.*, that only along the envelope of his partial waves would there be any observable intensity of light. This criticism is also based on a misunderstanding. It should be remembered that Huyghens was unaware that the waves of light are periodic disturbances having a definite wave-length. He assumed that light consists of *individual* waves which diverge in all directions from the original source and the partial waves contemplated in his theory would therefore also be of the same nature. The build-up of a finite intensity from the superposition of a very large number of such waves, each of which is extremely feeble, would accordingly be possible only if they arrive *simultaneously* at the point of observation. The diagram appearing in the first chapter of Huyghens' treatise is intended to assist the reader to appreciate the arguments set out in the text; *viz.*, at *each* point on the wave-front a great number of partial waves arrive *simultaneously* and build up the intensity at that point, while the entire wave may be itself considered as made up of a great number of elementary areas at which the light-intensity has thus been built up. In the later chapters in which Huyghens' theories of reflection and refraction and of the propagation of light in an inhomogeneous medium are expounded, the diagrams are intended to exhibit how the complete wave-front arising from these processes is built up out of its elementary parts or areas. Here again, the final result is an individual wave, and it may therefore be correctly described as the envelope of the partial waves which co-operate in building it up.

6. THE PARTIAL WAVES OF HUYGHENS

Since the concept of partial waves introduced by Huyghens in his treatise has played an important role in physical optics, it is appropriate that we consider it here in some detail. Though the words appear in several chapters of his treatise, it should be remarked that they do not have the same significance in each case. In the first chapter which seeks to explain the rectilinear propagation of

light, the partial waves arise as a consequence of the assumed discrete structure of the luminiferous medium; each particle in the medium is regarded as a source of such waves. In the second and third chapters, the partial waves are assumed to arise when the primary wave reaches the boundary separating the two media with different properties. The elements of area of the boundary are here regarded as the source of partial waves. Since they travel with different velocities, they are distinct from each other in the two media. In the fourth chapter which deals with the propagation of light in inhomogeneous media, the partial waves are assumed to diverge from the elements of area of the advancing wave-front in such a medium.

If the luminiferous medium were empty space, the assumption that it consists of discrete particles which can function as emitters of partial waves would be difficult to justify. In the case of material media, however, there is good reason for assuming that the discrete atoms of which they are composed could function as sources of secondary or partial waves. Even so, however, these partial waves would reinforce each other in the direction of propagation of the primary wave and merge with it, while in other directions they would interfere and cancel out each other's effects. Thus, they would, in all cases, cease to be observable. Accordingly, the notion of partial waves can, in such circumstances, be regarded only as hypothetical or virtual and not as an observable or physical reality. The same remarks would also be applicable in regard to the propagation of light in a medium which is inhomogeneous. Indeed, as already remarked, this particular case could be dealt with in a very simple manner without making any use of the concept of partial waves. Thus, finally, we are left with the phenomena arising from the incidence of light on the boundary between two material media. Huyghens' construction explains the geometric laws of reflection and refraction in so natural and convincing a fashion that it is difficult to resist the conclusion that his concept of partial waves is well-grounded and is a physical reality in these particular cases.

7. THE SO-CALLED PRINCIPLE OF HUYGHENS

It will be evident from what has been said above that the ideas of Huyghens were not correctly understood or appreciated by later writers. It is not surprising therefore that the whole of the vast literature which was subsequently published and which claims to base

itself on the ideas of Huyghens, in reality proceeds on a different basis altogether. This is evident from the fact that the mathematicians whose objective was to develop a "Rigorous Formulation of the Principle of Huyghens" concerned themselves with precisely the case in which Huyghens' concept of partial waves has no physical meaning or justification, namely the undisturbed propagation of waves from a source situated in a structureless and uniform continuum.

The well-known formula developed by Kirchhoff is an illustration of the foregoing remarks. Here, the disturbance due to the source at the point of observation is expressed as an integral taken over the area of a closed surface within which the point of observation is included but not the source. Each elementary area of the surface appears in the formula as a source from which waves diverge with amplitudes which vary with the direction of emission. The line joining the source and the point of observation is also the direction of maximum amplitude for the waves radiated by the element of area which lies on that line *between* them, and of zero amplitude for an element of area which also lies on the same line but on the *opposite side*. Kirchhoff's formula as actually developed refers to the case of sound-waves, and the attempts made to extend it to the case of light have not met with success. But our present concern is not with the mathematics of the formula but with the physics of the subject. The association of the formula with the name of Huyghens—honoured as the founder of the wave-theory of light—has naturally disposed whole generations of physicists to look upon it with favour. It has, however, been made clear by the foregoing remarks that Kirchhoff's approach to the subject is quite different from that of Huyghens. We have, therefore, to ask ourselves: Is Kirchhoff's formula really meaningful? Has it any claim to validity or acceptance considered from the standpoint of optical theory? We shall proceed to consider these questions.

As has already been remarked, one of Huyghens' striking successes is his explanation of the geometric laws of reflection and refraction. His concept of partial waves takes its clearest and most acceptable form in this case, *viz.*, that each element of area of the physical boundary acts as a source of partial waves. Since these move with different velocities in the two media, they should be considered as

distinct. In other words, the partial waves in each medium are hemispherical, and it becomes a meaningful physical problem to determine the dependence of the amplitude of the waves with direction on the surface of these hemispheres. It would presumably be a maximum in the direction of the normal to the boundary and zero in directions parallel to the boundary. On the other hand, the very generality of Kirchhoff's formula indicates that it has no physical validity or significance. For, it is not possible to discover or assign any reason why an element of area set at an arbitrary orientation

in a continuous structureless medium should function as a source of secondary waves with specific features related to that orientation. If the concept of partial or secondary waves is at all to be meaningful, the waves should have a physically recognizable origin, e.g., a local discontinuity in physical properties. In its absence, the formula ceases to have any physical content. Kirchhoff's formula thus reveals itself to be a mathematical abstraction which is not relevant or valid in relation to the actual problems of physical optics.

LUNAR CRATERS CAUSED BY COMETARY COLLISIONS

THE reported observation by Kozyrev of emission bands of carbon molecule in the lunar crater Alphonsus [see *Curr. Sci.*, 1958, 27 (12), 512 and 1959, 28 (2), 93] has reopened the age-old problem of the origin of lunar craters and lunar plains, and the dilemma between the volcanic and impact theories of their origin confronts us in a new form. Zdenek Kopal suggests (*Nature*-183, p.169, Jan. 17, 1959) that any theory of lunar surface features restricted to a consideration of impacts of solid bodies only is bound to remain seriously incomplete, and should be generalized by taking account of the effects which could be wrought on the lunar face by collisions with cometary heads.

According to the impact hypothesis most lunar craters were formed by solid bodies (meteorites, or asteroids) impinging on the Moon with cosmic velocities. It has been calculated that kinetic energies of the order of 10^{28} ergs are necessary to produce impact craters of 80 miles in diameter (like Alphonsus). Such an impinging solid would penetrate at least a few hundred yards into the lunar crust before total vaporization and ejection of crater walls by explosion. This would produce a "moonquake", characterized by a very shallow epicentre, with about one half of the kinetic energy converted into seismic waves.

The latest survey of earthquakes shows that the largest and the most destructive of them experienced so far entailed an energy release of 10^{25} ergs only—i.e., one thousandth of the hypothetical 'moonquake' which might have

caused Alphonsus crater. Considering that there are of the order of 10^5 craters of diameter varying between one mile and 150 miles on the visible half of the Moon alone, it is difficult to explain how any steep mountains or ridges anywhere on the Moon could have survived such a long series of sudden and devastating disturbances.

It is known that comets are at least as frequent at a distance of 1 A.U. from the Sun as are meteorites or asteroids of comparable masses. The wide distribution of cometary orbital elements is bound to render their high-velocity collisions (in the range 30-70 km./sec.) with the Moon much more frequent than would be the case with the asteroids. Moreover, cometary heads made up of loose conglomerates of mainly frozen hydrocarbons with an appreciable mixture of unstable chemical compounds will on impact behave like high explosives—thus releasing chemical energy in addition to the kinetic energy of the head as a whole. Not being solid, the impact of cometary heads would not penetrate too far into the crust of the Moon and produce destructive seismic waves. The heat produced by the impact explosion will be sufficient to melt the local lunar matter into fluid lava, thus explaining the origin of lunar maria.

It may be suggested that the gas discharge observed by Kozyrev may be an accidental release of some gas deposited there by cometary impact at a distant time in the past.