Historical introduction

THE physical principles underlying the optical phenomena with which we are concerned in this treatise were substantially formulated before 1900. Since that year, optics, like the rest of physics, has undergone a thorough revolution by the discovery of the quantum of energy. While this discovery has profoundly affected our views about the nature of light, it has not made the earlier theories and techniques superfluous; rather, it has brought out their limitations and defined their range of validity. The extension of the older principles and methods and their applications to very many diverse situations has continued, and is continuing with undiminished intensity.

In attempting to present in an orderly way the knowledge acquired over a period of several centuries in such a vast field it is impossible to follow the historical development, with its numerous false starts and detours. It is therefore deemed necessary to record separately, in this preliminary section, the main landmarks in the evolution of ideas concerning the nature of light.*

The philosophers of antiquity speculated about the nature of light, being familiar with burning glasses, with the rectilinear propagation of light, and with refraction and reflection. The first systematic writings on optics of which we have any definite knowledge are due to the Greek philosophers and mathematicians [Empedocles (*c.* 490–430 BC), Euclid (*c.* 300 BC)].

Amongst the founders of the new philosophy, René Descartes (1596–1650) may be singled out for mention as having formulated views on the nature of light on the basis of his metaphysical ideas.† Descartes considered light to be essentially a pressure transmitted through a perfectly elastic medium (the aether) which fills all space, and he attributed the diversity of colours to rotary motions with different velocities of the particles in this medium. But it was only after Galileo Galilei (1564–1642) had, by his

* For a more extensive account of the history of optics, reference may be made to: J. Priestley, *History and Present State of Discoveries relating to Vision, Light and Colours* (2 Vols., London, 1772); Thomas Young, *A Course of Lectures on Natural Philosophy and the Mechanical Arts* Vol. 1 (London, 1845), pp. 374–385; E. Wilde, *Geschichte der Optik vom Ursprung dieser Wissenschaft bis auf die gegenwärtige Zeit*, 2 Vols, (Berlin, 1838, 1843); Ernst Mach, *The Principles of Physical Optics*, A historical and philosophical treatment (First German edition 1913. English translation 1926, reprinted by Dover Publications, New York, 1953); E. Hoppe, *Geschichte der Optik* (Leipzig, Weber, 1926); V. Ronchi, *Storia della Luce* (Bologna: Zanichelli, 2nd. Ed., 1952). A comprehensive historical account up to recent times is E. T. Whittaker's *A History of the Theories of Aether and Electricity*, Vol. I (*The Classical Theories*), revised and enlarged edition 1952; Vol. II (*The Modern Theories 1900–1926*), 1953, published by T. Nelson and Sons, London and Edinburgh. The first volume was used as the chief source for this introductory section.

† R. Descartes, *Dioptrique, Météores* (published (anonymously) in Leyden in 1637 with prefactory essay 'Discours de la méthode'). *Principia Philosophiae* (Amsterdam, 1644).

development of mechanics, demonstrated the power of the experimental method that optics was put on a firm foundation. The law of reflection was known to the Greeks; the law of refraction was discovered experimentally in 1621 by Willebrord Snell* (Snellius, *c*. 1580–1626). In 1657 Pierre de Fermat (1601–1665) enunciated the celebrated *Principle of Least Time*† in the form 'Nature always acts by the shortest course'. According to this principle, light always follows that path which brings it to its destination in the shortest time, and from this, in turn, and from the assumption of varying 'resistance' in different media, the law of refraction follows. This principle is of great philosophical significance, and because it seems to imply a teleological manner of explanation, foreign to natural science, it has raised a great deal of controversy.

The first phenomenon of interference, the colours exhibited by thin films now known as 'Newton's rings', was discovered independently by Robert Boyle‡ (1627–1691) and Robert Hooke§ (1635–1703). Hooke also observed the presence of light in the geometrical shadow, the 'diffraction' of light but this phenomenon had been noted previously by Francesco Maria Grimaldi|| (1618–1663). Hooke was the first to advocate the view that light consists of rapid vibrations propagated instantaneously, or with a very great speed, over any distance, and believed that in an homogeneous medium every vibration will generate a sphere which will grow steadily.¶ By means of these ideas Hooke attempted an explanation of the phenomenon of refraction, and an interpretation of colours. But the basic quality of colour was revealed only when Isaac Newton (1642–1727) discovered** in 1666 that white light could be split up into component colours by means of a prism, and found that each pure colour is characterized by a specific refrangibility. The difficulties which the wave theory encountered in connection with the rectilinear propagation of light and of polarization (discovered by Huygens††) seemed to Newton so decisive that he devoted himself to the development of an emission (or corpuscular) theory, according to which light is propagated from a luminous body in the form of minute particles.

At the time of the publication of Newton's theory of colour it was not known whether light was propagated instantaneously or not. The discovery of the finite speed of light was made in 1675 by Olaf Römer (1644–1710) from the observations of the eclipses of Jupiter's satellites.‡‡

The wave theory of light which, as we saw, had Hooke amongst its first champions was greatly improved and extended by Christian Huygens†† (1629–1695). He enunciated the principle, subsequently named after him, according to which every point of the 'aether' upon which the luminous disturbance falls may be regarded as the centre of a new disturbance propagated in the form of spherical waves; these secondary waves

* Snell died in 1626 without making his discoveries public. The law was first published by Descartes in his *Dioptrique* without an acknowledgement to Snell, though it is generally believed that Descartes had seen Snell's manuscript on this subject.

† In a letter to Cureau de la Chambre. It is published in *Oeuvres de Fermat*, Vol. 2 (Paris, 1891) p. 354.

‡ *The Philosophical Works of* Robert Boyle (abridged by P. Shaw), Vol. II (Second ed. London, 1738), p. 70.

§ R. Hooke, *Micrographia* (1665), **47**.

|| F. M. Grimaldi, *Physico-Mathesis de lumine, coloribus, et iride* (Bologna, 1665).

¶ The early wave theories of Hooke and Huygens operate with single 'pulses' rather than with wave trains of definite wavelengths.

** I. Newton, *Phil. Trans.* No. 80 (Feb. 1672), 3075.

†† Chr. Huygens, *Traité de la lumière* (completed in 1678, published in Leyden in 1690).

‡‡ Olaf Römer, *Mém. de l'Acad. Sci. Paris*, **10** (1666–1699), 575; *J. de Sav.* (1676), 223.

combine in such a manner that their envelope determines the wave-front at any later time. With the aid of this principle he succeeded in deriving the laws of reflection and refraction. He was also able to interpret the double refraction of calc-spar [discovered in 1669 by Erasmus Bartholinus (1625–1698)] by assuming that in the crystal there is, in addition to a primary spherical wave, a secondary ellipsoidal wave. It was in the course of this investigation that Huygens made the fundamental discovery of polarization: each of the two rays arising from refraction by calc-spar may be extinguished by passing it through a second crystal of the same material if the latter crystal be rotated about the direction of the ray. It was, however, left to Newton to interpret these phenomena; he assumed that rays have 'sides'; and indeed this 'transversality' seemed to him an insuperable objection to the acceptance of the wave theory, since at that time scientists were familiar only with longitudinal waves (from the propagation of sound).

The rejection of the wave theory on the authority of Newton lead to its abeyance for nearly a century, but it still found an occasional supporter, such as the great mathematician Leonhard Euler (1707–1783).*

It was not until the beginning of the nineteenth century that the decisive discoveries were made which led to general acceptance of the wave theory. The first step towards this was the enunciation in 1801 by Thomas Young (1773–1829) of the principle of interference and the explanation of the colours of thin films.† However, as Young's views were expressed largely in a qualitative manner, they did not gain general recognition.

About this time, polarization of light by reflection was discovered by Étienne Louis Malus‡ (1775–1812). Apparently, one evening in 1808, he observed the reflection of the sun from a window pane through a calc-spar crystal, and found that the two images obtained by double refraction varied in relative intensities as the crystal was rotated about the line of sight. However, Malus did not attempt an interpretation of this phenomenon, being of the opinion that current theories were incapable of providing an explanation.

In the meantime the emission theory had been developed further by Pierre Simon de Laplace (1749–1827) and Jean-Baptiste Biot (1774–1862). Its supporters proposed the subject of diffraction for the prize question set by the Paris Academy for 1818, in the expectation that a treatment of this subject would lead to the crowning triumph of the emission theory. But their hopes were disappointed, for, in spite of strong opposition, the prize was awarded to Augustin Jean Fresnel (1788–1827), whose treatment§ was based on the wave theory, and was the first of a succession of investigations which, in the course of a few years, were to discredit the corpuscular theory completely. The substance of his memoir consisted of a synthesis of Huygens' Envelope Construction with Young's Principle of Interference. This, as Fresnel showed, was sufficient to explain not only the 'rectilinear propagation' of light but also the minute deviations from it – diffraction phenomena. Fresnel calculated the diffraction caused by straight edges, small apertures and screens; particularly impressive was the

* *L. Euleri Opuscula varii argumenti* (Berlin, 1746), p. 169.

† Th. Young, *Phil. Trans. Roy. Soc., London* xcii, **12** (1802) 387. *Miscellaneous works of the late Thomas Young*, Vol. I (London, J. Murray, 1885) pp. 140, 170.

‡ É. L. Malus, *Nouveau Bull. d. Sci., par la Soc. Philomatique*, Vol. 1 (1809), 266. *Mém. de la Soc. d'Arcueil*, Vol. 2 (1809).

§ A. Fresnel, *Ann. Chim. et Phys.*, (2), **1** (1816) 239; *Oeuvres*, Vol. 1, 89, 129.

experimental confirmation by Arago of a prediction, deduced by Poisson from Fresnel's theory, that in the centre of the shadow of a small circular disc there should appear a bright spot.

In the same year (1818), Fresnel also investigated the important problem of the influence of the earth's motion on the propagation of light, the question being whether there was any difference between the light from stellar and terrestrial sources. Dominique François Arago (1786–1853) found from experiment that (apart from aberration) there was no difference. On the basis of these findings Fresnel developed his theory of the partial convection of the luminiferous aether by matter, a theory confirmed in 1851 by direct experiment carried out by Armand Hypolite Lóuis Fizeau (1819–1896). Together with Arago, Fresnel investigated the interference of polarized rays of light and found (in 1816) that two rays polarized at right angles to each other never interfere. This fact could not be reconciled with the assumption of longitudinal waves, which had hitherto been taken for granted. Young, who had heard of this discovery from Arago, found in 1817 the key to the solution when he assumed that the vibrations were transverse.

Fresnel at once grasped the full significance of this hypothesis, which he sought to put on a more secure dynamical basis* and from which he drew numerous conclusions. For, since only longitudinal oscillations in a fluid are possible, the aether must behave like a solid body; but at that time a theory of elastic waves in solids had not yet been formulated. Instead of developing such a theory and deducing the optical consequences from it, Fresnel proceeded by inference, and sought to deduce the properties of the luminiferous aether from the observations. The peculiar laws of light propagation in crystals were Fresnel's starting point; the elucidation of these laws and their reduction to a few simple assumptions about the nature of elementary waves represents one of the greatest achievements of natural science. In 1832, William Rowan Hamilton† (1805–1865), who himself made important contributions to the development of optics, drew attention to an important deduction from Fresnel's construction, by predicting the so-called conical refraction, whose existence was confirmed experimentally shortly afterwards by Humphrey Lloyd‡ (1800–1881).

It was also Fresnel who (in 1821) gave the first indication of the cause of dispersion by taking into account the molecular structure of matter§, a suggestion elaborated later by Cauchy.

Dynamical models of the mechanism of aether vibrations led Fresnel to deduce the laws which now bear his name, governing the intensity and polarization of light rays produced by reflection and refraction.||

Fresnel's work had put the wave theory on such a secure foundation that it seemed almost superfluous when in 1850 Foucault¶ and Fizeau and Breguet** undertook a crucial experiment first suggested by Arago. The corpuscular theory explains refraction

* A. Fresnel, *Oeuvres Complètes d'Augustin Fresnel*, Vol. 2 (Paris, Imprimiere Imperiale, 1866–1870), pp. 261, 479).

† W. R. Hamilton, *Trans. Roy. Irish Acad.*, **17** (1833), 1. Also *Hamilton's Mathematical Papers*, eds. J. L. Synge and W. Conway, Vol. 1 (Cambridge, Cambridge University Press, 1931) p. 285.

‡ H. Lloyd, *Trans. Roy. Irish Acad.*, **17** (1833), 145.

§ A. Fresnel, *ibid*, p. 438.

|| A. Fresnel, *Mém. de l'Acad.*, **11** (1832), 393; *Oeuvres*, **1**, 767.

¶ L. Foucault, *Compt. Rend. Acad. Sci. Paris*, **30** (1850), 551.

** H. Fizeau and L. Breguet, *Compt. Rend. Acad. Sci. Paris*, **30** (1850), 562, 771.

in terms of the attraction of the light-corpuscles at the boundary towards the optically denser medium, and this implies a greater velocity in the denser medium; on the other hand the wave theory demands, according to Huygens' construction, that a smaller velocity obtains in the optically denser medium. The direct measurement of the velocity of light in air and water decided unambiguously in favour of the wave theory.

The decades that followed witnessed the development of the elastic aether theory. The first step was the formulation of a theory of the elasticity of solid bodies. Claude Louis Marie Henri Navier (1785–1836) developed such a theory*, discerning that matter consists of countless particles (mass points, atoms) exerting on each other forces along the lines joining them. The now customary derivation of the equations of elasticity by means of the continuum concept is due to Augustine Louis Cauchy† (1789–1857). Of other scientists who participated in the development of optical theory, mention must be made of Siméon Denis Poisson‡ (1781–1840), George Green§ (1793–1841), James MacCullagh|| (1809–1847) and Franz Neumann¶ (1798–1895). Today it is no longer relevant to enter into the details of these theories or into the difficulties which they encountered; for the difficulties were all caused by the requirement that optical processes should be explicable in mechanical terms, a condition which has long since been abandoned. The following indication will suffice. Consider two contiguous elastic media, and assume that in the first a transverse wave is propagated towards their common boundary. In the second medium the wave will be resolved, in accordance with the laws of mechanics, into longitudinal and transverse waves. But, according to Arago's and Fresnel's experiments, elastic longitudinal waves must be ruled out and must therefore be eliminated somehow. This, however, is not possible without violating the laws of mechanics expressed by the boundary conditions for strains and stresses. The various theories put forward by the authors mentioned above differ in regard to the assumed boundary conditions, which always conflicted in some way with the laws of mechanics.

An obvious objection to regarding the aether as an elastic solid is expressed in the following query: How is one to imagine planets travelling through such a medium at enormous speeds without any appreciable resistance? George Gabriel Stokes (1819–1903) thought that this objection could be met on the grounds that the planetary speeds are very small compared to the speeds of the aetherial particles in the vibrations constituting light; for it is known that bodies like pitch or sealing wax are capable of rapid vibrations but yield completely to stresses applied over a long period. Such controversies seem superfluous today since we no longer consider it necessary to have mechanical pictures of all natural phenomena.

A first step away from the concept of an elastic aether was taken by MacCullagh,** who postulated a medium with properties not possessed by ordinary bodies. The latter store up energy when the volume elements change shape, but not during rotation. In MacCullagh's aether the inverse conditions prevail. The laws of propagation of waves

* C. L. M. H. Navier, *Mém. de l'Acad.*, **7**, (submitted in 1821, published in 1827), 375.
† A. L. Cauchy, *Exercise de Mathématiques*, **3** (1828), 160.
‡ S. D. Poisson, *Mém. de l'Acad.*, **8** (1828), 623.
§ G. Green, *Trans. Camb. Phil. Soc.* (1838); *Math. Papers*, 245.
|| J. MacCullagh, *Phil. Mag.* (3), **10** (1837), 42, 382; *Proc. Roy. Irish Acad.*, **18** (1837).
¶ F. Neumann, *Abh. Berl. Akad., Math. Kl.* (1835), **1**.
J. MacCullagh, *Trans. Roy. Irish Acad.*, **21, Coll. Works, Dublin (1880), 145.

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in such a medium show a close similarity to Maxwell's equations of electromagnetic waves which are the basis of modern optics.

In spite of the many difficulties, the theory of an elastic aether persisted for a long time and most of the great physicists of the nineteenth century contributed to it. In addition to those already named, mention must be made of William Thomson* (Lord Kelvin, 1824–1908), Carl Neumann† (1832–1925), John William Strutt‡ (Lord Rayleigh, 1842–1919), and Gustav Kirchhoff§ (1824–1887). During this period many optical problems were solved, but the foundations of optics remained in an unsatisfactory state.

In the meantime researches in electricity and magnetism had developed almost independently of optics, culminating in the discoveries of Michael Faraday|| (1791–1867). James Clerk Maxwell¶ (1831–1879) succeeded in summing up all previous experiences in this field in a system of equations, the most important consequence of which was to establish the possibility of electromagnetic waves, propagated with a velocity which could be calculated from the results of purely electrical measurements. Actually, some years earlier Rudolph Kohlrausch (1809–1858) and Wilhelm Weber** (1804–1891) had carried out such measurements and the velocity turned out to be that of light. This led Maxwell to conjecture that light waves are electromagnetic waves; a conjecture verified by direct experiment in 1888 by Heinrich Hertz†† (1857–1894). In spite of this, Maxwell's electromagnetic theory had a long struggle to gain general acceptance. It seems to be a characteristic of the human mind that familiar concepts are abandoned only with the greatest reluctance, especially when a concrete picture of the phenomena has to be sacrificed. Maxwell himself, and his followers, tried for a long time to describe the electromagnetic field with the aid of mechanical models. It was only gradually, as Maxwell's concepts became more familiar, that the search for an 'explanation' of his equations in terms of mechanical models was abandoned; today there is no conceptual difficulty in regarding Maxwell's field as something which cannot be reduced to anything simpler.

But even the electromagnetic theory of light has attained the limits of its serviceability. It is capable of explaining, in their main features, all phenomena connected with the propagation of light. However, it fails to elucidate the processes of emission and absorption, in which the finer features of the interaction between matter and the optical field are manifested.

The laws underlying these processes are the proper object of modern optics, indeed of modern physics. Their story begins with the discovery of certain regularities in spectra. The first step was Josef Fraunhofer's (1787–1826) discovery‡‡ (1814–1817)

* W. Thomson, *Phil. Mag.*, (5), **26** (1888), 414. Baltimore Lectures (London, 1904).
† C. Neumann, *Math. Ann.*, **1** (1869), 325, **2** (1870), 182.
‡ J. W. Strutt, (Lord Rayleigh), *Phil. Mag.*, (4) **41** (1871), 519; **42** (1871), 81.
§ G. Kirchhoff, *Berl. Abh. Physik., Abteilg.* **2** (1876), 57; *Ges. Abh.* 352; *Berl. Ber.* (1882), 641; *Pogg. Ann. Physik. u. Chem.* (2), **18** (1883), 663; *Ges. Abh., Nachtrag.* 22.
|| M. Faraday, *Experimental Researches in Electricity* (London, 1839).
¶ J. C. Maxwell, *A Treatise on Electricity and Magnetism*, 2 Vols. (Oxford, 1873).
R. Kohlrausch and W. Weber, *Pogg. Ann. Physik u. Chem.* (2), **99 (1856), 10.
††H. Hertz, *Sitzb. Berl. Akad. Wiss.*, Feb. 2, 1888; *Wiedem. Ann.* **34** (1888), 551; English translation in his *Electric Waves* (London, Macmillan, 1893), p. 107.
‡‡J. Fraunhofer, *Gilberts Ann.*, **56** (1817), 264. W. H. Wollaston (1766–1828) observed these lines in 1802 (*Phil. Trans. Roy. Soc.*, London (1802), 365) but had not appreciated his discovery and interpreted them incorrectly.

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of the dark lines in the solar spectrum, since named after him; and their interpretation as absorption lines given in 1861 on the basis of experiments by Roger Wilhelm Bunsen (1811–1899) and Gustav Kirchhoff* (1824–1887). The light of the continuous spectrum of the body of the sun, passing the cooler gases of the sun's atmosphere, loses by absorption just those wavelengths which are emitted by the gases. This discovery was the beginning of spectrum analysis, which is based on the recognition that every gaseous chemical element possesses a characteristic line spectrum. The investigation of these spectra has been a major object of physical research up to and including the present; and since light is its subject, and optical methods are employed, it is often considered as a part of optics. The problem of how light is produced or destroyed in atoms is, however, not exclusively of an optical nature, as it involves equally the mechanics of the atom itself; and the laws of spectral lines reveal not so much the nature of light as the structure of the emitting particles. Thus, from being a part of optics, spectroscopy has gradually evolved into a separate discipline which provides the empirical foundations for atomic and molecular physics. This field is, however, beyond the scope of this book.

Concerning methods, it has become apparent that classical mechanics is inadequate for a proper description of events occurring within the atom and must be replaced by the quantum theory, originated in 1900 by Max Planck† (1858–1947). Its application to the atomic structure, led in 1913, to the explanation by Niels Bohr‡ (1885–1962) of the simple laws of line spectra of gases. From these beginnings and from the ever increasing experimental material, modern quantum mechanics developed (Heisenberg, Born, Jordan, de Broglie, Schrödinger, Dirac).§ By its means considerable insight has been obtained into the structure of atoms and molecules.

However, our concept of the nature of light has also been greatly influenced by quantum theory. Even in its first form due to Planck there appears a proposition which is directly opposed to classical ideas, namely that an oscillating electric system does not impart its energy to the electromagnetic field in a continuous manner but in finite amounts, or 'quanta' $\varepsilon = h\nu$, proportional to the frequency ν of the light, where $h = 6.55 \times 10^{-27}$ erg/s is Planck's constant. We may say that the occurrence of the constant h is the feature which distinguishes modern physics from the old.

It was only gradually that the paradoxical, almost irrational, character of Planck's equation $\varepsilon = h\nu$ was fully realized by physicists. This was brought about mainly by the work of Einstein and Bohr. On the basis of Planck's theory, Einstein (1879–1955) revived in 1905 the corpuscular theory of light in a new form|| by assuming that Planck's energy quanta exist as real light-particles, called 'light quanta' or 'photons'. He thereby succeeded in explaining some phenomena which had been discovered more recently in connection with the transformation of light into corpuscular energy,

* R. Bunsen and G. Kirchhoff, *Untersuchungen über das Sonnenspektrum und die Spektren der Chemischen Elemente., Abh. kgl. Akad. Wiss.* (Berlin, 1861) p. 1863.

† M. Planck, *Verh. d. deutsch phys. Ges.*, **2** (1900) 202, 237. *Ann. d. Physik* (4), **4** (1901), 553.

‡ N. Bohr, *Phil. Mag*. (6), **26** (1913), 1, 476, 857.

§ W. Heisenberg, *Z. Phys*., **33** (1925), 879; M. Born and P. Jordan, *ibid*., **34** (1925), 858; M. Born, W. Heisenberg, and P. Jordan, *ibid*., **35** (1926), 557; L. de Broglie, *Thèse* (Paris, 1924); *Ann. de Physique* (10), **3** (1925), 22; E. Schrödinger, *Ann. d. Physik* (4), **79** (1926), 361, 489 and 734; **80** (1926), 437; **81** (1926), 109. English translation: *Collected Papers on Wave Mechanics* by E. Schrödinger (London and Glasgow, Blackie, 1928); P. A. M. Dirac, *Proc. Roy. Soc.* A, **109** (1925), 642; *ibid*., **110** (1926), 561.

|| A. Einstein, *Ann. d. Physik* (4), **17** (1905), 132; **20** (1906), 199.

phenomena which were inexplicable by the wave theory. Chief among these are the so-called photoelectric effect and the fundamentals of photochemistry. In phenomena of this type light does not impart to a detached particle an energy proportional to its intensity, as demanded by the wave theory, but behaves rather like a hail of small shots. The energy imparted to the secondary particles is independent of the intensity, and depends only on the frequency of the light (according to the law $\varepsilon = h\nu$). The number of observations confirming this property of light increased year by year and the situation arose that the simultaneous validity of both wave and corpuscular theories had to be recognized, the former being exemplified by the phenomena of interference, the latter by the photoelectric effect. It is only in more recent years that the development of quantum mechanics has led to a partial elucidation of this paradoxical state of affairs, but this has entailed giving up a fundamental principle of the older physics, namely the principle of deterministic causality.

The detailed theory of the interaction between field and matter required the extension of the methods of quantum mechanics (field quantization). For the electromagnetic radiation field this was first carried out by Dirac* and these investigations form the basis of quantum optics. However, it was mainly the development of radically new light sources, the lasers, in the 1960s that led to the emergence of quantum optics as a new discipline. The invention of the laser provided new sources of very intense, coherent and highly directional light beams. Such sources are analogous to devices known as masers, developed a few years earlier, for generating and amplifying microwave radiation by conversion of atomic and molecular energy by the process of stimulated emission. Pioneering contributions which led to the invention of these devices were made notably by Basov, Prokhorov, Townes, Schawlow and Maiman.† Apart from providing an important tool for research in quantum optics, the invention of the laser led to numerous applications and originated several new fields such as quantum-electronics, nonlinear optics, fiber optics and others.

Another branch of optics, not touched upon in this work, is the optics of moving bodies. Like the quantum theory it has grown into a vast independent field of study. The first observed phenomenon in this field, recorded in 1728 by James Bradley‡ (1692–1762), was the aberration of 'fixed stars', i.e. the observation of slightly different angular positions of the stars according to the motion of the earth relative to the direction of the light ray. Bradley correctly interpreted this phenomenon as being due to the finite velocity of light and thus was able to determine the velocity. We have already mentioned other phenomena belonging to optics of moving media: Fresnel was the first to enquire into the convection of light by moving bodies and to show that it behaved as if the luminiferous aether participated in the movement only with a fraction of the speed of the moving bodies; Fizeau then demonstrated this partial convection experimentally with the aid of flowing water. The effect of the motion of the light source or of the observer was investigated by Christian Doppler§ (1803–1853) who formulated the well-known principle named after him. So long as the elastic theory of light held the field and the precision of measurements was sufficiently limited,

* P. A. M. Dirac, *Proc. Roy. Soc.*, A**114** (1927), 243, 710.

† N. G. Basov and A. M. Prokhorov, *Zh. Eksp. Teor. Fiz.*, **27** (1954), 431; A. L. Schawlow and C. H. Townes, *Phys. Rev.*, **112** (1958), 1940; T. H. Maiman, *Nature*, **187** (1960), 493.

‡ J. Bradley, *Phil. Trans.*, **35** (1728), 637.

§ Chr. Doppler, *Abh. Köngl. böhm. Geselsch*, **2** (1842), 466; *Pogg. Ann.*, **68** (1847), 1.

Fresnel's ideas on partial convection sufficed for a satisfactory explanation of all the phenomena. But the electromagnetic theory of light encountered difficulties of a fundamental nature. Hertz was the first to attempt to generalize Maxwell's laws to moving bodies. His formulae were, however, in conflict with some electromagnetic and optical experiments. Of great importance was the theory of Hendrik Antoon Lorentz (1853–1928) who assumed an 'aether in a state of absolute rest' to be the carrier of the electromagnetic field and deduced the properties of material bodies from the interaction of elementary electric particles – the electrons. He was able to show that Fresnel's coefficient of convection could be obtained correctly from his theory and that in general all phenomena known at the time (1895) lent themselves to explanation by this hypothesis.* But the enormous increase of precision in the determination of optical paths by means of the interferometer of Albert Abraham Michelson (1852–1931) led to a new anomaly: it proved impossible to demonstrate the existence of an 'aether drift' required by the theory of the 'stationary aether'.† The anomaly was resolved by Albert Einstein‡ in 1905 in his special theory of relativity. The theory is founded on a critique of the concepts of time and space and leads to the abandonment of Euclidian geometry and the intuitive conception of simultaneity. Its further development into the so-called general theory of relativity§ led to a completely new conception of gravitational phenomena by a 'geometrization' of the space-time manifold. The application of this theory involves the use of special mathematical and physical methods which, although relevant to optics in many cases, may easily be considered separately from it. The number of optical phenomena in which the motion of bodies (e.g. light sources) plays a significant part is rather small.

* H. A. Lorentz, *Versuch einer Theorie der electrischen und optischen Erscheinungen in bewegten Körpern* (Leiden, E. J. Brill 1895; reprinted by Teubner, Leipzig, 1906).

† A. A. Michelson, *Amer. Jour. Sci*. (3), **22** (1881), 20; A. A. Michelson and E. W. Morley, *Amer. Jour. Sci.* (3), **34** (1887), 333; *Phil. Mag.*, **24** (1887), 449.

‡ A. Einstein, *Ann. d. Physik* (4), **17** (1905), 891.

§ A. Einstein, *Berl. Sitz.* (1915), 778, 799, 831, 844. *Ann. d. Physik* (4) **49** (1916), 769.