Light

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Key Concepts

- Light is a transverse, electromagnetic wave that travels at a constant speed of 299,792,458 m/s in a vacuum–the maximum velocity possible, according to the theory of relativity.
- Early scientists, including Isaac Newton, proposed that light was a stream of particles. Later, Thomas Young proposed that light was a wave. In fact, light has a dual nature of being both a particle and a wave.
- Important light-based phenomena include reflection, refraction, diffraction, interference, and polarization.
- Corpuscular phenomena are those in which light behaves as energetic particles called photons. Among such phenomena are blackbody radiation, the photoelectric effect, and the Compton effect.
- Special relativity describes the effects of motion near the speed of light. General relativity explains how gravitation affects the propagation of light.

The term light, as commonly used, refers to the kind of radiant electromagnetic energy that is associated with vision. In a broader sense, light includes the entire range of radiation known as the electromagnetic spectrum. The branch of science dealing with light, its origin and propagation, its effects, and other phenomena associated with it is called optics. Spectroscopy is the branch of optics that pertains to the production and investigation of spectra. *See also:* OPTICS; SPECTROSCOPY.

Any acceptable theory of the nature of light must stem from observations regarding its behavior under various circumstances. Therefore, this article begins with a brief account of the principal facts known about visible light, including the relation of visible light to the electromagnetic spectrum as a whole, and then describes the apparent dual nature of light. The remainder of the article discusses various experimental and theoretical considerations pertinent to the study of this problem.

The electromagnetic spectrum is a broad band of radiant energy that extends over a range of wavelengths running from trillionths of inches to hundreds of miles; wavelengths of visible light are measured in hundreds of thousandths of an inch. Arranged in order of increasing wavelength, the radiation making up the electromagnetic spectrum is termed gamma rays, x-rays, ultraviolet rays, visible light, infrared waves, microwaves, radio waves, and very long electromagnetic waves. *See also:* ELECTROMAGNETIC RADIATION.

Speed of light

The fact that light travels at a finite speed or velocity is well established. In round numbers, the speed of light in vacuum or air may be said to be 186,000 mi/s or 300,000 km/s.

Measurements of the speed of light, c, which had attracted physicists for 308 years, came to an end in 1983 when the new definition of the meter fixed the value of the speed of light. The speed of light is one of the most interesting and important of the fundamental physical constants. It is used to convert light travel times to distance, as in laser and radio measurements of the distance to the Moon and planets. It relates mass m to energy E in Einstein's equation, $E = mc^2$. To fix the value of c in the new definition, highly precise values of c were obtained by extending absolute frequency measurements into a region of the electromagnetic spectrum where wavelengths can be most accurately measured. These advances were facilitated by the use of stabilized lasers and high-speed tungsten-nickel diodes which were used to measure the lasers' frequencies. The measurements of the speed of light and of the frequency of lasers yielded a value of the speed of light limited only by the standard of length which was then in use. This permitted a redefinition of the meter in which the value of the speed of light assumed an exact value, 299,792,458 m/s. The meter is defined as the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second. *See also:* ASTRONOMICAL UNIT; FUNDAMENTAL CONSTANTS; LASER.

Prior to the observations of O. Roemer in 1675, the speed of light was thought to be infinite. Roemer noted a variation of the orbiting periods of the moons of Jupiter that depended on the annual variation in the distance between Earth and Jupiter. He correctly ascribed the variation to the time it takes light to travel the varying distance between the two planets. The accuracy of Roemer's value of c was limited by a 30% error in the knowledge of the size of the planetary orbits at that time.

The first terrestrial measurement of c was performed by H. L. Fizeau in 1849. His measurement of the time it took light to travel to a distant mirror and return resulted in a value accurate to 15%.

J. C. Maxwell's theory of electromagnetic radiation showed that both light and radio waves were electromagnetic and hence traveled at the same speed in vacuum. This discovery soon led to another method of measuring c: it was the product of the frequency and wavelength of an electromagnetic wave. In 1891, R. Blondlot first used this method to determine a value of c by measuring both the wavelength and the frequency of an electromagnetic, radio-frequency wave. His measurement demonstrated that c was the same for radio and light waves. It is this method which now exhibits the greatest accuracy, and it is used in the most accurate measurements of c using a laser's frequency and wavelength.

In 1958, K. D. Froome reported the speed of light *c* to be 299,792,500 m/s, with an uncertainty of plus or minus 100 m/s. He measured both the frequency and the wavelength of millimeter waves from klystron oscillators to obtain this result. The major uncertainty lay in measuring the wavelength of the radiation. Since short wavelengths can be measured much more accurately than long wavelengths, a shorter-wavelength source was needed to improve the accuracy further; the stabilized laser soon provided such a source. However, a means of measuring its incredibly high frequency was needed. This problem, too, was soon overcome with the discovery of the tungsten-nickel point-contact diode.

Stabilized lasers. Before the advent of the laser, the most spectrally pure light came from the emission of radiation by atoms in electric discharges. The spectral purity of such radiation was about 1 part per million. Lasers, in contrast, have exhibited short-period spectral purities some 10^8 times greater than this. However, the frequency of this laser radiation was free to wander over the entire emission line, and a means of stabilizing and measuring the frequency was necessary before it could be used in a measurement of *c*. The technique of sub-Doppler saturated absorption spectroscopy permitted the "locking" of the frequency of the radiation to very narrow spectral features so that the frequency (and, of course, the wavelength) remained fixed. Several different lasers at different wavelengths have been stabilized, and they serve as precise frequency and wavelength sources. Three of the most common are: the helium-neon laser at a wavelength of 3.39 micrometers stabilized with a saturated absorption in methane, the 10-μm carbon dioxide (CO_2) laser stabilized to a saturated fluorescence in carbon dioxide, and the common red helium-neon laser stabilized to an iodine-saturated absorption. The frequencies and wavelengths of these three lasers have been measured to yield values of *c*. *See also:* LASER SPECTROSCOPY.

George W. Stroke

Measurement of wavelength. Precise measurements of wavelengths are commonly made in Fabry-Perot interferometers, in which two wavelengths are compared by the observation of interference fringes of waves reflecting between two mirrors. A bright fringe occurs when the optical path length between the high-reflectivity mirrors is a multiple of a half-wavelength.

With the use of special Fabry-Perot interferometers, wavelength measurements of stabilized lasers were made with accuracies limited by the length standard then in use, the 605.8-nanometer orange radiation from the krypton atom. This limitation affected all speed-of-light measurements, with a resulting uncertainty of about 4 parts in 10^9. *See also:* INTERFEROMETRY.

Frequency measurement. The measurement of the frequency of an electromagnetic wave in the laser region is performed by a heterodyne technique in which harmonics are generated in high-speed nonlinear devices. For the most accurate measurements of *c*, the accuracy of the frequency measurements was approximately ten times more accurate than the wavelength measurements; hence, the uncertainties were dominated by the wavelength measurements. *See also:* FREQUENCY MEASUREMENT.

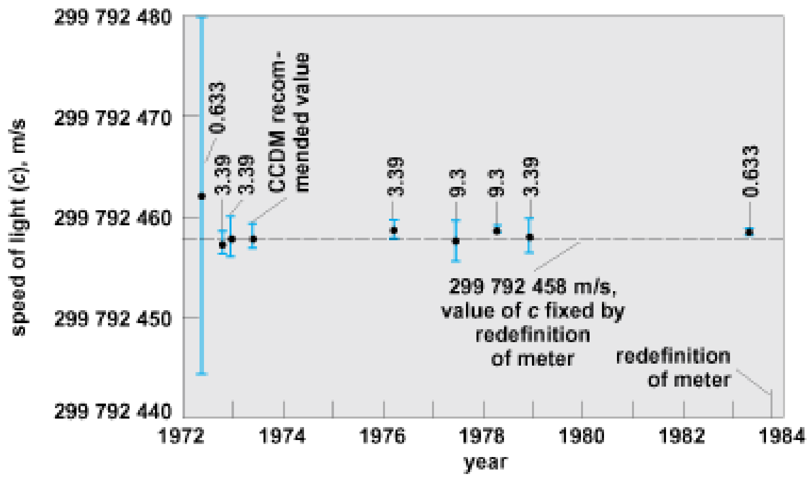

Fig. 1 **Laser speed-of-light measurement made from 1972 to 1984. Separate frequency and wavelength measurements were combined to obtain the 1976, 1977, and 1983 measurements. Numbers accompanying data bars indicate the wavelengths in micrometers at which the measurements were carried out.**

Results. The values of *c* obtained from the frequency and wavelength measurements of various lasers are shown in **Fig. 1**. Because of the stability and reproducibility of the stabilized lasers, separate frequency and wavelength measurements were sometimes combined to give independent values of *c*. The first 1972 measurement did not involve an absolute counting of the laser frequency and was somewhat less accurate. For the first time in history, the various values of the speed of light were in agreement. Prior to 1958, the measured values of *c* often varied outside the limits of error quoted by the experimenters, and even prompted some observers to think that *c* might be changing with time. The 1974 meeting of the Consultative Committee for the Definition of the Meter (CCDM) recommended that 299,792,458 m/s be the value of *c* to be used for converting wavelength to frequency and vice versa, and in all other precise applications involving *c*. This number was arrived at by the consideration of the first four values of *c* in Fig. 1. The subsequent measurements of *c* have shown that this was a good choice, and it is the value used in the redefinition of the meter. The 1983 measurement is the only entry for visible light, and is in excellent agreement with the others. In 1983, the General Conference on Weights and Measures (CGPM) used exactly 299,792,458 m/s in the redefinition of the meter. With this new definition, fixing the value of the speed of light, the era of speed-of-light measurements was at an end. *See also:* LENGTH.

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Diffraction and reflection

One of the most easily observed facts about light is its tendency to travel in straight lines. Careful observation shows, however, that a light ray spreads slightly when passing the edges of an obstacle. This phenomenon is called diffraction. The reflection of light is also well known. The Moon, as well as all other satellites and planets in the solar system, are visible only by reflected light; they do not emit large amount of visible light like the Sun. However, all celestial bodies emit heat radiation in the infrared spectral range. Reflection of light from smooth optical surfaces occurs so that the angle of reflection equals the angle of incidence, a fact that is most readily observed with a plane mirror. When light is reflected irregularly and diffusely, the phenomenon is termed scattering. The efficiency of light scattering by atoms or molecules increases rapidly with light frequency, reaching its maximum over the visible spectrum in the violet region. The human eye, however, responds differently to different colors according to the three types of color receptors, most strongly to blue light. This explains why the scattering of light by molecules and particles in the atmosphere is seen as the blue color of the sky. When a change in frequency (or wavelength) of the light occurs during scattering, the scattering is referred to as the Raman effect. *See also:* DIFFRACTION; HEAT RADIATION; RAMAN EFFECT; REFLECTION OF ELECTROMAGNETIC RADIATION; SCATTERING OF ELECTROMAGNETIC RADIATION.

Refraction

The type of bending of light rays called refraction is caused by the fact that light travels at different speeds in different media—faster, for example, in air than in either glass or water. Refraction occurs when light passes from one medium to another in which it moves at a different speed. Familiar examples include the change in direction of light rays in going through a prism, and the bent appearance of a stick partially immersed in water. *See also:* REFRACTION OF WAVES.

Interference and polarization

In the phenomenon called interference, rays of light emerging from two parallel slits combine on a screen to produce alternating light and dark bands. This effect can be obtained quite easily in the laboratory, and is observed in the colors produced by a thin film of oil on the surface of a pool of water. *See also:* INTERFERENCE OF WAVES.

Polarization is a property of light that describes the orientation of the electromagnetic wave oscillation. Polarization of light is usually demonstrated by using a polarizer, which transmitted light of one polarization. A polarizer can be quite transparent individually. When two of them are placed together, however, the degree of transparency of the combination depends upon the relative orientation of the polarizers. The transmission of light can be varied from high to low, simply by rotating one polarizer with respect to the other. *See also:* POLARIZED LIGHT.

Chemical effects

When light is absorbed by certain substances, chemical changes take place. This fact forms the basis for the science of photochemistry. Rapid progress has been made toward an understanding of photosynthesis, the process by which plants produce relatively complex substances such as sugars in the presence of sunlight. This is but one example of the all-important response of plant and animal life to light. *See also:* PHOTOCHEMISTRY; PHOTOSYNTHESIS.

Light pressure

When light strikes an object, it exerts a pressure on its surface that is proportional to the light intensity. An example of the action of such pressure is deflection of comet tails illuminated by solar radiation. This phenomenon has found an application in laser cooling of atoms and molecules. *See also:* LASER COOLING; RADIATION PRESSURE.

Historical approach

Early in the eighteenth century, light was generally believed to consist of tiny particles. Of the phenomena mentioned above, reflection, refraction, and the sharp shadows caused by the straight path of light were well known, and the characteristic of finite velocity was suspected. All of these phenomena except refraction clearly could be expected of streams of particles, and Isaac Newton showed that refraction would occur if the velocity of light increased with the density of the medium through which it traveled.

This theory of the nature of light seemed to be completely upset, however, in the first half of the nineteenth century. During that time, Thomas Young studied the phenomena of interference, and could see no way to account for them unless light were a wave motion. Diffraction and polarization had also been investigated by that time. Both were easily understandable on the basis of a wave theory of light, and diffraction eliminated the “sharp-shadow” argument for particles. Reflection and finite velocity were consistent with either picture. The final blow to the particle theory seemed to have been struck in 1849, when the speed of light was measured in different media and found to vary in just the opposite manner to that assumed by Newton. Therefore, in 1850, it seemed finally to be settled that light consisted of waves.

Even then, however, there was the problem of the medium in which light waves traveled. All other kinds of waves required a physical medium, but light traveled through a vacuum—faster, in fact, than through air or water. The term ether was proposed by James Clerk Maxwell and his contemporaries as a name for the unknown medium, but this scarcely solved the problem because no ether was ever actually found. Then, near the beginning of the twentieth century, came certain work on the emission and absorption of energy that seemed to be understandable only if light were assumed to have a particle or corpuscular nature. The external photoelectric effect, the emission of electrons from the surfaces of solids when light is incident on the surfaces, was one of these. At that time, then, science found itself in the uncomfortable position of knowing a considerable number of experimental facts about light, of which some were understandable regardless of whether light consisted of waves or particles, others appeared to make sense only if light were wavelike, and still others seemed to require it to have a particle nature. *See also:* ETHER HYPOTHESIS.

Theory

The study of light deals with some of the most fundamental properties of the physical world and is intimately linked with the study of the properties of submicroscopic particles on the one hand and with the properties of the entire universe on the other. The creation of electromagnetic radiation from matter and the creation of matter from radiation, both of which have been achieved, provide a fascinating insight into the unity of physics. The same is true of the deflection of light beams by strong gravitational fields, such as the bending of starlight passing near the Sun.

A classification of phenomena involving light according to their theoretical interpretation provides the clearest insight into the nature of light. When a detailed accounting of experimental facts is required, two groups of theories appear which, in the majority of cases, account separately for the wave and the corpuscular character of light. The quantum theories obviate questions concerning this dual character of light, and make the classical wave theory and the simple corpuscular theory appear as two very useful limiting theories. It happens that the wave theories of light can cope with a considerable part of the phenomena involving electromagnetic radiation. Geometrical optics, based on the wave theory of light, can solve many of the more common problems of the propagation of light, such as refraction, provided that the limitations of the underlying theory are not disregarded. *See also:* GEOMETRICAL OPTICS.

Phenomena involving light may be classed into three groups: electromagnetic wave phenomena, corpuscular or quantum phenomena, and relativistic effects. The relativistic effects appear to influence similarly the observation of both corpuscular and wave phenomena. The major developments in the theory of light closely parallel the rise of modern physics. These developments are charted in **Fig. 2**, and are discussed in the remainder of this article.

Wave phenomena

Interference and diffraction, mentioned earlier, are the most striking manifestations of the wave character of light. Their fundamental similarity can be demonstrated in a number of experiments. The wave aspect of the entire spectrum of electromagnetic radiation is most convincingly shown by the similarity of diffraction pictures produced on a photographic plate, placed at some distance behind a diffraction grating, by radiations of different frequencies, such as x-rays and visible light. The interference phenomena of light are, moreover, very similar to interference of electronically produced microwaves and radio waves.

Polarization demonstrates the transverse character of light waves. Further proof of the electromagnetic character of light is found in the possibility of inducing, in a transparent body that is being traversed by a beam of plane-polarized light, the property of rotating the plane of polarization of the beam when the body is placed in a magnetic field. *See also:* FARADAY EFFECT.

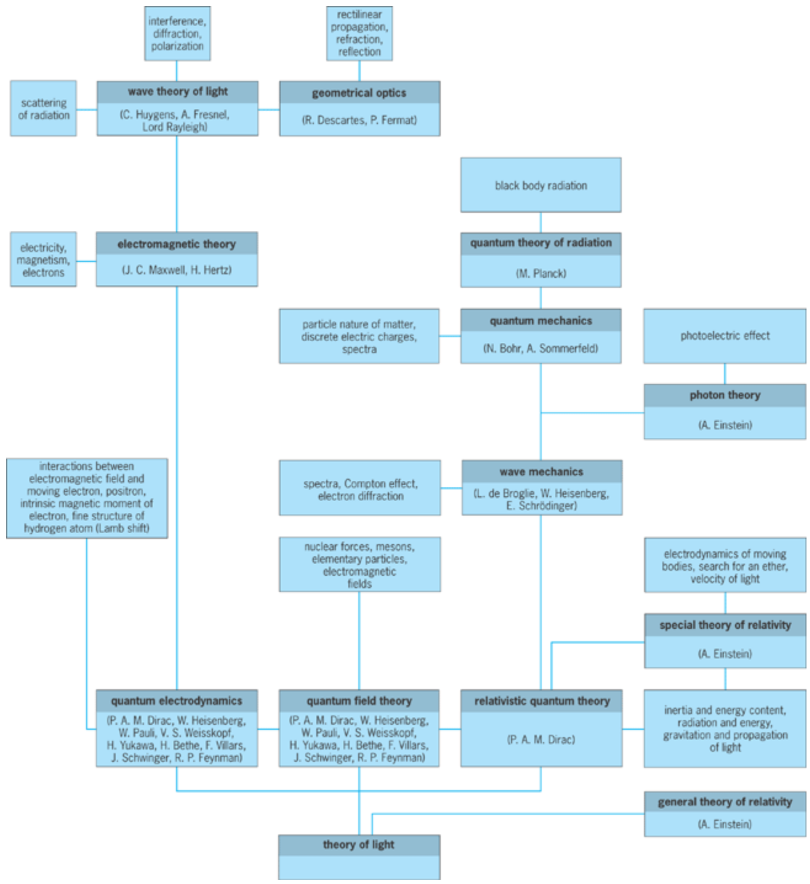

Fig. 2 **Chart of important developments in the theory of light.**

The fact that the velocity of light had been calculated from electric and magnetic parameters (permittivity and permeability) was at the root of Maxwell's conclusion in 1865 that "light, including heat and other radiations if any, is a disturbance in the form of waves propagated . . . according to electromagnetic laws." Finally, the observation that electrons and neutrons can give rise to diffraction patterns quite similar to those produced by visible light has made it necessary to ascribe a wave character to particles. *See also:* ELECTRON DIFFRACTION; NEUTRON DIFFRACTION.

Electromagnetic-wave propagation. Electromagnetic waves can propagate through free space, devoid of matter and fields, and with a constant gravitational potential; through space with a varying gravitational potential; and through more or less absorbing material media which may be solids, liquids, or gases. Radiation can be transmitted through waveguides with cylindrical, rectangular, or other boundaries, the insides of which can be either evacuated or filled with a dielectric medium. *See also:* WAVEGUIDE.

From electromagnetic theory, and especially from the well-known equations formulated by Maxwell, a plane-wave disturbance of a single frequency f is propagated in the x direction with a phase velocity $\upsilon = \lambda f =$

$\lambda\omega/2\pi$, where λ is the wavelength and $\omega = 2\pi f$. The wave can be described by the equation $y = A \cos(\omega t - kx)$, where $k = \omega/\upsilon$ is the wavenumber. Two disturbances of same amplitude A, of respective angular frequencies ω_1 and ω_2, and of wavenumbers k_1 and k_2, propagated in the same direction, yield the resulting disturbance y', defined in Eq. (1).

$$y' = y_1 + y_2 = 2A \cos {}^1/_2 \, [(\Delta\omega)\, t - (\Delta k) x] \times \cos(\omega t - kx) \tag{1}$$

Here, $\Delta\omega = \omega_1 - \omega_2$, $\Delta k = k_1 - k_2$, and $\omega = 1/2(\omega_1 + \omega_2)$, $k = 1/2\,(k_1 + k_2)$. The ratio $u = \Delta\omega/\Delta k$ is defined as the group velocity, which is the speed of a light signal, and the ratio ω/k is defined as the phase velocity, which is the speed of the wavefront. In the limit of small $\Delta\omega$, $u = d\omega/dk$. Noting that $\omega = 2\pi\upsilon/\lambda$, $d\omega = 2\pi(\lambda\, d\upsilon - \upsilon\, d\lambda)/\lambda^2$, and $dk = -2\pi\, d\lambda/\lambda^2$, an important relation, Eq. (2), relating

$$u = \upsilon - \lambda \frac{d\upsilon}{d\lambda} \tag{2}$$

the group and phase velocity is obtained. This shows that the group velocity u is different from the phase velocity υ in a medium with dispersion $d\upsilon/d\lambda$. In a vacuum, $u = \upsilon = c$. With the help of Fourier theorems, the preceding expression for u can be shown to apply to the propagation of a wave group of infinite length, but with frequencies extending over a finite small domain. Furthermore, even if the wave train were emitted with an infinite length, modulation or "chopping" would result in a degrading of the monochromaticity by introduction of new frequencies, and hence in the appearance of a group velocity. Such considerations of this nature were not trivial in earlier measurements of the velocity of light, but were quite fundamental to the conversion of instrumental readings to a value of c. Similar considerations apply to the incorporation of the effects of the medium and the boundaries involved in the experiments. Complications arise in the regions of anomalous dispersion (absorption regions), where the phase velocity can exceed c and $d\upsilon/d\lambda$ is positive. *See also:* DISPERSION (RADIATION); FOURIER SERIES AND TRANSFORMS; GROUP VELOCITY; MAXWELL'S EQUATIONS; PHASE VELOCITY; WAVE EQUATION; WAVE MOTION.

Refractive index and dispersion. A plane wavefront, in going from a medium in which its phase velocity is υ into a second medium where the velocity is υ', changes direction at the interface. By geometry, it can be shown that $\sin i / \sin i' = \upsilon/\upsilon'$, where i and i' are the angles which the light path forms with a normal to the interface in the two media. It can also be shown that the path between any two points in this system is that which minimizes the time for the light to travel between the points (Fermat's principle). This path would not be a straight line unless $i = 90°$ or $\upsilon = \upsilon'$. Snell's law states that $n \sin i = n' \sin i'$, where n is the index of refraction of the medium. It follows that the refractive index of a medium is $n = c/\upsilon$, because the refractive index of a vacuum, where $\upsilon = c$, has the value 1.

In terms of the refractive index, Eq. (2) can be rewritten in the form of Eq. (3), where

$$u = \frac{c}{n - \lambda_0 \frac{\partial n}{\partial \lambda_0}} \qquad (3)$$

$\lambda_0 = 2\pi c/\omega$ is the wavelength in a vacuum. As one can see, the group velocity can be much less than the speed of light in a vacuum or even can be negative in the spectral range where the dispersion $\partial n/\partial\lambda_0$ is large. There are a number of mechanisms that can lead to a large variation of the refractive index in a narrow wavelength interval. Among them are nonlinear optical effects such as electromagnetically induced transparency, coherent population oscillation, and four-wave mixing. An extremely slow group velocity of laser pulses, hundreds of millions times slower than the speed of light in a vacuum, was obtained in ultracold atomic clouds known as a Bose-Einstein condensate. *See also:* BOSE-EINSTEIN CONDENSATION; NONLINEAR OPTICS.

The dispersion $d\upsilon/d\lambda$ of a medium can be obtained easily from measurements of the refractive index for different wavelengths of light. Experimental evidence, based on astronomical observations, show that the dispersion of vacuum is very small if not equal to zero. Observation of the light reaching the Earth from the eclipsing binary star Algol, 120 light-years distant (1 light-year $\cong 6 \times 10^{12}$ mi or 9.5×10^{12} km is the distance traversed in vacuum by a beam of light in 1 year), shows that the light of all colors is received simultaneously. The eclipsing occurs every 68 h 49 min. If there were a difference of velocity for red light and for blue light in interstellar space as great as 1 part in 10^6, this star would show a measurable time difference in the occurrence of the eclipses in these two colors. *See also:* BINARY STAR.

In artificial materials, fabricated as periodic structures with elements smaller than the wavelength of light and known as metamaterials, the refractive index can be negative. Light rays striking an interface with such a material are refracted on the same side of the normal to the interface. *See also:* NEGATIVE REFRACTION.

Nonlinear effects. When the intensity of light waves is so large that their electric field amplitude is appreciable in comparison with the internal electric fields in a material, the interaction of light with a medium is essentially modified. The related phenomena can be described in terms of the nonlinear polarization of the material which leads to a change of the spectral composition of the light field. In particular, two light beams of frequencies ω_1 and ω_2 propagating in a nonlinear medium generate two second-harmonic fields of frequencies $2\omega_1$ and $2\omega_2$, as well as sum-frequency and difference-frequency components at frequencies $\omega_1 \pm \omega_2$. Other nonlinear effects such as the optical Kerr effect and self-focusing are well described by the change in the refractive index proportional to the light wave intensity. Lasers, particularly pulsed lasers with high instantaneous electric fields, are often used to observe nonlinear effects of light. *See also:* KERR EFFECT; LASER; NONLINEAR OPTICS.

Corpuscular phenomena

In its interactions with matter, light exchanges energy only in discrete amounts, called quanta. This fact is difficult to reconcile with the idea that light energy is spread out in a wave, but is easily visualized in terms of corpuscles, or photons, of light. *See also:* PHOTON.

Blackbody (heat) radiation. The radiation from theoretically perfect heat radiators, called blackbodies, involves the exchange of energy between radiation and matter in an enclosed cavity. The observed frequency distribution of the radiation emitted by the enclosure at a given temperature of the cavity can be correctly described by theory only if it is assumed that light of frequency ν is absorbed in integral multiples of a quantum of energy equal to $h\nu$, where h is a fundamental physical constant called Planck's constant. This startling departure from classical physics was made by Max Planck early in the twentieth century. *See also:* HEAT RADIATION.

Photoelectric effect. When a monochromatic beam of electromagnetic radiation illuminates the surface of a solid (or less commonly, a liquid), electrons are ejected from the surface in the phenomenon known as photoemission, or the external photoelectric effect. The kinetic energies of the electrons can be measured electronically by means of a collector which is negatively charged with respect to the emitting surface. It is found that the emission of these photoelectrons, as they are called, is almost instantaneous, and independent of the intensity of the light beam, even at very low light intensities. This fact excludes the possibility of accumulation of energy from the light beam until an amount corresponding to the kinetic energy of the ejected electron has been reached. The number of electrons is proportional to the intensity of the incident beam. The velocities of the electrons ejected by light at varying frequencies agree with Eq. (4),

$$^{1}/_{2} m v_{\max}^{2} = h(\nu - \nu_0) \tag{4}$$

where m is the mass of the electron, $v_{\max}$ the maximum observed velocity, ν the frequency of the illuminating light beam, and ν_0 a threshold frequency characteristic of the emitting solid.

In 1905, Albert Einstein showed that the photoelectric effect could be accounted for by assuming that, if the incident light is composed of photons of energy $h\nu$, part of this energy, $h\nu_0$, is used to overcome the forces binding the electron to the surface. The rest of the energy appears as kinetic energy of the ejected electron.

Compton effect. The scattering of x-rays of frequency ν_0 by the lighter elements is caused by the collision of x-ray photons with electrons. Under such circumstances, both a scattered x-ray photon and a scattered electron are observed, and the scattered x-ray has a lower frequency than the impinging x-ray. The kinetic energies of the impinging x-ray, the scattered x-ray, and the scattered electron, as well as their relative directions, are in agreement with calculations involving the conservation of energy and momentum. *See also:* COMPTON EFFECT.

Quantum theories

The need for reconciling Maxwell's theory of the electromagnetic field, which describes the electromagnetic wave character of light, with the particle nature of photons, which demonstrates the equally important corpuscular character of light, has resulted in the formulation of several theories which go a long way toward giving a satisfactory unified treatment of the wave and the corpuscular picture. These theories incorporate, on one hand, the theory of quantum electrodynamics, first set forth by P. A. M. Dirac, P. Jordan, W. Heisenberg, and W. Pauli, and on the other, the earlier quantum mechanics of L. de Broglie, Heisenberg, and E. Schrödinger. Unresolved theoretical difficulties persist, however, in the higher-than-first approximations of the interactions between light and elementary particles. The incorporation of a theory of the nucleus into a theory of light is bound to call for additional formulation.

Dirac's synthesis of the wave and corpuscular theories of light is based on rewriting Maxwell's equations in a Hamiltonian form resembling the Hamiltonian equations of classical mechanics. Using the same formalism involved in the transformation of classical into wave-mechanical equations by the introduction of the quantum of action $h\nu$, Dirac obtained a new equation of the electromagnetic field. The solutions of this equation require quantized waves, corresponding to photons. The superposition of these solutions represents the electromagnetic field. The quantized waves are subject to Heisenberg's uncertainty principle. The quantized description of radiation cannot be taken literally in terms of either photons or waves, but rather is a description of the probability of occurrence in a given region of a given interaction or observation. *See also:* HAMILTON'S EQUATIONS OF MOTION; NONRELATIVISTIC QUANTUM THEORY; QUANTUM ELECTRODYNAMICS; QUANTUM FIELD THEORY; QUANTUM MECHANICS; RELATIVISTIC QUANTUM THEORY; UNCERTAINTY PRINCIPLE.

Quantum optics

The quantum properties of light manifest themselves in a variety of phenomena that are the subject matter of quantum optics. Its development was first motivated by the problems that had been posed by laser physics. In particular, to describe the output of a single-frequency laser well above the laser threshold one has to introduce the coherent quantum state. This state corresponds to a minimum-uncertainty field with equal uncertainties in the amplitude and phase of the field. On the other hand, one can generate quantum states in which fluctuations are reduced below the coherent state limit in one variable at the cost of enhanced fluctuations in the other canonically conjugate variable. Such squeezed states have diverse applications in optical communication, photon detection techniques, and noise-free amplification. A number of quantum effects are related also to the quantum statistical correlations of light. Another example is the quantum superposition of photons in different polarization states known as entangled photons. Entangled states of photons have been used in experiments on quantum teleportation and hold considerable promise for applications ranging from imaging and precision measurement to communications and computation. *See also:* COHERENCE; LASER; PHOTON; QUANTUM COMPUTATION; QUANTUM TELEPORTATION; SQUEEZED QUANTUM STATES.

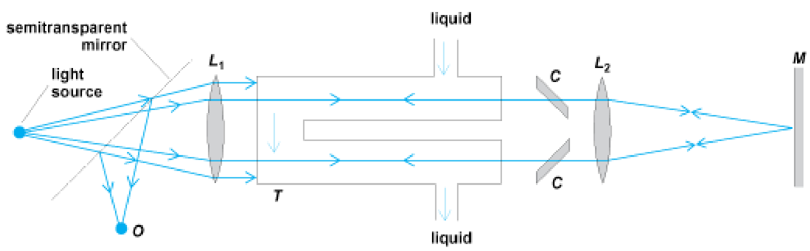

Fig. 3 **Fizeau's experiment. *C*, compensator plates; *M*, mirror; L_1, L_2, lenses; *T*, tube; *O*, interference fringes.**

Relativistic effects

The measured magnitudes of such characteristics as wavelength and frequency, velocity, and the direction of the radiation in a light beam are affected by a relative motion of the source with respect to the observer, occurring during the emission of the signal-carrying electromagnetic wave trains. *See also:* DOPPLER EFFECT.

A difference in gravitational potential also affects these quantities. Several important observations of this nature are listed in this section, followed by a discussion of several important results of general relativity theory involving light. For extended discussions of both the special theory of relativity and the general theory of relativity *See also:* RELATIVITY.

Velocity in moving media. In 1818, A. Fresnel suggested that it should be possible to determine the velocity of light in a moving medium, for example, to determine the velocity of a beam of light traversing a column of liquid of length d and of refractive index n, flowing with a velocity υ relative to the observer, by measuring the optical thickness nd. The experiment was carried out by Fizeau in a modified Rayleigh interferometer, shown in **Fig. 3**, by measuring the fringe displacement in O corresponding to the reversing of the direction of flow. If υ' is the phase velocity of light in the medium (deduced from the refractive index by the relation $\upsilon = c/n$), it is found that the measured velocity υ_{m} in the moving medium can be expressed as $\upsilon_{\mathrm{m}} = \upsilon' + \upsilon\,(1 - 1/n^2)$ rather than $\upsilon_{\mathrm{m}} = \upsilon' + \upsilon$, as would be the case with a Newtonian velocity addition.

Aberration. J. Bradley discovered in 1725 a yearly variation in the angular position of stars, the total variation being 41 seconds of arc. This effect is in addition to the well-known parallax effect, and was properly ascribed to the combination of the velocity of the Earth in its orbit and the speed of light. Bradley used the amplitude of the variation to arrive at a value of the velocity of light. George Airy compared the angle of aberration in a telescope before and after filling it with water, and discovered, contrary to his expectation, that there was no difference in angle. *See also:* ABERRATION OF LIGHT.

Michelson-Morley experiment. The famous Michelson-Morley experiment, one of the most significant experiments of all time, was performed in 1887 to measure the relative velocity of the Earth through inertial space. Inertial space is space in which Newton's laws of motion hold. Dynamically, an inertial frame of reference is one in which the observed accelerations are zero if no forces act. A point in an orbit is the center of such a frame. *See also:* FRAME OF REFERENCE.

The rotation of the Earth about its axis, with tangential velocities never exceeding 0.3 mi/s (0.5 km/s) is easily demonstrated mechanically (Foucault's pendulum, precession of gyroscopes) and optically (Michelson's rectangular interferometer). The surface of the Earth is not an inertial frame. In its orbit around the Sun, on the other hand, the Earth has translational velocities of the order of 18 mi/s (30 km/s), but this motion cannot be detected by mechanical experiments because of its orbital nature. The hope existed, however, that optical experiments would permit the detection (and measurement) of the relative motion of the Earth through inertial space by comparing the times of travel of two light beams, one traveling in the direction of the translation through inertial space, and the other at right angles to it. The hope was based on the now disproven notion that the velocity of a light would be equal to the constant c only when measured with respect to the inertial space, but would be measured as smaller $(c - \upsilon)$ or greater $(c + \upsilon)$ with respect to a reference frame, such as the Earth, moving with a velocity υ in inertial space if a light beam were projected respectively in the direction and in the opposite direction of translation of this frame. According to classical velocity addition theorems (which, as is now known, do not apply to light), a velocity difference of 2υ would be detected under such circumstances. *See also:* EARTH ROTATION AND ORBITAL MOTION.

Not only does the Earth move in an orbit around the Sun, but it is carried with the Sun in the galactic rotation toward Cygnus with a velocity of several hundreds of miles per second, and the Galaxy itself is moving with a high speed in its local spiral group. Speeds of hundreds and possibly thousands of miles per second should be detectable by measurements on Earth in two orthogonal directions, assuming of course that the Earth motion is itself with respect to inertial space, or indeed that such a space has the physical meaning ascribed to it. The unexpected result of the experiment was that no such velocity difference could be detected, that is, no relative motion could be detected by optical means.

The Michelson-Morley apparatus (**Fig. 4**) consists of a horizontal Michelson interferometer with its two arms at right angles. The mirrors are adjusted so that the central white-light fringe falls on the cross hair of the observing telescope. This indicates equality of optical phase, and therefore an equality of the times taken by the light beams to travel from the beam-splitting surface to each of the two mirrors and back. Rotation of the entire system by 90°, or indeed by any angle, as well as repetition of the experiment at various times of the year all are found to leave the central white-light fringe and associated fringe system undisplaced, indicating no change in the time required by the light to traverse the two arms of the interferometer when their directions relative to the direction of the Earth's motion are varied. Had there been a difference in the velocity of light in the two directions *OM* and *ON*, the two arms would be of unequal length in the initial adjustment. For example, if the light traveled faster in the direction *OM* (on the average, going back and forth), then the corresponding arm would have to be longer so as to make the time of travel equal in both arms. If the apparatus were turned through 90°, the shorter arm would take the place of the longer arm, and the "faster" light would now travel in the shorter arm, and the "slower" light in the longer arm; a noticeable fringe displacement would, but actually does not, take place.

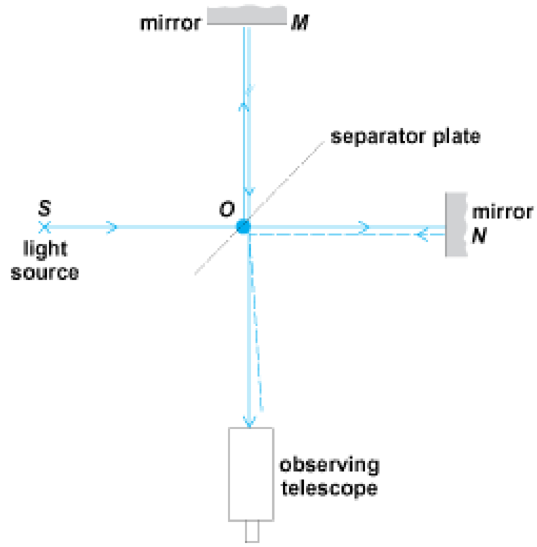

Fig. 4 **Michelson-Morley experiment.**

Einstein's theory accounts for the null result by the simple explanation that no relative motion between the apparatus and the observer exists in the experiment. No change in measured length has occurred in either direction, and because the propagation of light is isotropic, no velocity difference or detection of relative motion should be expected.

Gravitational and cosmological redshifts. Two different kinds of shifts, or displacements of spectral lines toward the red end of the spectrum, are observed in spectrograms taken with starlight or light from nebulae. One is the rare, but extremely significant, gravitational redshift or Einstein shift, which has been measured in some spectra from white dwarf stars. The other, much more widely encountered, is the redshift in spectra from external galaxies usually described as being caused by a radial Doppler effect characterizing an "expansion of the universe."

The most famous example of the gravitational redshift is that observed in the spectrum of the so-called dark companion of Sirius. The existence of this companion was predicted by F. W. Bessel in 1844 on the basis of a perturbation in the motion of Sirius, but because of its weak luminosity (1/360 that of the Sun, 1/11,000 that of Sirius), it was not observed until 1861. This companion is a white dwarf of a mass comparable to that of the Sun (0.95), but having a relatively small radius of 11,000 mi (18,000 km) and the fantastically high density of 61,000 times that of water. This companion shows a shift in its spectral lines relative to the ones emitted by Sirius itself; the shift of 0.03 nm for the Balmer β-line of hydrogen was reliably determined by W. S. Adams. In 1960, R. V. Pound and G. A. Rebka, Jr., measured the gravitational redshift in a laboratory experiment involving the Mössbauer effect. *See also:* GRAVITATIONAL REDSHIFT.

The cosmological redshift is a systematic shift observed in the spectra of all galaxies, best measured with the calcium H and K absorption lines. Distances of galaxies are determined photometrically by measurements of their intensities, and it is found that the wavelength shift toward the red increases with the distance of the galaxies from the Earth. (The Earth does not have a privileged position if expansion of the universe is indeed involved. Rather its position is somewhat like that of a person in a crowd which is dispersing—each individual experiencing an ever-increasing distance from every other one.) The change of wavelength with distance d is given by Eq. (5), where $1/H$ is $1\text{–}2 \times 10^{10}$ light-years.

$$\frac{\Delta\lambda}{\lambda} = Hd \tag{5}$$

See also: REDSHIFT.

Results of general relativity. The propagation of light is influenced by gravitation. This is one of the fundamental results of Einstein's general theory of relativity which has been subjected to experimental tests and found to be verified. Three important results involving light need to be singled out.

1. The velocity of light, measured by the same magnitude c independently of the state of motion of the frame in which the measurement is being carried out, depends on the gravitational potential Φ of the field in which it is being measured according to Eq. (6).

$$c = c_0 \left(1 + \frac{\Phi}{c^2}\right) \tag{6}$$

Here $\Phi = -GM/R$, where G is the universal constant of gravitation (6.670×10^{-11} in SI units), M the mass of the celestial body, R the radius of the body, and c_0 the velocity of light in a vacuum devoid of fields.

For example, the absolute value of the term Φ/c^2 is about 3000 times greater on the Sun than on Earth, making the measurements of c smaller by two parts in 10^6 on the Sun as compared to those on Earth.

2. The frequency ν of light emitted from a source in a gravitational field with the gravitational potential Φ is different from the frequency ν_0 emitted by an identical source (atomic, nuclear, molecular) in a field-free region, according to Eq. (7).

$$\nu = \nu_0 \left(1 + \frac{\Phi}{c^2}\right) \tag{7}$$

Spectral lines in sunlight should be displaced toward the red by two parts in 10^6 when compared to light from terrestrial sources.

3. Light rays are deflected when passing near a heavenly body according to Eq. (8),

$$\alpha = \frac{4GM}{c^2 R} \tag{8}$$

where α is the angular deflection in radians, and R the distance of the beam from the center of the heavenly body of mass M. The deflection is directed so as to increase the apparent angular distance of a star from the center of the Sun when starlight is passing near the edge of the Sun. The deflection according to this equation should be 1.75 seconds of arc, a value which compares favorably with eclipse measurements of the star field around the Sun in 1931. These measurements indicated values up to 2.2 seconds of arc when compared with photographs of the same field 6 months earlier. Measurements of the deflection of radio waves from extremely small diameter celestial radio sources in 1974–1975 agreed with Einstein's theory to within 1%. This prediction of Einstein's theory might seem less surprising today when the corpuscular-photon character of light is widely known, and when a Newtonian M/R^2 attraction might be considered to be involved in the motion of a corpuscle with the velocity c past the Sun. However, application of Newton's law predicts a deviation only half as great as the well verified relativistic prediction.

Matter and radiation

The possibility of creating a pair of electrons—a positively charged one (positron) and a negatively charged one (negatron)—by a rapidly varying electromagnetic field (gamma rays of high frequency) was predicted as a consequence of Dirac's wave equation for a free electron and has been experimentally verified. I. Curie and F. Joliot, as well as J. Chadwick, P. M. S. Blackett, G. P. Occhialini, and others have compared the number of positrons and negatrons ejected by gamma rays passing through a thin sheet of lead (and other materials) and have found them to be the same, after accounting for two other groups of electrons also appearing in the experiment (photoelectrons and recoil electrons). Other examples of negatron-positron pair production include the collision of two heavy particles, a fast electron passing through the field of a nucleus, the direct collision of two electrons, the collision of two light quanta in a vacuum, and the action of a nuclear field on a gamma ray emitted by the nucleus involved in the action.

Evidence of the creation of matter from radiation, as well as that of radiation from matter, substantiates Einstein's equation (9),

$$E = mc^2 \tag{9}$$

which was first expressed in the following words: "If a body [of mass m] gives off the energy E in the form of radiation, its mass diminishes by E/c^2." In regard to exchanges of energy and momentum, electromagnetic waves behave like a group of particles with energy as in Eq. (10) and momentum as in Eq. (11).

$$E = mc^2 = h\nu \tag{10}$$

$$p = \frac{h\nu}{c} = \frac{h}{\lambda} \tag{11}$$

Finally, many experiments with photons show that they also possess an intrinsic angular momentum, as do particles. Circularly polarized light, for example, carries an experimentally observable angular momentum, and it can be shown that, under certain circumstances, an angular momentum can be imparted to unpolarized or linearly polarized light (for example, in the case of a plane wave passing through a finite circular aperture). In any case, the angular momentum is quantized in units of $h/2\pi$.

The inverse process to the creation of electron pairs is the annihilation of a positron and a negatron, resulting in the production of two gamma-ray quanta (two-quantum annihilation). Nuclear chain reactions are known to involve similar processes. *See also:* CHAIN REACTION (PHYSICS); ELECTRON-POSITRON PAIR PRODUCTION; ELEMENTARY PARTICLE.

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Keywords

light; speed of light; photons; electromagnetic radiation; electromagnetic waves.

Test Your Understanding

1. List the colors of the visible spectrum from lowest to highest frequency.
2. How is the energy of a photon related to its frequency?
3. Critical Thinking: What is an example of a way in which light behaves like a particle? Like a wave?
4. Critical Thinking: What happens to the mass of an electron as it is accelerated near the speed of light?
5. Critical Thinking: Explain how the observed redshifts of distant galaxies indicate that the universe is expanding.

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Speed of Light