ENCYCLOPAEDIC DICTIONARY OF PHYSICS

Volume 1

A to COMPENSATED BARS

ENCYCLOPAEDIC DICTIONARY OF PHYSICS

GENERAL, NUCLEAR, SOLID STATE, MOLECULAR
CHEMICAL, METAL AND VACUUM PHYSICS
ASTRONOMY, GEOPHYSICS, BIOPHYSICS
AND RELATED SUBJECTS

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FOREWORD

IT IS nearly forty years (1922–23) since a comprehensive Dictionary of Physics — the Dictionary of Applied Physics, edited by Sir Richard Glazebrook — appeared in English. The need has long been felt for another Dictionary of comparable size, so that the appearance of the present Encyclopaedic Dictionary of Physics would appear to be timely, although it may be as well to say at once that the work is not a modern version of "Glazebrook"; its basis is quite different. The title "Encyclopaedic Dictionary of Physics" was chosen only after a great deal of discussion and we hope our readers will agree that it adequately describes the work. The use of adjectives such as "pure" and "applied" were considered and discarded, as it became speedily apparent that each meant different things to different people.

Many fundamental advances in physics have been made since 1922, and the impact, for example of wave-mechanics and of modern developments of the quantum theory could not even have been foreseen at that time. With these advances has come, inevitably it would seem, an ever-growing tendency towards specialization. At the same time, modern physical ideas, paradoxically enough, have achieved a remarkable degree of unification, not only of physics itself, but of many branches of science that at one time might well have been considered to be almost unrelated. For instance, we now take it for granted that physics forms the basis of much of chemistry and metallurgy. Physics is also being applied more and more to the study of living matter. The present Dictionary aims, therefore, at covering not only Physics proper but also to a greater or lesser extent such subjects as Mathematics, Astronomy, Aerodynamics, Hydraulics, Geophysics, Metrology, Physical Metallurgy, Radiation Chemistry, Physical Chemistry, Structural Chemistry, Crystallography, Medical Physics, Biophysics and Photography. It should be useful not only to physicists (and would-be physicists) but to those who are concerned with any of the many branches of science mentioned or implied above, which have a physical basis. The articles are, in general, of graduate or near-graduate standard. They are not written primarily for specialists, but a few, mainly theoretical or mathematical in nature, are inevitably of a more advanced character.

The reader may perhaps be interested to learn how we set about such an ambitious enterprise as the publication of a Dictionary of Physics on the present scale. Once the main principles were settled, the work was tackled in two main stages. The first was to draw up a list of articles to be written, to decide their approximate lengths, and to select which of them did not merit separate articles but could be treated in other articles. The second was to commission the articles and get them written; not the easiest of tasks, for either editor or author, owing to the inevitably lengthy period during which the Dictionary has been in the course of preparation. The decision to include borderline subjects meant of course that we were faced with the problem of selection. Where does one draw the line between Physics and Chemistry, or Metallurgy, or Astronomy, or any of the other subjects whose borders overlap with those of Physics? No two people will have the same ideas on such questions, so we have made such a choice as seemed appropriate to us.

In the first of the two stages mentioned we have had the assistance of many specialist consultants in various branches of Physics and related subjects; their names are listed inside the back cover of each volume as consultant editors. In consequence, a comprehensive coverage has been achieved, possibly at the cost of a little overlapping; a small price to pay, however. The second stage has been carried out, in the main, by authors recommended by the specialist consultants as authorities in their own particular fields, to ensure, as far as possible, that the articles should be authoritative and up-to-date. It is self-evident, however, that no work of this kind can be entirely up-to-date; but we feel confident that, within the obvious limitations by which we are bound, we have made a good attempt. A list of the authors who have contributed to each volume is given at the beginning of that volume. The author's name is given in full at the foot of each article, except for a few short articles written by the staff of the Dictionary.

In 1922 Glazebrook wrote: "It is clear that, with so large a range of subjects, any individual worker will probably be concerned mainly with one branch, and, with this in mind, the volumes have been arranged as far as possible, into subjects." This type of arrangement has not been adopted in the present work for, as we have already said, the increasing compass of modern physics has been accompanied by a corresponding unification within physics and the subjects bordering on it. The result is that no worker can now afford to ignore other branches of physics if he is to understand his own branch adequately. No attempt has been made, therefore, to segregate subjects in different volumes. Indeed the overlapping that would occur between such volumes would prohibit such a procedure; and the Dictionary has, in consequence, been arranged in strictly alphabetical form. Nevertheless the order of words is such that, where possible, terms related to some main topic are listed together. For example the various types of nuclear reactor are listed as special examples of the term *Nuclear reactor*. Thus we have: *Nuclear reactor, breeder type; Nuclear reactor, thermal type;* and so on. The result of this arrangement is that some articles which the reader might expect to find in a particular volume will appear to be absent because they are entered elsewhere. Reference to the index volume will readily show, however, where such articles appear, since the index gives all reasonable variations of the word order of every term in the Dictionary. The index also shows where those topics which do not form the subjects of separate articles are treated in the Dictionary. Such topics are denoted, in the articles where they occur, by being printed in bold type the first time they are mentioned. Where the treatment is implicit rather than explicit this course of action has, naturally, not been possible.

It is to be expected that many of those who wish to consult the Dictionary will be busy people who will not have the time or inclination to read an exhaustive account of all the various aspects of a subject in order to find the topic of interest. Indeed, many of them, being anxious to clear up some one particular point, will be well acquainted with the bulk of the material that would be contained in such an account. On the other hand there will be others, less knowledgeable or with more time, who wish to become familiar with a subject in all its ramifications. In order to cater for both extremes, it was decided that, with a few exceptions, no article would be longer than 2000–3000 words; many are much shorter. Each is self-contained, but, to permit the reader to follow a subject as far as he wishes, cross references to related articles are appended where necessary. Bibliographies are also provided to enable him to pursue his studies further.

Generally speaking, the cross references to which we have just alluded, do not include mention of neighbouring articles which are clearly devoted to different aspects of the same main topic. Where, however, not all the neighbouring articles are relevant, those that are of interest are then entered as cross-references.

We have already said that the order of terms is strictly alphabetical. This makes for a considerable degree of simplification; but, even so, difficulties can arise in term order associated with the use of the terminal letters. The convention adopted has been to avoid the use of the plural and apostrophes wherever possible, and to ignore the latter in deciding the order of terms in the Dictionary.

From the start we decided to impose the minimum conditions on authors as regards symbols and units and the main rule we have tried to follow is that an author shall be consistent, and shall explain the symbols and abbreviations he uses. We have not, for example, decided for or against the use of any particular systems of units so long as authors are clear and self-consistent. However, there is a necessary minimum of conformity; and so we have adopted the following symbols for the general physical constants, taken from British Standards No. 1991.

Term	*Symbol*	*Term*	*Symbol*
speed of light	c	Planck's constant	h
Avogadro's number	N	Bohr's magneton	β
gas constant per mole	R	Rydberg's constant	R
Boltzmann's constant	k	Stefan-Boltzmann constant	σ
Faraday's constant	F	gravitational constant	G
charge of electron	$-e$	gravitational acceleration, standard value	g
mass of electron	m		

In addition we have used the abbreviations for internationally accepted units that are recommended in the same document.

We have also adopted the convention by which, in writing the symbols for chemical elements or nuclides the numerals attached have the following significance:

upper left — mass number
lower left — nuclear charge
lower right — number of atoms in molecule.

Thus ${}^{7}_{3}Li$ represents a lithium nucleus of mass 7 and ${}^{2}_{1}H_2$ or D_2 represents a molecule of deuterium. By extension ${}^{1}_{0}n$ represents a neutron.

It only remains to pay tribute to the assistance rendered by advisors, authors and referees. And to acknowledge the help and encouragement given by the publishers; in the early days by Dr. P. Rosbaud and later by Captain I. R. Maxwell. Of the Associate Editors, Dr. D. J. Hughes carried out much of the commissioning in the U.S.A. until his untimely death and Dr. A. R. Meetham, in this country, has rendered invaluable assistance in many ways, besides being largely responsible for the planning of the Multi-language Glossary. I should also like to mention Mr. R. C. Glass who took over the duties of Associate Editor at a critical time and I cannot close without reference to the staff at the Pergamon Press, who have worked in the background, often against odds and always against time. Finally I owe a big depth of gratitude to my wife who has been of constant help in a variety of ways from the outset; and who indeed constituted, for a time, the total secretarial and office staff of the Dictionary.

HARWELL
September 1960

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ERRATA

P. 73. Col. I. See also: for Antenna read: Various articles beginning "Antenna".
P. 114. Col. I. line 42 should read: — i.e. ratio of total scattered energy to incident energy.
P. 220. Col. I line 40: — for 1 (a) read 1 (b)
P. 243. Col. I. See also: for "Spectrograph grating" read "Spectrograph, concave grating".
For ampére (unit) read ampere.
For Ampére read Ampère.

PUBLISHER'S NOTE AND SUGGESTIONS TO READERS ON HOW TO USE THE ENCYCLOPAEDIC DICTIONARY

The appearance of this comprehensive work marks the culmination of many years of painstaking effort by the Editors, Editorial Consultants, Advisers and contributors, numbering over 3000 in all. The vast expansion of physics during the past 20 years has made the publication of a successor to Glazebrook an urgent necessity.

It is a pleasure to express my gratitude and thanks to Dr. and Mrs. J. Thewlis, Dr. A. R. Meetham, Mr. R. C. Glass and Dr. D. J. Hughes (whose tragic untimely death is such a great loss to physics), for their untiring efforts to bring this work to fruition. My appreciation is also extended to the Editorial Consultants, Advisers, and contributors who have given so generously of their time and effort in the furtherance of this project of education and the ready availability of authoratative and up-to-date information in physics.

All important terms are the subject of individual articles but many items are not given separate entries but are covered in other relevant articles. The reader should, therefore, in the first instance, refer to the index where the location of the topic will be given. At the end of most articles will be found various cross-references to other articles where additional information can be obtained, together with a bibliography of useful sources for further reading.

Oxford
December, 1960

ROBERT MAXWELL
Publisher at Pergamon Press

ABBÉ REFRACTOMETER. A device for the direct determination of the refractive indices of liquids.

It employs the principle of total internal reflection in a small quantity of the liquid under test which is placed between the diagonal faces of two polished right-angled prisms of dense flint glass. Observations are made by a telescope moving over a graduated scale which gives a direct reading of refractive indices. The telescope is set so that its cross wires are upon a clear line of demarcation of difference of intensity in the field of view.

The prisms are enclosed in a water jacket to allow control of temperature.

The scale may also be calibrated to read concentrations of sugar solutions since the refractive index of a solution is a function of its concentration.

J.A. Farnham and G.W. Canning

ABEL EQUATION. Abel's equation is the integral equation

$$\int_0^x \frac{\varphi(s)\,\mathrm{d}s}{(x-s)^p} = f(x)$$

where $f(x)$ is known, $f(0) = 0$, $0 < p < 1$ and it is desired to find the function $\varphi(s)$. The solution is

$$\varphi(x) = \frac{\sin p\pi}{\pi} \int_0^x \frac{f'(s)\,\mathrm{d}s}{(x-s)^{1-p}}\,.$$

I.N. Sneddon

ABERRATION OF LENS SYSTEMS. According to the principles of geometrical optics an ideal optical system should form point images of point objects and deviations from this behaviour are termed aberrations. Since the wavefronts (or surfaces of constant optical path) are orthogonal to the rays an aberration may be considered as either non-concurrence of a ray-bundle or non-sphericity of a wavefront.

Take a rectangular co-ordinate system (Fig. 1) with origin A at the centre of the exit pupil, z-axis along the principal ray and y-axis on the meridian or tangential plane (the plane containing the optical axis and the principal ray). Let S be a spherical surface, the reference sphere, with centre O on the z-axis and radius OA. The point O is the image point to which the aberrations are referred; it may be the Gaussian image point or the intersection of Oz, with any chosen image surface. Let Σ be the wavefront of the imaging pencil which passes through A. Then the *wavefront aberration* W at a point P on the wavefront can be defined as the optical path length between Σ and S, measured along a ray and taken as positive when Σ

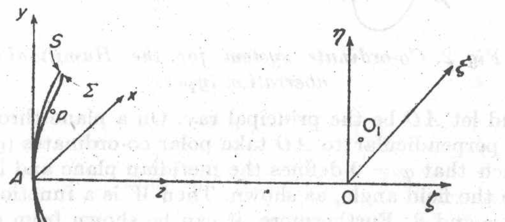

Fig. 1. To illustrate the definitions of aberrations.

is in advance of S as in the diagram. So defined, W is a function of the position of P and of the obliquity of the principal ray Oz.

Take rectangular axes $O\xi\eta$ in the image plane as shown and let the ray through P meet the $\xi\eta$-plane in O_1, with co-ordinates (ξ, η). Then (ξ, η) are the components of the *transverse ray aberration* for the ray in question.

The components of *angular ray aberration* may be defined in terms of the projections on the (x, z) and (y, z) planes of the angle between the ray PO_1, and the line PO, a normal to the reference sphere. When the aberrated ray intersects the principal ray we can define a longitudinal ray aberration as the distance between this intersection point and the image plane.

It can be seen that in every case the magnitudes of the aberrations depend on the position of the image plane. When the principal ray does not coincide with the optical axis the image plane is often taken as the Gaussian image plane and is thus oblique to the principal ray. Also the centre of the reference sphere, i.e. the origin for measurement of transverse ray aberrations, is often taken as the Gaussian image point.

If W is expressed as a function of x and y, the coordinates of P, the transverse aberration is given in terms of W to a certain order of approximation by

$$\left.\begin{aligned} \xi &= \frac{R}{n}\frac{\partial W}{\partial x} \\ \eta &= \frac{R}{n}\frac{\partial W}{\partial y} \end{aligned}\right\} \qquad (1)$$

See Index for location of terms not found in this volume

where R is the radius of the reference sphere, i.e. the distance AO, and n is the refractive index.

The Hamilton theory of aberration types. The aberrations of a symmetrical optical system, i.e. one composed of refracting or reflecting elements with a common axis of rotational symmetry, were classified by Hamilton by expressing the total aberration as a power series in the pupil and field variables. We can do this for the wavefront aberration W as follows. Referring to Fig. 2, let A be the centre of the exit pupil

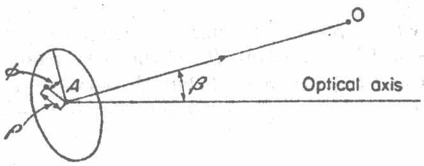

Fig. 2. Co-ordinate system for the Hamiltonian aberration types.

and let AO be the principal ray. On a plane through A perpendicular to AO take polar co-ordinates (ϱ, φ) such that $\varphi = 0$ defines the meridian plane and let β be the field angle, as shown. Then W is a function of ϱ, φ and β. Furthermore, it can be shown from considerations of symmetry that it must be a function of the variables ϱ^2, $\varrho\beta\cos\varphi$ and β^2. Thus the power series for W will be, with an obvious notation for the coefficients,

$$C_{000} + C_{100}\varrho^2 + C_{010}\varrho\beta\cos\varphi + C_{001}\beta^2 + C_{200}\varrho^4 + \\ + C_{110}\varrho^3\beta\cos\varphi + C_{020}\varrho^2\beta^2\cos^2\varphi + C_{101}\varrho^2\beta^2 + \\ + C_{011}\varrho\beta^3\cos\varphi + C_{002}\beta^4 + \text{higher orders}\ldots \quad (2)$$

(In an alternative development, due to F. Zernike, terms of the form $\cos n\varphi$ appear instead of $\cos^n\varphi$; the terms obtained differ in the higher orders, neglected in equation 2.)

The constant term may be ignored since it denotes merely a constant displacement between the wavefront and the reference sphere and the same applies to the C_{001} and C_{002} terms. The C_{100} term corresponds to a longitudinal displacement between the centre of the reference sphere and the focus of the wavefront, i.e. a longitudinal focal shift, and the C_{010} term corresponds to a transverse displacement. If we postulate that the reference sphere is to be centred on the Gaussian image point both of these terms must vanish. The remaining five terms correspond to the so-called first-order, primary or Seidel aberrations. We next describe the wavefront shapes, and the corresponding transverse ray aberration patterns, which are obtained by application of equation 1 or its equivalent in polar co-ordinates.

The term in C_{200} is called **spherical aberration.** The aberration follows a fourth power law and is independent of azimuth (φ) or field angle (Fig. 3). The ray intersection pattern is as shown in Fig. 4. The rays intersect the Gaussian image plane in a central bright core surrounded by a fainter outer halo and a better image is obtained by changing the focus, for example to plane ab, where the rays cover a minimum circle (the disk of least confusion). The envelope OQ

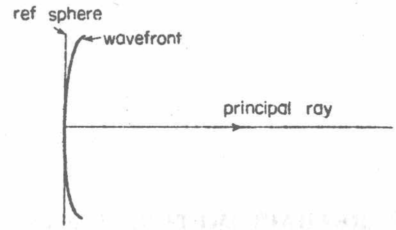

Fig. 3. Cross-section of wavefront with positive spherical aberration, referred to reference sphere of infinite radius.

of the rays is the *caustic*; the surfaces of revolution defined by the caustic and the axis of symmetry together form the evolute surfaces of the ray bundle.

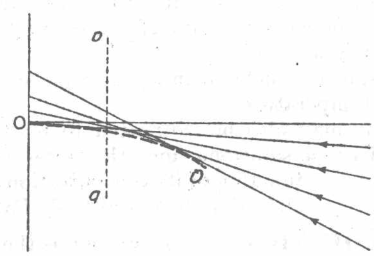

Fig. 4. The ray pattern in spherical aberration.

The term in C_{110} is *coma* (Figs. 5 and 6). It follows a cubic law in the meridian section and the wavefront aberration is zero in the sagittal section although the transverse ray aberration is not. The latter is best described in terms of the intersections of the rays in

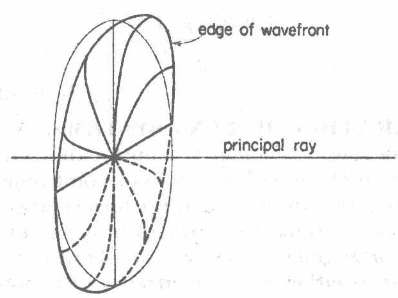

Fig. 5. Coma as a wavefront aberration referred to a reference sphere of infinite radius of curvature. The radial lines show the intersection of planes of constant φ with the wavefront.

the image plane corresponding to constant ϱ in the pupil. The result, shown in Fig. 6, is a pattern in which each circle is described twice as the value of φ in the pupil goes from 0 to 2π. The linear dependence on β means that the reduction of coma is important in securing a good image near the optical axis. Even if spherical aberration is eliminated it is conceivable that the size of the coma pattern may be greater than the distance of the Gaussian image point from the axis, in which case no recognizable image of an extended object would be obtained.

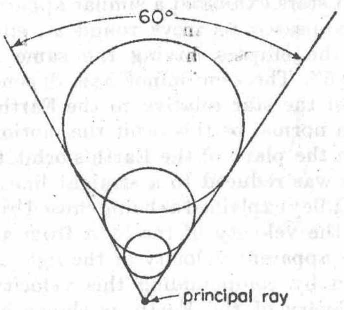

Fig. 6. Ray intersection pattern for coma.

No improvement in the coma image is obtained by changing the focus but on the other hand the maximum ray concentration in the image plane does not occur at the Gaussian image point; this may be considered as a transverse shift of focus.

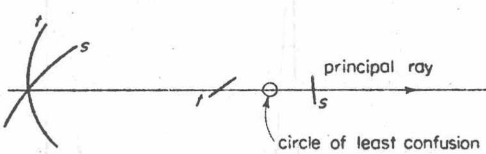

Fig. 7. Astigmatic wavefront and focal lines.

The term in C_{020} is *astigmatism* and the wavefront shape is that of a surface with two different curvatures in the meridian and sagittal sections (Fig. 7), i.e. a surface of double curvature in the ordinary sense of differential geometry. We note here that the orders of magnitude of ϱ which are neglected are different for the different Seidel aberrations. This is because the order of the aberration is defined in terms of the sum of the powers of ϱ and β. The ray pattern for astigmatism is shown in Fig. 7. The rays in the meridian section focus at t and those in the sagittal section at S, and it is found that *all* rays pass through a line in the section perpendicular to the axis at t and through a line in the t section perpendicular to the axis at S. These are called respectively the *meridian* (or *tangential*) and *sagittal* (or *radial*) *focal lines*. At a point midway between the focal lines the rays fall within a circle which is again called the circle of least confusion and the "best image" is usually said to lie here.

The dependence of astigmatism on field angle is best discussed in conjunction with *field curvature*, the term in C_{101}; this is simply a longitudinal focus change and both this and astigmatism depend on the square of β. Thus the image region can be represented as in Fig. 8, where OC represents the image surface with field curvature. If, in addition, there is astigmatism the sagittal focal lines will lie on this surface since the astigmatism term is zero at $\varphi = \pi/2$ but the tangential focal lines will lie on another surface OT.

The last term, C_{011} is *distortion.* It is a transverse displacement of the image point depending on the cube of the field angle. The effect is as in Fig. 9 where

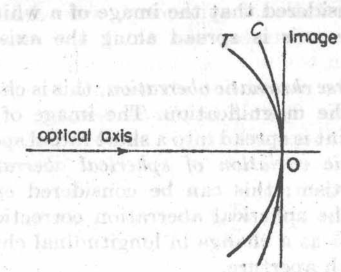

Fig. 8. Image surfaces with astigmatism and field curvature.

(a) is a square in the object plane and (b) and (c) are the corresponding images with positive and negative distortion. They are known as barrel and pin-cushion distortion respectively.

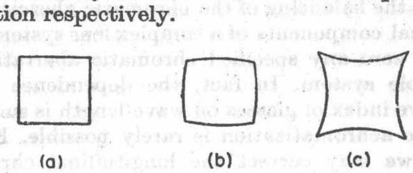

Fig. 9. Images of a square with distortion.

Higher order aberrations are those corresponding to higher terms in the power series (1). The most important are the higher-order spherical aberration terms, depending on ϱ^6, ϱ^8, etc. There is no agreed nomenclature for the other aberration types but a rough classification can be made according to whether the aberration is axially symmetric (spherical aberration type), has two planes of symmetry (astigmatic type) or only one plane of symmetry (coma type). It has been noted by E. Wolf that there is no unique order-to-order correspondence between higher-order wavefront and ray aberrations.

Characteristic function or *eikonal* are names for various potential functions which have been used to describe the aberrations of the symmetrical optical instrument. They are defined as the optical path lengths between points in the object and image spaces, the independent variables being the co-ordinates of these points, and the ray aberrations can be obtained as partial derivatives. The development of aberration theory along these lines has been given by G. C. Steward and by J. L. Synge.

Chromatic aberration. The aberrations of an optical system are functions of the constructional data, i.e. curvatures, separations and refractive indices and since all optical glasses have dispersion it follows that the aberrations as described above will be functions of the wave-length of the light transmitted by the system. This effect, chromatic aberration, is chiefly of

 See Index for location of terms not found in this volume

importance in three cases, of which the first two are strictly not aberrations at all but simply variations of the Gaussian or paraxial properties.

(1) *Longitudinal chromatic aberration;* this is chromatic variation of the position of the axial image point. It may be considered that the image of a white point source on the axis is spread along the axis into a spectrum.

(2) *Transverse chromatic aberration;* this is chromatic variation of the magnification. The image of an off-axis object point is spread into a short radial spectrum.

(3) *Chromatic variation of spherical aberration,* or spherochromatism; this can be considered either as a change in the spherical aberration correction with wave-length or as a change in longitudinal chromatic aberration with aperture.

The remaining chromatic effects on aberrations are generally so small as not to merit consideration in practical optical systems, although in special cases they may have to be taken into account.

***Achromatization** of lens systems.* This term is applied to the balancing of the chromatic aberrations of individual components of a complex lens system to reduce to zero any specified chromatic aberration for the whole system. In fact, the dependence of the refractive index of glasses on wave-length is such that complete achromatization is rarely possible. For example, we may correct the longitudinal chromatic aberration of a doublet objective so that the foci for the C and F hydrogen lines coincide, but there will then be a residual longitudinal chromatic aberration for other wave-lengths; the axial spectrum mentioned above is folded over to produce a minimum focus but there is a residual *secondary spectrum.*

Colour correction of lenses. This is the term used to denote the particular pair of wave-lengths for which a system is achromatized. For example, in the case mentioned above the system would be said to be corrected "C to F", which is the usual condition for instruments for visual use. For photography with non-colour-sensitive emulsions a system might be corrected for the range "F to G'", i.e. blue-green to violet. This usually applies more specifically to longitudinal chromatic aberration but the other chromatic aberrations would be similarly corrected.

See also: Optical calculations.

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W. T. WELFORD

ABERRATION OF LIGHT. Stars appear to alter their relative position during the year as a consequence of the Earth's motion about the Sun. This is a parallax effect dependent upon distance, only perceptible for the nearer stars, and on which a unit of stellar distance, the parsec, is based. In 1725/6 James Bradley, while attempting to measure the parallax of the star γ in Draco, observed a motion not attributable to parallax, and subsequently found that other fixed stars exhibited a similar apparent motion. All stars appeared to move round an ellipse in one year, all the ellipses having the same semi-major axis of 20·5″. The semi-minor axis depended on the direction of the star relative to the Earth's orbit: in a direction normal to this orbit the motion appeared circular, in the plane of the Earth's orbit, the ecliptic, the ellipse was reduced to a straight line.

This, Bradley explained as being caused by the magnitude c of the velocity of the light from a star being finite. The apparent velocity of the light from a star is obtained by compounding this velocity with the orbital velocity of the Earth as shown in Fig. 1(b). The angle α between the real and apparent directions of the star A is given by $\tan \alpha = v/c$.

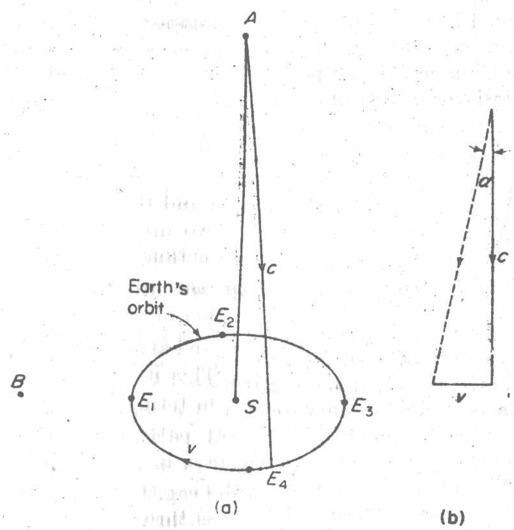

Fig. 1

As SA is normal to the Earth's orbit the magnitude of the angle of aberration α will be the same throughout the year. The direction of apparent displacement of A however is in the direction of the Earth's velocity and A therefore appears to move round a small circular path each year. A star at B on the other hand does not appear displaced at all when the Earth is in positions E_2 and E_4 (Fig. 1(a)) and has equal and opposite angles of aberration when the Earth is at E_1 and E_3. The apparent motion of B is therefore a straight line and stars in positions between A and B follow elliptical "orbits". Bradley knew v reasonably accurately and from the measured maximum value of α was able to estimate c, the velocity of light. He then calculated the maximum discrepancy to be expected between calculated and observed times of eclipses of Jupiter's satellites caused by the finite time taken for light to transverse the Earth's orbit. His result of $\pm$ 8 min 12 sec agreed well with observation.

Airy's experiment. If the aberration of light were to be observed in a telescope filled with water, then, the velocity of light in the telescope being c/n, the expected maximum aberration would be $\tan^{-1}v/(c/n)$, i.e. the aberration would be increased by a factor n. Fresnel saw that this would be altered by the ether drag and showed that the observed aberration should not be affected by the presence of the water.

In Fig. 2, light from a star is incident in a direction SA. An air-filled telescope has to be pointed in a direction DA such that $\angle DAB = \alpha$, the angle of aberration, in order that D shall move to B while the light traverses AB. If the telescope AD is now filled with water, the incident light would be refracted along the path AB' if there were no motion relative to the ether. Any motion of the observer will result in aberration, i.e. in effect turning the light path from the direction AB' towards the direction AD by the angle of aberration in water. If there is ether drag with drag coefficient $1 - 1/n^2$ the light waves will now be given a component of velocity $v(1 - 1/n^2)$ in the direction of v. The relative motion of the telescope in this direction is now decreased to $v - v(1 - 1/n^2) = v/n^2$. The velocity of light in water is c/n so that the angle of aberration in water is $\tan^{-1}(v/n^2)/(c/n) \doteqdot \alpha/n$. But $\alpha/\beta = n$ and it therefore follows that the effective light path through the water-filled telescope is AD; the combined effect of refraction and ether drag is to give the same total angle of aberration as in an air-filled telescope.

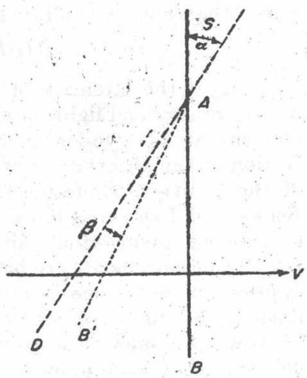

Fig. 2

This result was confirmed experimentally by Airy in 1871.

In all the above, only aberration produced by the motion of the earth about the sun — **annual aberration** — has been considered. The motion of the observer caused by the rotation of the earth about its axis will also produce an aberration dependent, of course, on the latitude of the observer — **diurnal aberration.** The relative velocities concerned, however, are much smaller and the effect is correspondingly reduced.

This problem has been treated classically and this is appropriate in view of the importance of this topic in classical theories of the ether. The aberration of light may also be readily explained in accordance with the Special Theory of Relativity — although the *magnitude* of the velocity of light *in vacuo* is unaffected by a Lorentz transformation the *direction* is altered by an amount in first-order agreement with the angle of aberration obtained classically. It is also interesting to note that the relativistic treatment of the problem of the velocity of propagation in a transparent medium moving with respect to a source of light yields a result very similar to that obtained by Fresnel and Stokes (Fresnel drag coefficient). The result of Airy's experiment can therefore be explained.

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W. F. WILLIAMS

ABNEY LAW. If a spectral colour is desaturated by adding white light, its hue shifts towards the red end of the spectrum if the wave-length is less than 5700 Å and towards the blue if the wave-length is greater than 5700 Å.

W.T. WELFORD

ABNEY MOUNTING. The Abney mounting is a modification of the Rowland mounting of a concave diffraction grating. The grating and plate-holder are mounted at opposite ends of a beam whose length is equal to the diameter of the Rowland circle. At the centre is pivoted a second beam of length equal to the radius of the Rowland circle; at the end of this beam the slit is mounted. By rotating the beam the slit can be set in different positions on the Rowland circle and so different spectral regions are focused on the photographic plate.

See also: Rowland circle. Rowland mounting.

P.K. CARROLL

ABSOLUTE ZERO. The existence of **absolute temperature** (or Kelvin temperature) follows from the first and second laws of thermodynamics. Regardless of the *unit* of temperature chosen there must then be a least possible temperature, the absolute zero of temperature, the same for all substances. At this temperature the constituent molecules would be devoid of heat energy though still retaining the zero-point energy attributed to them by quantum mechanics.

See also: Thermodynamics. Zero-point energy.

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J. W. HERIVEL

ABSOLUTE ZERO, UNATTAINABILITY OF. It is impossible by any procedure, no matter how idealized, to reduce the temperature of any system to the absolute zero in a finite number of operations. This theorem can be derived from the third law of thermodynamics which states that the entropy change in any reversible isothermal process tends to zero as the absolute temperature tends to zero. A simple derivation is obtained by using the entropy–temperature plot. Let the state of a system be