Aberration of light

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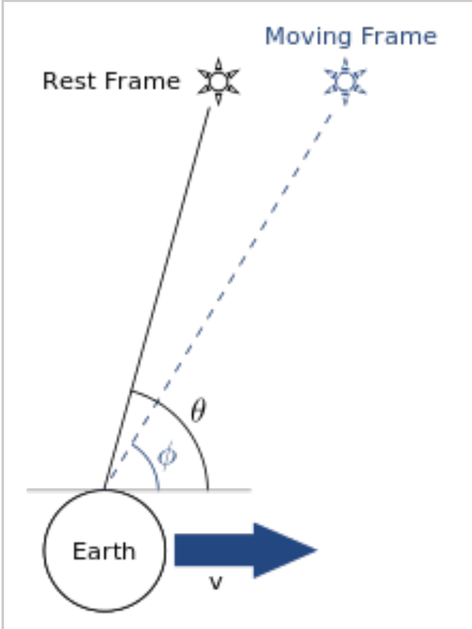

The apparent position of a star viewed from the Earth depends on the Earth's velocity. The effect is typically much smaller than illustrated.

The **aberration of light** (also referred to as **astronomical aberration** or **stellar aberration**) is an astronomical phenomenon which produces an apparent motion of celestial objects about their locations dependent on the velocity of the observer. Aberration causes objects to appear to be angled or tilted towards the direction of motion of the observer compared to when the observer is stationary. The change in angle is typically very small, on the order of v/c where c is the speed of light and v the velocity of the observer. In the case of "stellar" or "annual" aberration, the apparent position of a star to an observer on Earth varies periodically over the course of a year as the Earth's velocity changes as it revolves around the Sun, by a maximum angle of approximately 20 arcseconds in right ascension or declination.

Aberration is historically significant because of its role in the development of the theories of light, electromagnetism and, ultimately, the theory of special relativity. It was first observed in the late 1600s by astronomers searching for stellar parallax in order to confirm the heliocentric model of the Solar System, much to their surprise. In 1729, James Bradley provided a classical explanation for it in terms of the finite speed of light relative to the motion of the Earth in its orbit around the Sun,[1][2] which he used to make one of the earliest measurements of the speed of light. However, Bradley's theory was incompatible with 19th century theories of light, and aberration became a major motivation for the aether drag theories of Augustin Fresnel (in 1818) and G. G. Stokes (in 1845), and for Hendrick Lorentz' aether theory of electromagnetism in 1892. The aberration of light, together with Lorentz' elaboration of Maxwell's electrodynamics, the moving magnet and conductor problem, the negative aether drift experiments, as well as the Fizeau experiment, led Albert Einstein to develop the theory of special relativity in 1905, which provided a conclusive explanation for the aberration phenomenon.[3]

The term 'aberration' has historically been used to refer to a number of related phenomena concerning the propagation of light in moving bodies .[4] Aberration should not be confused with stellar parallax. The latter is caused by a change in the position of the observer looking at a relatively nearby object (theoretically, at any object outside the Solar System); the former is related to light-time correction and relativistic beaming, although it is often considered separately from these effects. The term *aberration* may also be used to refer to unrelated phenomena in optical systems — optical aberration.

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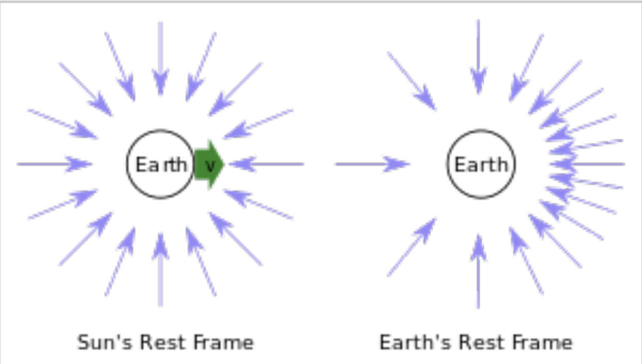
Explanation

Aberration may be explained as the difference in angle of a beam of light in different inertial frames of reference. A common analogy is to the apparent direction of falling rain: If rain is falling vertically in the frame of reference of a person standing still, then to a person moving forwards the rain will appear to arrive at an angle, requiring the moving observer to tilt their umbrella forwards. The faster the observer moves, the more tilt is needed.



Light rays striking the earth in the Sun's rest frame compared to the same rays in the Earth's rest frame according to special relativity. The effect is exaggerated for illustrative purposes.

The net effect is that light rays striking the moving observer from the sides in a stationary frame will come angled from ahead in the moving observer's frame. This effect is sometimes called the "searchlight" or "headlight" effect.

In the case of annual aberration of starlight, the direction of incoming starlight as seen in the Earth's moving frame is tilted relative to the angle observed in the Sun's frame. Since the direction of motion of the Earth changes during its orbit, the direction of this tilting changes during the course of the year, and causes the apparent position of the star to differ from its true position as measured in the inertial frame of the Sun.

While classical reasoning gives intuition for aberration, it leads to a number of physical paradoxes observable even at the classical level (see history). The theory of special relativity is required to correctly account for aberration. The relativistic explanation is very similar to the classical one however, and in both theories aberration may be understood as a case of velocity addition.

Classical explanation

In the Sun's frame, consider a beam of light with velocity equal to the speed of light c, with x and y velocity components u_x and u_y, at an angle $\tan(\theta) = u_y/u_x$. If the Earth is moving at velocity v in the x direction relative to the Sun, then by velocity addition the x component of the beam's velocity in the Earth's frame of reference is $u_x' = u_x - v$, and the y velocity is unchanged, $u_y' = u_y$. (Note that you need the velocity of the Sun with respect to the Earth which is the negative of the velocity of the Earth with respect to the Sun. Also note that we are only using vectors here without indication of direction.) Thus the angle of the light in the Earth's frame in terms of the angle in the Sun's frame is

$$\tan(\phi) = \frac{u_y'}{u_x'} = \frac{u_y}{(u_x - v)} = \frac{\sin(\theta)}{(\cos(\theta) - v/c)}$$

In the case of $\theta = 90^\circ$, this result reduces to $\tan(\theta - \phi) = -v/c$.

Relativistic explanation

The reasoning in the relativistic case is the same except that the relativistic velocity addition formulae must be used, which can be derived from Lorentz transformations between different frames of reference. These formulae are

$$u_x' = (u_x - v)/(1 - u_x v/c^2)$$
$$u_y' = u_y/\gamma(1 - u_x v/c^2)$$

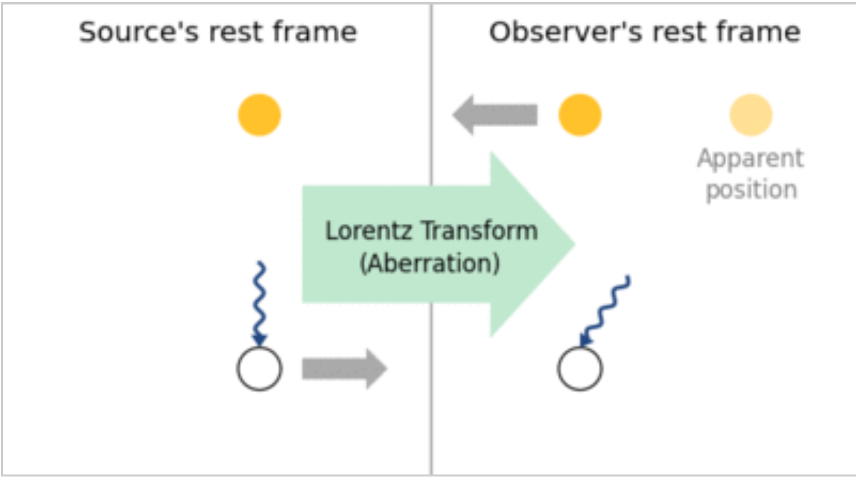
where $\gamma = 1/\sqrt{1 - v^2/c^2}$, giving the components of the light beam in the Earth's frame in terms of the components in the Sun's frame. The angle of the beam in the Earth's frame is thus [5]

$$\tan(\phi) = \frac{u_y'}{u_x'} = \frac{u_y}{\gamma(u_x - v)} = \frac{\sin(\theta)}{\gamma(\cos(\theta) - v/c)}$$

In the case of $\theta = 90^\circ$, this result reduces to $\sin(\theta - \phi) = -v/c$, and in the limit $v/c \ll 1$ this may be approximated by $\theta - \phi = -v/c$. This relativistic derivation keeps the speed of light $\sqrt{u_x^2 + u_y^2} = c$ constant in all frames of reference, unlike the classical derivation above.

Relationship to light-time correction and relativistic beaming

Aberration is related to two other phenomena, light-time correction, which is due to the motion of an observed object during the time taken by its light to reach an observer, and relativistic beaming, which is an angling of the light emitted by a moving light source. It can be considered equivalent to them but in a different inertial frame of reference. In aberration, the observer is considered to be moving relative to a (for the sake of simplicity[6]) stationary light source, while in light-time correction and relativistic beaming the light source is considered to be moving relative to a stationary observer.



Aberration, light-time correction, and relativistic beaming can be considered the same phenomenon depending on the frame of reference.

Consider the case of an observer and a light source moving relative to each other at constant velocity, with a light beam moving from the source to the observer. At the moment of emission, the beam in the observer's rest frame is tilted compared to the one in the source's rest frame, as understood through relativistic beaming. During the time it takes the light beam to reach the observer the light source moves in the observer's frame, and the 'true position' of the light source is displaced relative to the apparent position the observer sees, as explained by light-time correction. Finally, the beam in the observer's frame at the moment of observation is tilted compared to the beam in source's frame, which can be understood as an aberrational effect. Thus, a person in the light source's frame would describe the apparent tilting of the beam in terms of aberration, while a person in the observer's frame would describe it as a light-time effect.

The relationship between these phenomena is only valid if the observer and source's frames are inertial frames. In practice, because the Earth is not an inertial rest frame but experiences centripetal acceleration towards the Sun, many aberrational effects such as annual aberration on Earth cannot be considered light-time corrections. However, if the time between emission and detection of the light is short compared to the orbital period of the Earth, the Earth may be approximated as an inertial frame and aberrational effects are equivalent to light-time corrections.

Types of aberration

There are a number of types of aberration, caused by the differing components of the Earth's motion:

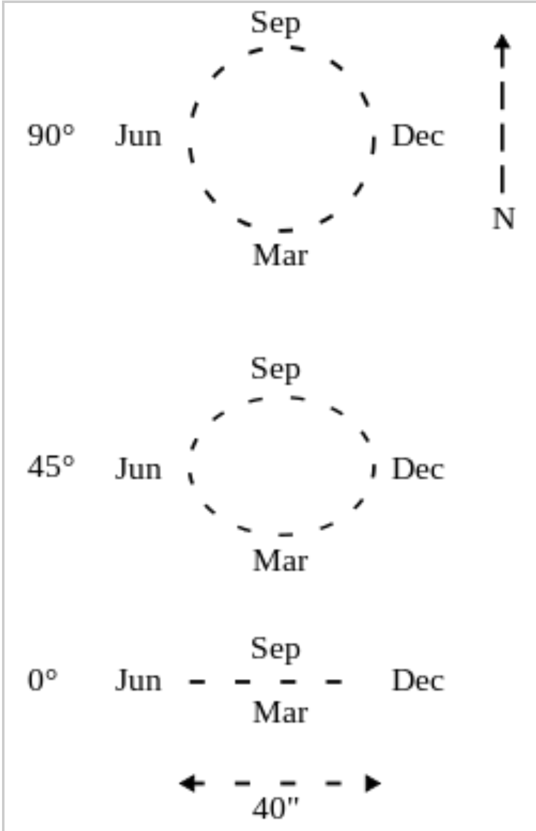
- **Annual aberration** is due to the revolution of the Earth around the Sun.
- **Planetary aberration** is the combination of aberration and light-time correction.
- **Diurnal aberration** is due to the rotation of the Earth about its own axis.
- **Secular aberration** is due to the motion of the Sun and solar system relative to other stars in the galaxy.

Annual aberration

Annual aberration is caused by the motion of an observer on the Earth revolving around the Sun. The velocity v of the Earth (in the Sun's rest frame) varies periodically over the course of a year as the Earth traverses its orbit and consequently the aberration also varies periodically, typically causing stars to appear to move in small ellipses.

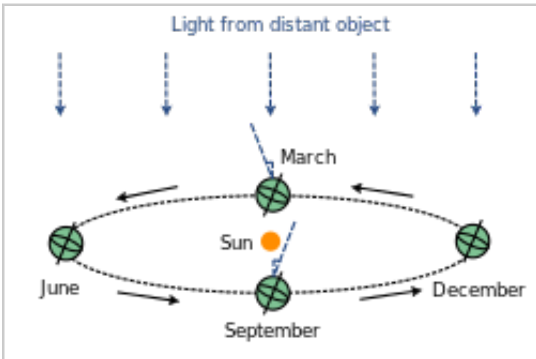
Approximating the Earth's orbit as circular, the maximum displacement of a star due to annual aberration is known as the *constant of aberration*, conventionally represented by κ. It may be calculated using the relation $\kappa = \theta - \phi \approx v/c$ substituting the Earth's average speed in the Sun's frame for v and the speed of light c. Its accepted value is 20″.49552 arcseconds (at J2000).[7]

Assuming a circular orbit, annual aberration causes stars exactly on the ecliptic (the plane of the Earth's orbit) to appear to move back and forth along a straight line, varying by κ on either side of their position in the Sun's frame. A star that is precisely at one of the ecliptic poles (at 90 degrees from the ecliptic plane) will appear to move in a circle of radius κ about its true position, and stars at intermediate ecliptic latitudes will appear to move along a small ellipse.



Stars at the ecliptic poles appear to move in circles, stars exactly in the ecliptic plane move in lines, and stars at intermediate angles move in ellipses. Shown here are the apparent motions of stars with the ecliptic latitudes corresponding to these cases, and with ecliptic longitude of 270 degrees.

For illustration, consider a star at the northern ecliptic pole viewed by an observer on the 'top' of the earth (towards the ecliptic pole), at a point on the arctic circle. At the time of the March equinox, the Earth's orbit carries the observer in a southwards direction, and the star's apparent declination is therefore displaced to the south by an angle of κ. At the September equinox, the star's position is displaced to the north by an equal and opposite amount. At the June and December solstices, the displacement in declination is zero. Conversely, the amount of displacement in right ascension is zero at either equinox and maximum at the solstices.



The direction of aberration of a star at the northern ecliptic pole differs at different times of the year.

In practice the Earth's orbit is slightly elliptic rather than circular and its speed changes somewhat over the course of its orbit, which means the description above is only approximate. Aberration is more accurately calculated using the Earth's instantaneous velocity relative to the center of mass of the Solar System.[7]

Note that the displacement due to aberration is orthogonal to any displacement due to parallax. If parallax were detectable, the maximum displacement to the south would occur in December, and the maximum displacement to the north in June. It is this apparently anomalous motion that so mystified early astronomers.

Solar annual aberration

A special case of annual aberration is the nearly constant deflection of the Sun from its position in the Sun's rest frame by κ towards the *west* (as viewed from Earth), opposite to the apparent motion of the Sun along the ecliptic (which is from west to east, as seen from Earth). The deflection thus makes the Sun appear to be behind (or retarded) from its rest-frame position on the ecliptic by a position or angle κ.

This deflection may equivalently be described as a light-time effect due to motion of the Earth during the 8.3 minutes that it takes light to travel from the Sun to Earth. This is possible since the transit time of sunlight is short relative to the orbital period of the Earth, so the Earth's frame may be approximated as inertial. In the Earth's frame, the Sun moves by a distance $\Delta x = vt$ in the time it takes light to reach Earth, $t = R/c$ for the orbit of radius R. This gives an angular correction $\tan(\theta) \approx \theta = \Delta x/R$ which can be solved to give $\theta = v/c = \kappa$, the same as the aberrational correction.

Planetary aberration

Planetary aberration is the combination of the aberration of light (due to Earth's velocity) and light-time correction (due to the object's motion and distance), as calculated in the rest frame of the Solar System. Both are determined at the instant when the moving object's light reaches the moving observer on Earth. It is so called because it is usually applied to planets and other objects in the Solar System whose motion and distance are accurately known.

Diurnal aberration

Diurnal aberration is caused by the velocity of the observer on the surface of the rotating Earth. It is therefore dependent not only on the time of the observation, but also the latitude and longitude of the observer. Its effect is much smaller than that of annual aberration, and is only $0''.32$ in the case of an observer at the equator, where the rotational velocity is greatest.

Secular aberration

The Sun and Solar System are revolving around the center of the Galaxy. Aberration due to this motion is known as secular aberration and affects the apparent positions of distant stars and extragalactic objects. However, since the galactic year is about 230 million years the aberration varies very slowly the change in aberration is extremely difficult to observe. Therefore secular aberration is usually ignored when considering the positions of stars. In other words, star maps show the observed apparent positions of the stars, not their calculated true positions after accounting for secular aberration.

For stars significantly less than 230 million light years away, the Solar System may be approximated as an inertial frame and so the effect of secular aberration is equivalent to a light-time correction. This includes stars in the Milky Way, since the Milky Way is about 100,000 light years in diameter. For these stars the true position of the star is then easily computed from the product of its proper motion (in arcseconds per year) and its distance (in light years).

Secular aberration is typically a small number of arcminutes, for example the stationary star Groombridge 1830 is displaced by approximately 3 arcminutes.[8] due to secular aberration. This is roughly 8 times the effect of annual aberration, as one would expect since the velocity of the Solar System relative to the Milky

Way is about 8 times the velocity of the Earth relative to the Sun.

Discovery and first observations

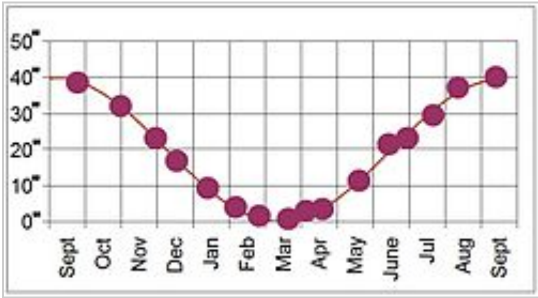
The discovery of the aberration of light was totally unexpected, and it was only by extraordinary perseverance and perspicacity that Bradley was able to explain it in 1727. Its origin is based on attempts made to discover whether the stars possessed appreciable parallaxes. The Copernican theory of the solar system – that the Earth revolved annually about the Sun – had received confirmation by the observations of Galileo and Tycho Brahe and the mathematical investigations of Kepler and Newton.

Search for stellar parallax

As early as 1573, Thomas Digges had suggested that parallactic shifting of the stars should occur according to the heliocentric model of the Solar System, and consequently if such stellar parallaxes could be observed they would help confirm the heliocentric theory. Many observers claimed to have determined such parallaxes, but Tycho Brahe and Giovanni Battista Riccioli concluded that they existed only in the minds of the observers, and were due to instrumental and personal errors. In 1680 Jean Picard, in his *Voyage d'Uranibourg,* stated, as a result of ten years' observations, that Polaris, or the Pole Star, exhibited variations in its position amounting to 40″ annually. Some astronomers endeavoured to explain this by parallax, but these attempts were futile, for the motion was at variance with that which parallax would produce. John Flamsteed, from measurements made in 1689 and succeeding years with his mural quadrant, similarly concluded that the declination of the Pole Star was 40″ less in July than in September. Robert Hooke, in 1674, published his observations of γ Draconis, a star of magnitude 2^m which passes practically overhead at the latitude of London, and whose observations are therefore free from the complex corrections due to astronomical refraction, and concluded that this star was 23″ more northerly in July than in October.

James Bradley's observations

When James Bradley and Samuel Molyneux entered this sphere of astronomical research in 1725, there consequently prevailed much uncertainty whether stellar parallaxes had been observed or not; and it was with the intention of definitely answering this question that these astronomers erected a large telescope at the house of the latter at Kew.[2] They determined to reinvestigate the motion of γ Draconis; the telescope, constructed by George Graham (1675–1751), a celebrated instrument-maker, was affixed to a vertical chimney stack, in such manner as to permit a small oscillation of the eyepiece, the amount of which (i.e. the deviation from the vertical) was regulated and measured by the introduction of a screw and a plumb line.



Bradley's data on the north-south component of the aberration of γ-Draconis in 1727 establishing stellar aberration.[9]

The instrument was set up in November 1725, and observations on γ Draconis were made starting in December. The star was observed to move 40″ southwards between September and March, reversing its course from March to September. These results were unexpected and inexplicable by existing theories.

Early hypotheses

This motion was evidently not due to parallax nor was it due to observational errors. Bradley and Molyneux discussed several hypotheses in the hope of finding the solution.

Bradley first hypothesized that the apparent motion could be due to oscillations in the orientation of the Earth's axis relative to the celestial sphere – a phenomenon known as nutation. This could be tested using the fact the apparent position of stars on the opposite side of the celestial sphere would be affected by an equal and opposite amount. Bradley tested this using a star with a right ascension nearly exactly opposite to that of γ Draconis. This star was seen to possess an apparent motion which could be consistent with nutation, but since its declination varied only one half as much as in the case of γ Draconis, it was obvious that nutation did not supply the requisite solution. Although nutation could not explain the observed stellar motion, Bradley later went on to discover that the Earth does indeed nutate.

Bradley also investigated the possibility that the motion was due to an irregular distribution of the Earth's atmosphere, thus involving abnormal variations in the refractive index, but again obtained negative results.

On August 19, 1727, Bradley then embarked upon a further series of observations using a telescope of his own erected at the Rectory, Wanstead. This instrument had the advantage of a larger field of view and he was able to obtain precise positions of a large number of stars over the course of about two years. This established the existence of the phenomenon of aberration beyond all doubt, and also allowed Bradley to formulate a set of rules that would allow the calculation of the effect on any given star at a specified date.

Development of the theory of aberration

Bradley eventually developed the explanation of aberration in about September 1728 and his theory was presented to the Royal Society in mid January the next year. Based on his early calculations, Bradley was able to estimate the constant of aberration at 20", and with this was able to estimate the speed of light at 183,300 miles (295,000 km) per second.[10] One well-known story was that he saw the change of direction of a wind vane on a boat on the Thames, caused not by an alteration of the wind itself, but by a change of course of the boat relative to the wind direction. [8] However, there is no record of this incident in Bradley's own account of the discovery, and it may therefore be apocryphal.

The discovery and elucidation of aberration is now regarded as a classic case of the application of scientific method, in which observations are made to test a theory, but unexpected results are sometimes obtained that in turn lead to new discoveries. It is also worth noting that part of the original motivation of the search for stellar parallax was to test the Copernican theory that the Earth revolves around the Sun, but of course the existence of aberration also establishes the truth of that theory.

Historical theories of aberration

The phenomenon of aberration became a driving force for many physical theories during the 200 years between its observation and the conclusive explanation by Albert Einstein.

The first classical explanation was provided in 1729 by James Bradley as described above, who attributed it to the finite speed of light and the motion of Earth in its orbit around the Sun.[1][2] However, this explanation proved inaccurate once the wave nature of light was better understood, and correcting it became a major goal of the 19th century theories of luminiferous aether. Augustin-Jean Fresnel proposed a correction due to the motion of a medium (the aether) through which light propagated, known as "partial aether drag". He proposed that objects partially drag the aether along with them as they move, and this became the accepted explanation for aberration for some time. George Stokes proposed a similar theory, explaining that aberration occurs due to the flow of aether induced by the motion of the Earth. Accumulated evidence against these explanations combined with new understanding of the electromagnetic nature of light led Hendrik Lorentz to develop an electron theory which featured an immobile aether, and he explained that objects contract in length as they move through the aether. Motivated by these previous theories, Albert Einstein then developed the theory of special relativity in 1905, which provides the modern account of aberration.

Bradley's classical explanation

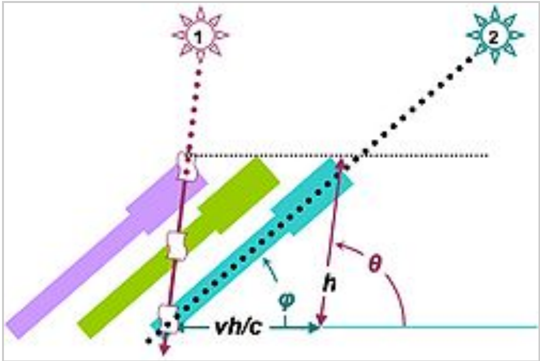


Figure 2: As light propagates down the telescope, the telescope moves requiring a tilt to the telescope that depends on the speed of light. The apparent angle of the star ϕ differs from its true angle θ.

Bradley conceived of an explanation in terms of a corpuscular theory of light in which light is made of particles unaffected by gravity.[4] His classical explanation appeals to the motion of the earth relative to a beam of light-particles moving at a finite velocity, and is developed in the Sun's frame of reference, unlike the classical derivation given above.

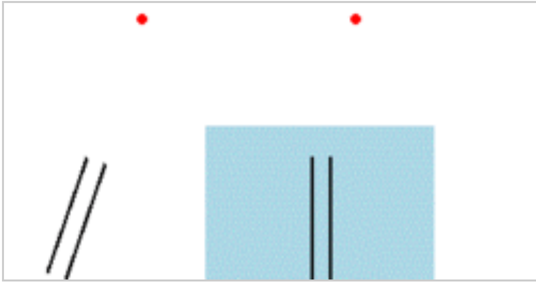
Consider the case where a distant star is motionless relative to the Sun, and the star is extremely far away, so that parallax may be ignored. In the rest frame of the Sun, this means light from the star travels in parallel paths to the Earth observer, and arrives at the same angle regardless of where the Earth is in its orbit. Suppose the star is observed on Earth with a telescope, idealized as a narrow tube. The light enters the tube from the star at angle θ and travels at speed c taking a time h/c to reach the bottom of the tube, where it is detected. Suppose observations are made from Earth, which is moving with a speed v. During the transit of the light, the tube moves a distance vh/c. Consequently, for the particles of light to reach the bottom of the tube, the tube must be inclined at an angle ϕ different from θ, resulting in an *apparent* position of the star at angle ϕ. As the Earth proceeds in its orbit it changes direction, so ϕ changes with the time of year the observation is made. The apparent angle and true angle are related using trigonometry as:

$$\tan(\phi) = \frac{h\sin(\theta)}{hv/c + h\cos(\theta)} = \frac{\sin(\theta)}{v/c + \cos(\theta)}.$$

In the case of $\theta = 90°$, this gives $\tan(\theta - \phi) = v/c$. While this is different from the more accurate relativistic result described above, in the limit of small angle and low velocity they are approximately the same, within the error of the measurements of Bradley's day. These results allowed Bradley to make one of the earliest measurements of the speed of light.[11][12]

Luminiferous aether

In the early nineteenth century the wave theory of light was being rediscovered, and in 1804 Thomas Young adapted Bradley's explanation for corpuscular light to wavelike light traveling through a medium known as the luminiferous aether. His reasoning was the same as Bradley's, but it required that this medium be immobile in the Sun's reference frame and must pass through the earth unaffected, otherwise the medium (and therefore the light) would move along with the earth and no aberration would be observed. [13] He wrote:



Young reasoned that aberration could only be explained if the aether was immobile in the frame of the Sun. On the left, stellar aberration occurs if an immobile aether is assumed, showing that the telescope must be tilted. On the right, the aberration disappears if the aether moves with the telescope, and the telescope does not need to be tilted.

> Upon consideration of the phenomena of the aberration of the stars I am disposed to believe that the luminiferous aether pervades the substance of all material bodies with little or no resistance, as freely perhaps as the wind passes through a grove of trees.
>
> —Thomas Young, *1804*[4]

However, it soon became clear Young's theory could not account for aberration when materials with a non-vacuum index of refraction were present. An important example is of a telescope filled with water. The velocity of the light in such a telescope will be slower than in vacuum, and is given by c/n rather than c where n is the index of refraction of the water. Thus, by Bradley and Young's reasoning the aberration angle is given by

$$\tan(\phi) = \frac{\sin(\theta)}{v/(c/n) + \cos(\theta)}.$$

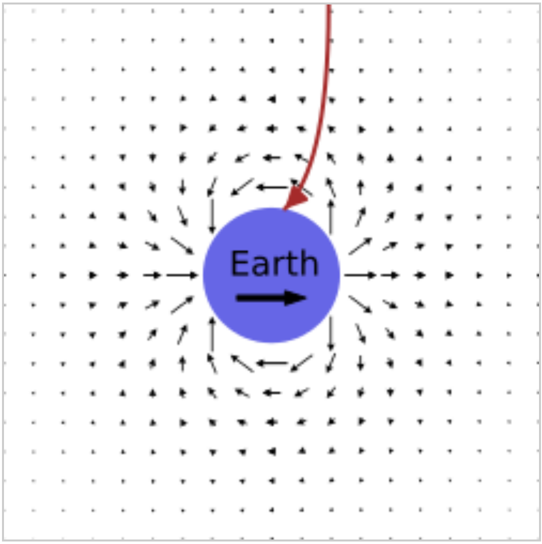
which predicts a medium-dependent angle of aberration. When refraction at the telescope's objective is taken into account this result deviates even more from the vacuum result. In 1810 François Arago performed a similar experiment and found that the aberration was unaffected by the medium in the telescope, providing solid evidence against Young's theory. This experiment was subsequently verified by many others in the following decades, most accurately by Airy in 1871, with the same result.[13]

Aether drag models

Fresnel's aether drag

In 1818 Augustin Fresnel developed a modified explanation to account for the water telescope and for other aberration phenomena. He explained that the aether is generally at rest in the Sun's frame of reference, but objects partially drag the aether along with them as they move. That is, the aether in an object of index of refraction n moving at velocity v is partially dragged with a velocity $(1 - 1/n^2)v$ bringing the light along with it. This factor is known as "Fresnel's dragging coefficient". This dragging effect, along with refraction at the telescope's objective, compensates for the slower speed of light in the water telescope in Bradley's explanation. [nb 1] With this modification Fresnel obtained Bradley's vacuum result even for non-vacuum telescopes, and was also able to predict many other phenomena related to the propagation of light in moving bodies. Fresnel's dragging coefficient became the dominant explanation of aberration for the next decades.

Stokes' aether drag



Conceptual illustration of Stokes' aether drag theory. In the rest frame of the Sun the Earth moves to the right through the aether, in which it induces a local current. A ray of light (in red) coming from the vertical becomes dragged and tilted due to the flow of aether.

However, the fact that light is polarized (discovered by Fresnel himself) led scientists such as Cauchy and Green to believe that the aether was a totally immobile elastic solid as opposed to Fresnel's fluid aether. There was thus renewed need for an explanation of aberration consistent both with Fresnel's predictions (and Arago's observations) as well as polarization.

In 1845 Stokes proposed a 'putty-like' aether which acts as a liquid on large scales but as a solid on small scales, thus supporting both the transverse vibrations required for polarized light and the aether flow required to explain aberration. Making only the assumptions that the fluid is irrotational and that the boundary conditions of the flow are such that the aether has zero velocity far from the Earth, but moves at the Earth's velocity at its surface and within it, he was able to completely account for aberration.[nb 2] The velocity of the aether outside of the Earth would decrease as a function of distance from the Earth so light rays from stars would be progressively dragged as they approached the surface of the Earth. The Earth's motion would be unaffected by the aether due to D'Alembert's paradox.

Both Fresnel and Stokes' theories were popular. However, the question of aberration was put aside during much of the second half of the 19th century as focus of inquiry turned to the electromagnetic properties of aether.

Lorentz' length contraction

In the 1880s once electromagnetism was better understood, interest turned again to the problem of aberration. By this time flaws were known to both Fresnel's and Stokes' theories. Fresnel's theory required that the relative velocity of aether and matter to be different for light of different colors, and it was shown that the boundary conditions Stokes had assumed in his theory were inconsistent with his assumption of irrotational flow.[4][13][14] At the same time, the modern theories of electromagnetic aether could not account for aberration at all. Many scientists such as Maxwell, Heaviside and Hertz unsuccessfully attempted to solve these problems by incorporating either Fresnel or Stokes' theories into Maxwell's new electromagnetic laws.

Hendrik Lorentz spent considerable effort along these lines. After working on this problem for a decade, the issues with Stokes' theory caused him to abandon it and to follow Fresnel's suggestion of a (mostly) stationary aether (1892, 1895). However, in Lorentz's model the aether was *completely* immobile, like the electromagnetic aethers of Cauchy, Green and Maxwell and unlike Fresnel's aether. He obtained Fresnel's dragging coefficient from modifications of Maxwell's electromagnetic theory, including a modification of the time coordinates in moving frames ("local time"). In order to explain the Michelson–Morley experiment (1887), which apparently contradicted both Fresnel's and Lorentz's immobile aether theories, and apparently confirmed Stokes' complete aether drag, Lorentz theorized (1892) that objects undergo "length contraction" by a factor of $\sqrt{1 - v^2/c^2}$ in the direction of their motion through the aether. In this way, aberration (and all related optical phenomena) can be accounted for in the context of an immobile aether. Lorentz' theory became the basis for much research in the next decade, and beyond. Its predictions for aberration are identical to those of the relativistic theory.[13][15]

Special relativity

Lorentz' theory matched experiment well, but it was complicated and made many unsubstantiated physical assumptions about the microscopic nature of electromagnetic media. In his 1905 theory of special relativity, Albert Einstein reinterpreted the results of Lorentz' theory in a much simpler and more natural conceptual framework which disposed of the idea of an aether. His derivation is given above, and is now the accepted explanation. Robert S. Shankland reported some conversations with Einstein, in which Einstein emphasized the importance of aberration:[16]

> He continued to say the experimental results which had influenced him most were the observations of stellar aberration and Fizeau's measurements on the speed of light in moving water. "They were enough," he said.

Other important motivations for Einstein's development of relativity were the moving magnet and conductor problem and (indirectly) the negative aether drift experiments, already mentioned by him in the introduction of his first relativity paper. Einstein wrote in a note in 1952:[3]

> My own thought was more indirectly influenced by the famous Michelson-Morley experiment. I learned of it through Lorentz' path breaking investigation on the electrodynamics of moving bodies (1895), of which I knew before the establishment of the special theory of relativity. Lorentz' basic assumption of a resting ether did not seem directly convincing to me, since it led to an [struck out: to me artificial appearing] interpretation of the Michelson-Morley experiment, which [struck out: did not convince me] seemed unnatural to me. My direct path to the sp. th. rel. was mainly determined by the conviction that the electromotive force induced in a conductor moving in a magnetic field is nothing other than an electric field. But the result of Fizeau's experiment and the phenomenon of aberration also guided me.

While Einstein's result is the same as Bradley's original equation except for an extra factor of γ, it should be emphasized that Bradley's result does not merely give the classical limit of the relativistic case, in the sense that it gives incorrect predictions even at low relative velocities. Bradley's explanation cannot account for situations such as the water telescope, nor for many other optical effects (such as interference) that might occur within the telescope. This is because in the Earth's frame it predicts that the direction of propagation of the light beam in the telescope is not normal to the wavefronts of the beam, in contradiction with Maxwell's theory of electromagnetism. It also does not preserve the speed of light c between frames. However, Bradley did correctly infer that the effect was due to relative velocities.

See also

- Aberration
- Nutation
- Proper motion
- Apparent place
- Fresnel, Augustin-Jean
- List of astronomical topics
- Stokes, George Gabriel
- Timeline of electromagnetism and classical optics
- Stellar aberration (derivation from Lorentz transformation)

Wikimedia Commons has media related to ***Aberration of light***.

Wikisource has the text of the 1911 *Encyclopædia Britannica* article ***Aberration***.

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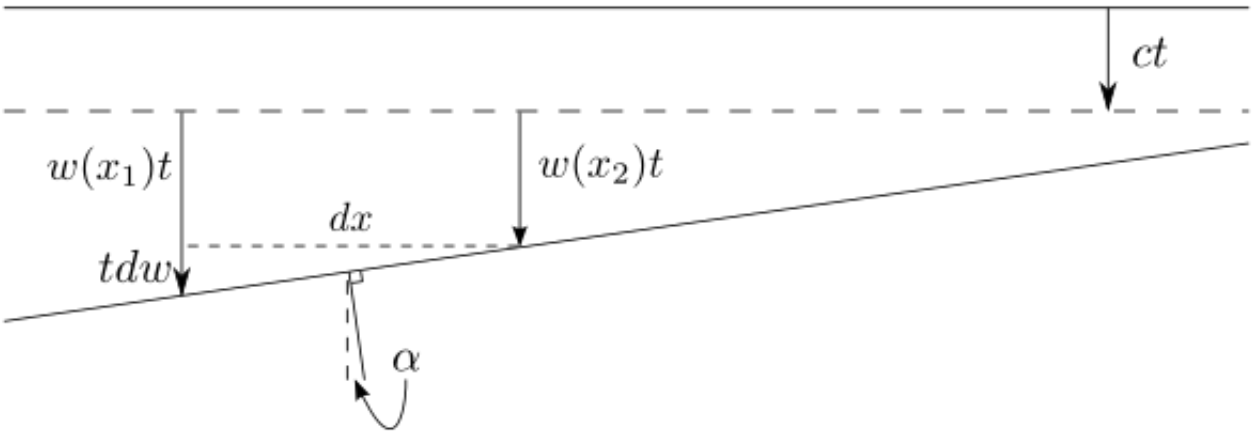
Notes

1. More in detail, Fresnel explains that the incoming light of angle θ is first refracted at the end of the telescope, to a new angle ψ within the telescope. This may be accounted for by Snell's law, giving $\sin(\theta - \phi) = n \sin(\psi - \phi)$. Then drag must be accounted for. Without drag, the x and y components of the light in the telescope are $(c/n)\sin(\psi)$ and $(c/n)\cos(\psi)$, but drag modifies the x component to $(c/n)\cos(\psi) - (1 - 1/n^2)v$ if the Earth moves with velocity v. If α is angle and v_l is the velocity of the light with these velocity components, then by Bradley's reasoning $\tan(\phi) = \dfrac{h\sin(\alpha)}{vt + h\cos(\alpha)}$ where h is the modified path length through the water and t is the time it takes the light to travel the distance h, $t = h/v_l$. Upon solving these equations for ϕ in terms of θ one obtains Bradley's vacuum result.
2. 

   Stokes' derivation may be summarized as follows: Consider a wavefront moving in the downwards z direction. Say the aether has velocity field u, v, w as a function of x, y, z. Now, motion of the aether in the x and y directions does not affect the wavefront, but the motion in the z direction advances it (in addition to the amount it advances at speed c). If the z velocity of the aether varies over space, for example if it is slower for higher x as shown in the figure, then the wavefront becomes angled, by an angle $\tan(\alpha) = tdw/dx$. Now, say in time t the wavefront has moved by a span $dz \approx ct$ (assuming the speed of the aether is negligible compared to the speed of light). Then for each distance dz the ray descends, it is bent by an angle $\alpha \approx (dw/dx)(dz/c)$, and so the total angle by which it has changed after travelling through the entire fluid is

$$\alpha \approx \frac{1}{c}\int \frac{\partial w}{\partial x} dz$$

   If the fluid is irrotational it will satisfy the Cauchy-Riemann equations, one of which is

$$\frac{\partial w}{\partial x} = \frac{\partial u}{\partial z}.$$

Inserting this into the previous result gives an aberration angle $\alpha = (u_2 - u_1)/c$ where the us represent the x component of the aether's velocity at the start and end of the ray. Far from the earth the aether has zero velocity, so $u_2 = 0$ and at the surface of the earth it has the earth's velocity v. Thus we finally get

$$\alpha \approx \frac{v}{c}$$

which is the known aberration result.

External links

- Stellar Aberration (http://www.mathpages.com/rr/s2-05/2-05.htm) at MathPages
- Courtney Seligman (http://cseligman.com/text/history/bradley.htm) on Bradley's observations

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- The standard treatise in English is H. D. Taylor, *A System of Applied Optics* (1906);
- Reference may also be made to R. S. Heath, *A Treatise on Geometrical Optics* (2nd ed., 1895); and L. A. Herman [sic; actually Robert Alfred], *A Treatise on Geometrical Optics* (1900).
- The ideas of Abbe were first dealt with in S. Czapski, *Theorie der optischen Instrumente nach Abbe*, published separately at Breslau in 1893, and as vol. ii. of Winkelmann's *Handbuch der Physik* in 1894;
- A second edition, by Czapski and O. Eppenstein, was published at Leipzig in 1903 with the title, *Grundzüge der Theorie der optischen Instrumente nach Abbe*, and in vol. ii. of the 2nd ed. of Winkelmann's *Handbuch der Physik*.
- The collection of the scientific staff of Carl Zeiss at Jena, edited by M. von Rohr, *Die bilderzeugung in optischen Instrumenten vom Standpunkte der geometrischen Optik* (Berlin, 1904), contains articles by A. König and M. von Rohr specially dealing with aberrations.