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Aberration and relativity

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The aberration of starlight seems to be one of the simplest phenomena of astronomical observation. However, the story of misunderstandings is long and lasts till now. It is nearly forgotten that the problem of stellar aberration was the cornerstone of the development and the acceptance of relativity. In addition, there seems to be no essentially final point in the discussion of its interpretation, the discussion seems to merely be given up. Of course, with the correct relativistic formulas, there is no need of interpetation any more. The price of this consists in the many incorrect descriptions and interpretations that arise if a textbook tries to explain in words the mere formulas. We try to review the problems discussed in the last three centuries and to give them a final, i.e. geometrical form. We are convinced that this teaches a lot about the geometry of the space-time union.

Key words: Relativity, Aberration, Astrometry

1. The problems

In 1728, Bradley was trying to solve the riddle of parallaxes. In the years since 1666, when Hooke (Grant 1858) tried to measure the parallax of the earth's orbit, the evidence was always considered to be shaky because of an apparently curious phase shift of the effect. Cassini rejected 1699 observations of Flamstead because of a phase shift of 90^o against the expected parallax.[1] Bradley established projection ellipses (Bradley 1728). They were independent of the distance of the star and their phase indicated that they were projections of the hodogram of the eath's orbit. The effect was called the aberration and explained as outflow of an additive composition of the velocities of the light and of the earth (Fig. 1). Light was expected to be an emanation of particles, leaving the source with a certain velocity, which had been measured by Olaf Roemer in the order of nearly 2 astronomical units per 1000 seconds. Indeed, Bradley interpreted his findings as a proof of the motion of the earth. Some years before, Flamstead is reported to have seen aberration ellipses too, but he was rejected by Cassini (Caplan 1998). The latter considered the phase shift with respect to the ellipses of the expected parallax to be the obvious indication of an observational error.

The natural consequence of the emanation theory was the expectation that the light velocity is to be composed with that of the star too. In addition, a dependence of the emanation velocity on the properties of the star was expected, leading Laplace to the belief in the possible existence of stars which withhold their light from emanation at all. However, no dependence of the (longitudinal) velocity of light on the radial motion of the star is observed. Such a dependence would have dramatic effects: If a double star is distant enough, its companion should be seen at more than one place at the same time (Fig. 4, 5). This has never been observed. The velocity of light coming from the individual stars is always the same.

The paradox was solved by the undulatory theory of light. Based on the interfenece phenomena, the theory of light as a wave was developed, and the universality of the velocity of light propagation was obvious. However, to the great disappointment of Fresnel, waves (strictly the normals of wave-fronts) are not subject to aberration (Fig. 3). Now, after relativity theory has solved this problem, it is nearly forgotten in spite of the fact that it was the most difficult problem for aether waves, and the clue to relativity.

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[1] This has brought to our attention by J.Caplan from Marseille (Caplan 1998).

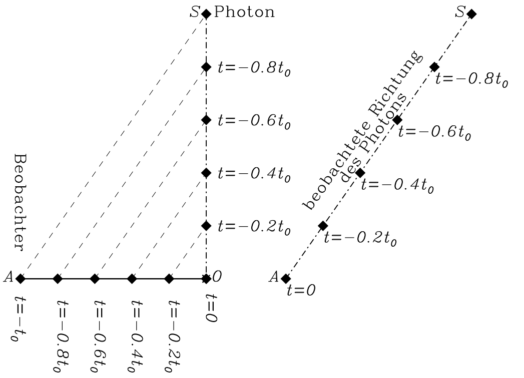

Fig. 1: Aberration through composition of velocities.
At left, the observer is in motion. When the photon is at S, he is at A. The observation, when both meet, happens at O. At right, all positions are referred to the actual position of A, i.e., we are in the rest frame of the observer. The photon moves along SA. In a spark chamber, this could be checked in detail. The angle between OS and AS is the stellar aberration.

Fresnel's solution uses the fact that a conventional telescope does not observe the phase-fronts, but an interference pattern, i.e. the image in the primary focus of the objective lens. Patterns are moving like particles and shifted like particles, if the carrier medium, the aether, is freely flowing through the telescope and is not influenced by the presence of the earth (Fig 6). This hypothesis of a freely flowing aether was always difficult to accept. The final blow to Fresnels construction came with the Michelson experiment. It clearly demonstrated that the aether (if existing) was carried with the earth.

Lorentz and Drude showed the appearance of a new concept of time through Maxwell's equations. They called it *local time* or *effective time*. Equal aberration for particles and waves requires this revision of simultaneity. The geometry of space-time demonstrates this in an elementary fashion (Fig. 8, 9). Today, the aberration is formally derived in textbooks mostly from the relativistic transformation of the phase. Aberration is understood as aberration of the wave-front normals. Such an aberration is the corollary of the relative simultaneity. Alternatively, the relativistic composition of velocities is used. The composition law is equivalent to relative simultaneity, but this equivalence is not so obvious.

The popular adaption of the theory of relativity saw relativity everywhere. It was lightly written that aberration is an effect depending on the relative velocity between observer and source. However, this is a trap. Obviously, no effect of the motion of the source can exist (Fig. 10). The aberration is a correction to be applied between *observers in relative motion*. Nevertheless, without this deeper consideration, many authors claimed erroneously that relativity theory would imply dependence on the relative motion between observer and source and would consequently predict an effect produced by the motion of the source. The observed absence of such effects would necessitate a revision of the theory of relativity.

2. Historical remarks

In the eighteens century, the emanation theory of light had to withstand many arguments mainly concerning the theory of colors. At the end of the century, questions about the dependence of the velocity on the state and the motion of the source are found in the written statements (Michell 1767; Mayer 1778; Fuss 1782; Schröter 1792; Soldner 1800). Camerer (1797) is the first to explicitely expect that the aberration depends on the motion of the source, which is called later *active aberration*. Of course, observations of double stars were rare and difficult (Herschel 1803). The nineteens century began with the triumph of the undulatory theory of light (Huygens 1690; Young 1800, 1804). It turned out soon that aberration poses a characteristic problem in undulation theory (Fresnel 1814) that could be solved only by an apparently telescope-dependent construction (Fresnel 1818). This construction had

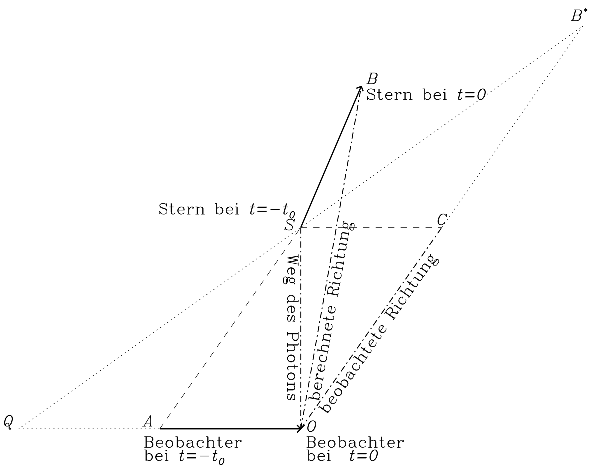

Fig. 2: Stellar and planetary aberration.

We repeat figure 1 and extend it for a motion of the source (Turner 1909). As in figure 1, the signal moves from S at $t = -t_0$ to O at $t = 0$. The star moves in the same time interval from S to B. The observer in his frame states at O the direction $AS = OC$. OS is the direction which he would find if he were at rest in O.

When we know the retardation time t_0 and the velocity and the distance of the source, we can infer the direction OB to the position B of the source at the time of the observation. The angle $\angle BOS$ is called planetary aberration. Stellar and planetary aberration compensate each other (i.e. $\angle B^*OC = 0$) when the star attains at $t = 0$ a position B^* on the connecting line OC. In this case, the motion of the source in the frame of the observer is radial. There is a point Q where both observer and source had met if both were in uniform motion.

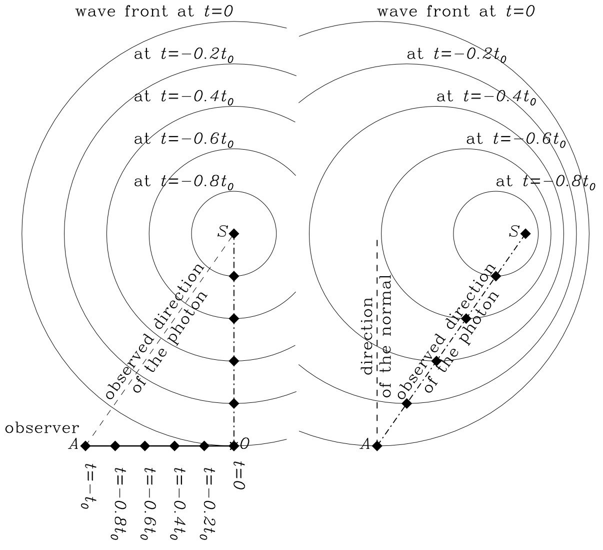

Fig. 3: A spherical wave seen from a moving observer

At left, we show the observer in motion and a spherical wave with isotropic propagation. On the wave crest, the position of some structure (wave group, photon, signal) is marked. At right, all positions are drawn with respect to the observer, i.e., the propagation is composed with its motion. The orientation of the wave-front normal does not show aberration but the signal does.

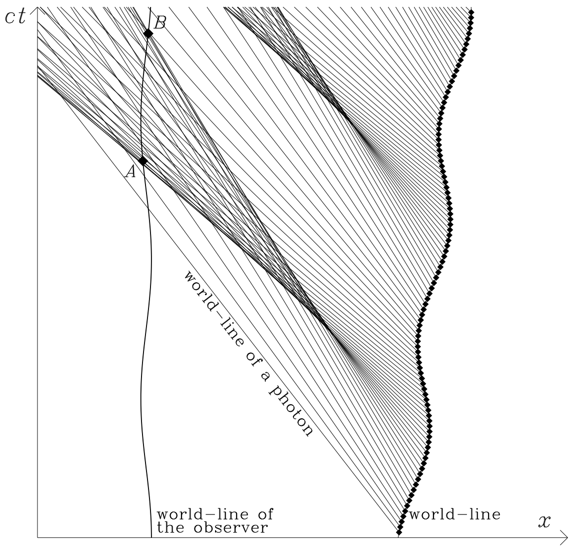

Fig. 4: Multiple images for ballistic models of radiation.

If light consists of particles, or if we observe particle emanation in general, the velocity of the particles with respect to the source should have a given value. If this velocity is to be composed with that of the source, we obtain for appropriate motions of the source and large enough distance an anomalously large time equation and multiple images.

In our draft the source has a periodic motion with radial component (only this component is shown). In the intervall between A and B, the observer sees light from three different emission times and, consequently, from three different places simultaneously.

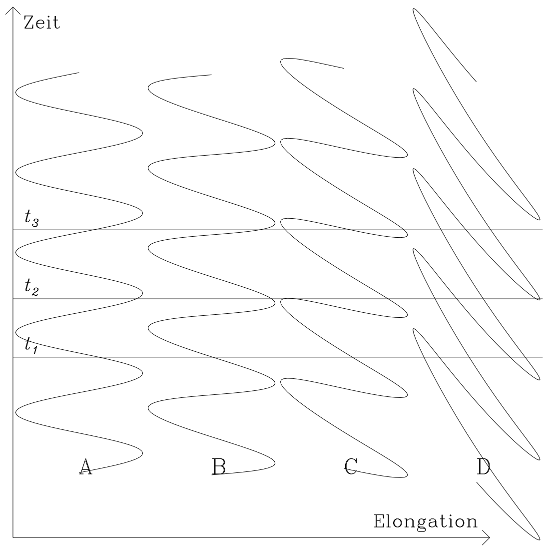

Fig. 5: The apparent motion on a circular orbit.

The apparent motion is shown in a diagram that is known from the presentation of the motion of the Jovian satellites in astronomic calendars.

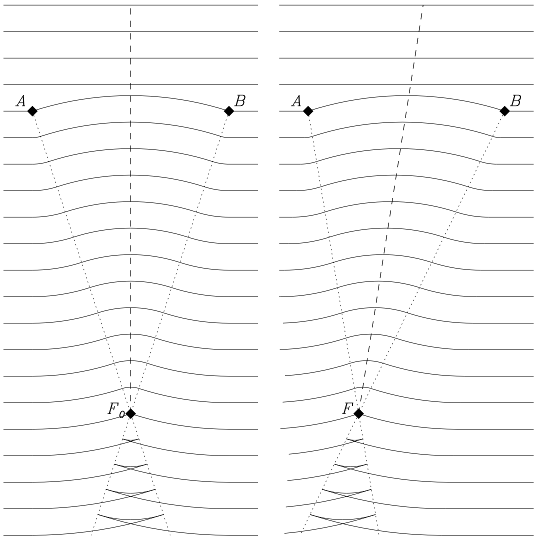

Fig. 6: Aberration of waves.

In order to explain aberration in wave theory, Fresnel was forced to refer to the construction of the telescopes of the time, i.e., to the existence of an aperture diaphragm. It cuts a piece out of the wave front. This piece moves like a particle because of its being localized and shows the usual aberration.

At left, the medium is at rest, at right, the medium is flowing from the right. We see the motion of the wave front as constructed by Huygens's method. This motion is decelerated in the aperture lens and reaches a focus F. At left, the construction is symmetric because of the medium being at rest, at right, the wave fronts are shifted to the left with progressing time. The focus is found in the position expected by the particle-type aberration argument.

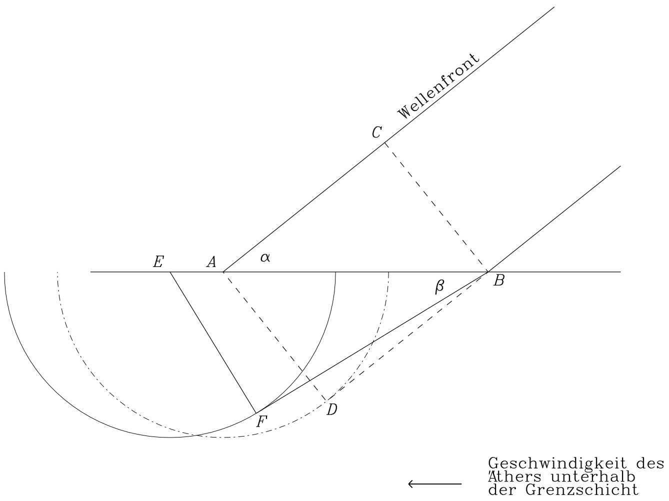

Fig. 7: Stokes's refraction.

Above the horizontal discontinuity along the line AB, the aether is at rest. Below this line it is assumed to move to the left with some constant velocity v. With the inclination α, a wave front propagates from above to this line. In the time t given by $ct = CB$ we have to draw a semicircle around A with this radius and to shift it to the left by $AE = vt$. Huygens's construction results in the refraction law

$$\sin\beta = \frac{EF}{EB} = \frac{ct}{vt + ct/\sin\alpha} = \frac{\sin\alpha}{1 + \frac{v}{c}\sin\alpha} \ .$$

The relative sign of α and v is to be noticed (Brylinski 1924).

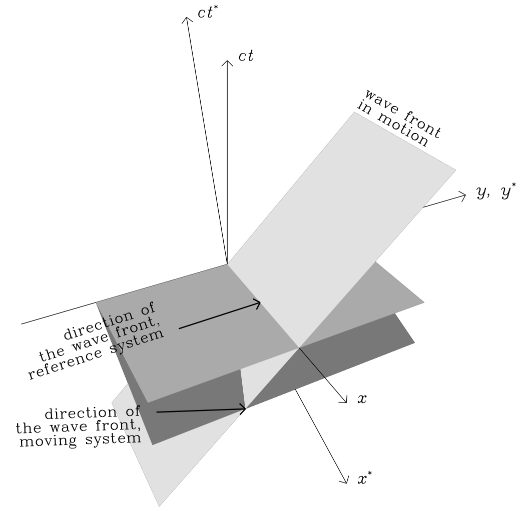

Fig. 8: Aberration of a plane wave.

When we require that wave fronts and rays are to have the same aberration (which could be tested with adaptive optics, for instance), simultaneity cannot be absolute. We are forced to revise the notion of time and obtain the Minkowski world of the special theory of relativity.

We show a wave front propagating in the direction of the y axis. It is respresented by a plane in the (here (2+1)–dimensional) space-time. Its position for a given instant of time (here $t = 0$) is the intersection with the corresponding plane of simultaneous events. If the simultaneity is absolute, i.e., if this plane is the same for all observers, no aberration of the wave-front normal is possible. Consequently, such an aberration requires the relativity of simultaneity, i.e., every observer has its own orientation of the planes of equal time. In our draft, the second observer moves to the left (axis ct^*). In the Minkowski world, the plane of simultaneous events ($ct^* = 0$) is now tilted as indicated. it intersects the wave front in another line corresponding to the expected aberration. On the other hand, the requirement of equal aberration of wave-fronts and rays forces the planes $ct^* = 0$ to be tilted in the indicated way which is equivalent to the Minkowski geometry.

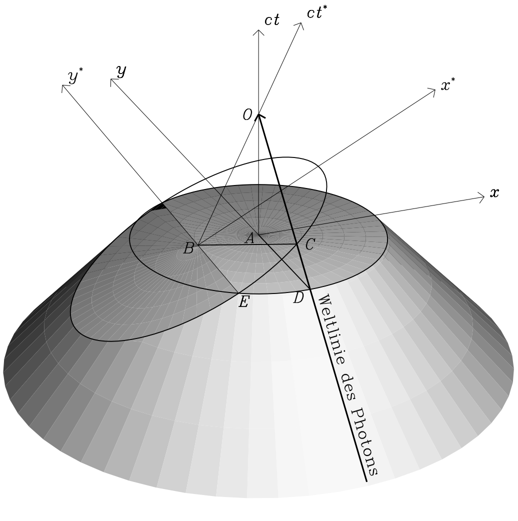

Fig. 9: Aberration and relative simultaneity.

When we require both wave fronts and rays to yield the same aberration, the plane of simultaneous events for any observer must intersect the light cone in a curve for which all normals intersect in the position of the observer. Consequently, the intersection is a curve symmetric about this position: The light velocity is apparently isotropic. This yields the Minkowski world of Einstein's theory of relativity.

We repeat the former figure for the case of relative simultaneity in order to show how ray and normal directions coincide now. The observer with the world-line AO sees the horizontal plane as simultaneous, the observer with the world-line BO is tilted again. The ray direction CB now coincides with the normal at C when we accept units in which the intersection curve is a circle.

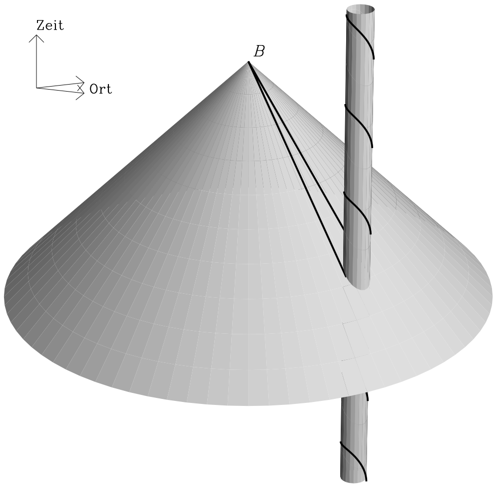

Fig. 10: The apparent size of a Kepler orbit.

The theory of relativity states that there is no particular frame of isotropic propagation of light in order to yield a reference for other velocities. Consequently, the dependence on velocity of any physical effect is reduced to the dependence on only relative velocities of material objects. When one forgets that the definition of an angle reqires the positions of three objects, one easily falls into the trap of considering only the relative velocity between source and observer. This velocity, however, is not involved at all. The aberration is a conversion of apparent positions between two observers and depends only of their relative velocity.

In a space-time diagram, we draw the world-lines of all photons observed at the event B by the observer. Because the propagation velocity does not depend on the motion of the source, these world-lines form a cone. The world-line of a double stars of given average position is wound around a cylinder with axis parallel to the time axis. The apparent size of the orbit is equal to the apparent size of this cylinder. The observer obtains it by evaluating the angle marked on the cone. This angle (as well as the cylinder) does not depend on the velocity os the star on its orbit: There is no active aberration.

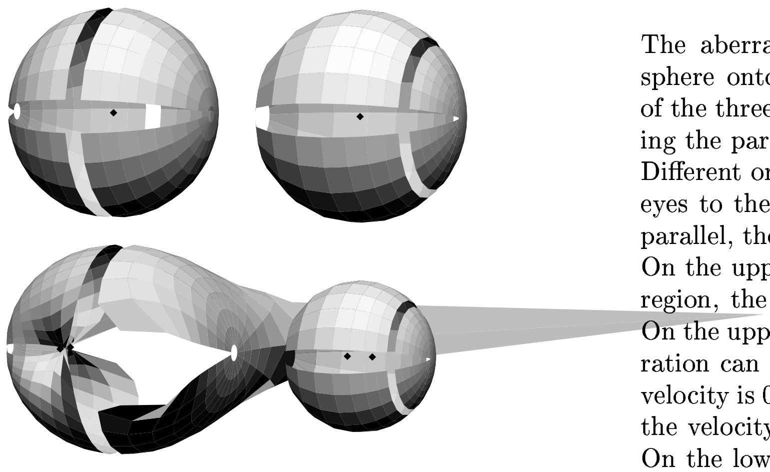

Fig. 11: Aberration of a finite sphere.

The aberration yields a conformal map of the apparent sphere onto itself. This map can be extended to a map of the three-dimensional space by using two eyes and infering the parallax.

Different orientations of the relative position of the pair of eyes to the velocity yield different maps. If both are not parallel, the map develops singularities.

On the upper left, the sphere is shown with the equatorial region, the pole caps, and a meridional segment omitted. On the upper right, the conformal image produced by aberration can be seen. The observers moves to the right, the velocity is 0.7 c. On the lower right, two eyes are parallel to the velocity. The map is regular and shows a contraction. On the lower left, the eyes are abreast. Here, the velocity is only 0.4 c in order to obtain a not too extreme map.

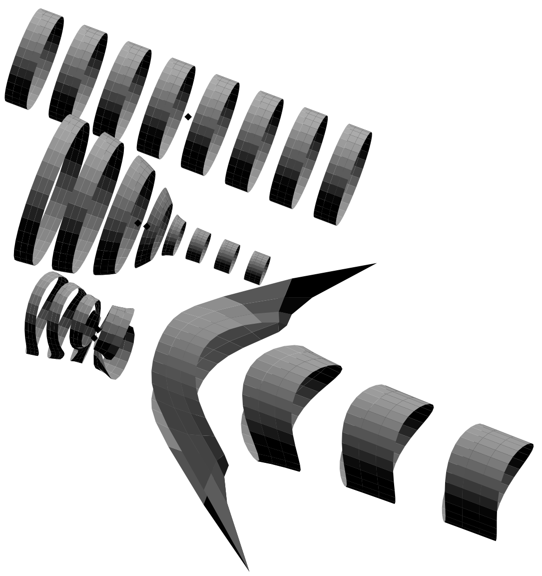

Fig. 12: Aberration of a cylinder.

Here, we see the stereoscopic aberration of a cylinder. First we draw eight segments as seen from an observer at rest. If the relative position of the eyes is parallel to the velocity, an observer moving from left to right sees at any given instant the form in the middle. If the eyes are oriented abreast, the moving observer sees the lower form (in bith cases, the velocity is 0.7 c). The contraction apparent in the form in the middle is the immediate expression of the Lorentz contraction of the distance of the eyes.

to suppose a freely flowing aether, admitting transversal shear waves instead of longitudinal compression waves. In addition, if Fresnel had had access to adaptive optics, he would have found that wave fronts show aberration *in contrast to* his expectation. There is one famous attempt by Stokes (1845, 1846) to overcome the hypothesis of a free flow of the aether. He tried to work in a picture of an aether locally at rest with respect to moving objects and to construct aberration as an appropriate refraction in the region between the universal aether and the locally co-moving aether. Figure 7 demonstrates the refraction at a laminar discontinuity of the aether velocity. However, in order to obtain approximate at least aberration formulas, intricate streaming laws for the aether had to be assumed. In a simple laminar flow, no aberration would be found for perpendicular directions in contrast to the observation. The hesitation to accept either explanation is evident in Veltmanns (1870) articles and Ketteler's book (1873). The divergence between wave-fronts and rays is even declared to be the essence of aberration (Ketteler 1871; Veltmann 1873). The situation approached its climax with the result of Michelson's experiment which clearly demonstrated that the aether does not freely flow around the earth and through his instruments (Michelson 1881; Michelson & Morley 1886). Now, even Kirchhoff (1891), Poincaré (1891), or Helmholtz (1897) did not dare to expose the problem to students. In their textbooks, they did not touch the questions of the aberration at all. It was Lorentz (1899) and Drude (1900) who introduced a new concept of time like that explained in figure 8. After Einstein (1905) demonstrated the reality and exclusive definability of a relative simultaneity, the divergence between ray and wave-front vanished. The calculation with a wave-front normal or phase through Lorentz transformation turned out to be identical to that with a particle through Einstein's composition rule for velocities (Born 1920). Consequently, formulas are derived in later textbooks either by the first (Varićak 1910; Joos 1956; Sommerfeld 1959; Bohm 1965; Herlt & Salié 1978; Schneider 1979) or the second method (Landau & Lifshic 1962; Rindler 1986; Goenner 1996). To the latter category, we should put v.Laue (1911) who considers the transformation of the Poynting vector.

The problems with prerelativistic aberration are rarely mentioned, and the ordinary experience leads into a characteristic trap. Since the relativistic formula is derived first, one suggests that the prerelativistic formulas are obtained by setting the Lorentz factor to 1. This works for the composition of velocities, but not for the aberration of wave-fronts. The latter is the immediate expression of the relative simultaneity, and this is an effect of *first* order. The corrsponding statements in Joos (1956) and Liebscher (1973) are wrong, other authors are dark, to say the least (Wiener 1919; Fürth 1970; Herlt & Salié 1978; Toretti 1984; Ruder & Ruder 1994; Goy 1996; Spencer & Shams 1996).

The other line of reasoning concerning the supposed relativity between observer and source has a similarly long tradition. Camerer's conjecture (Camerer 1797) was used by Houzeau (1844) who tried to explain an deviation in the parallax of 61 Cygni as active aberration. He was answered by Herschel jr. (1844) who argued in the line of our figure 10 that no active aberration can be expected. In spite of this answer, Folie (1884) claims again to see active aberration. He is cited by Höffler (1895) as proof of its existence. In the beginning of our century, the observational evidence for the lack of *longitudinal* additions to the velocity of light by the *radial* motion of the source (Guthnick 1913; deSitter 1913; Zurhellen 1914), later improved for extragalactic objects (Strömberg 1931; Heckmann 1960; Schmidt 1964; Brecher 1977; Barnet, Davis and Sanders 1985), convinced about the observational absence of active aberration. This absence was tested first by H.Seeliger (1884) and Nyrén (1888). However, the theory of relativity was misunderstood now in the statement that it would predict active aberration because of the relativity between observer and source. The lack of observational confirmation was interpreted as error in the theory of relativity and as a hint that the latter had to be modified accordingly (Hayn 1920, 1923, 1925; LaRosa 1924; Tomaschek 1924,1925; Osten 1925; v.Brunn 1925; Freiesleben 1926; Mohorovičić 1928). Curiously, even Einstein (1916) and Pauli (1921) contributed to this misunderstanding in writing explicitely about the relativity between observer and star. We found only one article by Emden (1926) where the situation is explained correctly, even if Emden overdoes it a bit. He writes that relativity knows of no aberration of the light ray at all, leaving the impression that he does not define aberration in the usual way. It seems to be remarkable that the discussion about relativity merely ends without some final strong statement like that of Herschel in 1844. Possible no one liked to touch the question any more because of the political touch it had in the twenties. The consequence is that the formulations of Einstein and Pauli prevail although they are misleading at least (Melcher 1974; Toretti 1984; Krautter et al. 1994; Marmet 1996; Spencer & Shams 1996) and really led into a trap (Treder 1985). The explicit statement that aberration is an effect between observers in relative motion is rare (Fock 1960, Rindler 1986).

3. Planetary aberration

We have to add one point excusing the misunderstandings about the relativity of aberration. In the former sections, the direction to the *event of emission* was considered exclusively. However, if we know about the motion of the source, we can try to infer its position at the moment of observation. The apparent distance of the positions of the emission event and the inferred position at the moment of observation is called *planetary* aberration. It is an addition of a completely different from stellar aberration origin, but it created a lot of confusion.

In calculating with the inferred position at the moment of observation, we can form a new angle between the observed and the inferred position. This angle vanishes when there is no relative velocity between source and observer. Too fast, it is concluded that this angle, combined from stellar aberration and motion in the retardation time, in general only depends on the relative velocity of source and observer. This angle, given emission and observation event, depends on velocities and position in an involved fashion. In prerelativistic theory first, the velocity of the aether with respect to the configuration of observer and source enters in all cases where the source has a proper motion in the frame of the observer (fig. 2). Secondly, in the relativistic wave theory, the position *at the moment of observation* depends on the frame in which simultaneity is taken. Only after the convention that we choose simultaneity in the rest frame of the observer, this angle depends only on the relative velocity as expected, but this is trivial now. The combination of stellar aberration and motion in the retardation time produces in any case a calculated angle, which can be observed in special cases only. Liebert (1995) presented correctly the relation between stellar and planetary aberration.

4. The visibility of the Lorentz contraction

There is a famous theorem about the aberration map. The observer sees any object moving by rotated, but not contracted in the direction of motion (Terrell 1959; Penrose 1959; Rindler 1986; Ruder & Ruder 1994). This is valid for observations with only one eye open. When one observed with two eyes, the map of the apparent sky is extended to a map of the space through use of the parallax. To give two examples, we show the three-dimensional images of a finite sphere (fig. 11) and a cylindric tunnel (fig. 12).

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References

Barnet,C., Davis,R., Sanders,W.L. 1985, Astrophys.J. 295, 24-27.
VanBiesbroeck,G. 1932, Astrophys.J. 75, 64-65.
Bohm,D. 1965, The special theory of relativity, W.A.Benjamin.
Born,M. 1920, Die Relativitätstheorie Einsteins, Vieweg Verlag Braunschweig.
Bradley,J. 1728, Phil.Trans.London 35, 637, 1729, reprinted in W.Magie ed., A source book of physics, Cambridge MS, Harvard 1935.
Bradley,J. 1728, Proc.Roy.Soc.London 35, 308-321.
Brecher,K. 1977, Phys.Rev.Lett. 39, 1051-1054.
v.Brunn,A. 1925, Astron.Nachr. 224, 67-68.
Brylinski,E. 1924, Comptes Rendus 179, 1034-1036.
Camerer,J.W. 1797, Astronomisches Jahrbuch für das Jahr 1798, 139-142.
Caplan,J. 1998, Spring meeting of the Astronomische Gesellschaft, Gotha.
Cassini,J. 1699, Mém.Acad,Sci. , 177.Champeney,D.C., Isaak,G.R., Khan,A.M. CIK63A1963Phys.Lett.7241-243 An aether drift experiment based on the Mössbauer effect, Es wird gezeigt, daß die absolute Lichtgeschwindigkeit in einem Experiment gezeigt werden kann, wo das Licht nicht den gleichen Weg hin und zurück laufen muß. Die Zusammensetzung der Geschwindigkeiten wird dabei in erster Ordnung geprüft und nicht nur in zweiter, wie das beim Michelson-Versuch der Fall ist.
Courvoisier,L. 1921, Astron.Nachr. 213, 281-288 (5106).
Courvoisier,L. 1926, Astron.Nachr. 226, 241-264 (5416).
Courvoisier,L. 1931, AN 241, 201-212 (5772).
Drude,P. 1900, Lehrbuch der Optik, Leipzig, Hirzel.
Einstein,A. 1905, Ann.d.Physik 18, 639-641.
Einstein,A. 1916, Über spezielle und allgemeine Relativitätstheorie, Braunschweig, Vieweg.
Emden,R. 1926, Die Naturwissenschaften 14, 327-335.
Fock,V.A. 1960, Theorie von Raum-Zeit und Gravitation, Berlin, Akademie-Verlag.
Folie,F. 1884, Astron.Nachr. 109, 225-238 (2607).
Freiesleben,H.-Ch. 1926, Beiträge zum Problem der astronomischen Aberration, Weida, Thomas & Hubert.
Fresnel,A. 1814, Oeuvres complètes 2, 820-824, Paris, Imprimerie impériale 1868.
Fresnel,A. 1818, Oeuvres complètes 2, 627, Paris, Imprimerie impériale 1868.
Führt 1970, Fundamental principles of modern theoretical physics, London, Pergamon Press.
Fuß,N. 1782, Astronomisches Jahrbuch für das Jahr 1785, 132-150, speziell 148.
Guthnick,P. 1913, Astron.Nachr. 195, 265-272 (4670).
Goenner,H. 1996, Einführung in die spezielle und allgemeine Relativitätstheorie, Heidelberg, Spektrum AV.
Goy,F. 1996, Found.Phys.Lett. 9, 165-174.
Grant,R. 1852, History of physical astronomy, p. 548 [reprinted by Johnson Reprint in 1966].Hayn,A.N.HAN20A1920Astron.Nachr.21117-22 (5042) Didaktisches zur Aberration, *Die Aberration wird bedingt durch die relative Bewegung gegen den Ort* (falsch: Ereignis muß hier stehen), *von dem das Licht ausging, aber* nicht *durch die relative Bewegung Gestirn-Erde* (richtig).
Hayn,A.N. 1920, Astron.Nachr. 211, 191-192.
Hayn,A.N. 1920, Astron.Nachr. 212, 81-88 (5070).
Hayn,A.N. 1923, Astron.Nachr. 218, 11-12.
Hayn,A.N. 1925, Astron.Nachr. 224, 287-290.
Heckmann,O. 1960, Ann.d'Astrophysique 23, 168-173.
v.Helmholtz,H. 1897, Vorlesungen über die elektromagnetische Theorie des Lichts, Hamburg, L.Voss.
Herlt,E., Salié,N. 1978, Spezielle Relativitätstheorie, Berlin, Akademie-Verlag.
Herschel,W. 1803, Phil.Trans.London 93, 339.
Herschel,J.F.W. 1844, Astron.Nachr. 22, 249-254 (520).
Höffler,F. 1895, Untersuchungen über die Existenz der objectiven Aberration, Dissertation Zürich.
Houzeau,J.C. 1844, Astron.Nachr. 21, 241-248 (496), 273-278 (498).
Huygens,Ch. 1690, Traîté de la lumière, Le Hague.
Joos,G. 1956, Lehrbuch der theoretischen Physik, Leipzig, Geest & Portig, 9.Aufl..
Ketteler,E. 1871, Ann.d.Physik u.Chemie 144, 109-127, 287-300, 363-375, 550-562.
Ketteler,E. 1873, Astronomische Undulationstheorie oder die Lehre von der Aberration des Lichts, .
Kirchhoff,G. 1891, Vorlesungen über Mathematische Physik, II. Mathematische Optik, Leipzig, Teubner.
Landau,L.D., Lifshic,E.M. 1962, Klassische Feldtheorie, Berlin, Akademie-Verlag 1964.
Krautter,J., Sedlmayr,E., Schaifers,K., Traving,G. 1994, Meyers Handbuch Weltall, 535, 7.Aufl. Mannheim, Meyers Lexikonverlag.
v.Laue,M. 1911, Das Relativitätsprinzip, Vieweg, Braunschweig.
Liebert,J. 1995, Die Sterne 71, 76-83.
Liebscher,D.-E. 1973, Theoretische Physik, Berlin, Akademie-Verlag, S. 201, erste Formel.
Lorentz,H.A. 1899, KNAWPr 1, 427.
Marmet,P. 1996, Physics Essays 9, 96-99.
Mayer,Ch. 1778, Vertheidigung neuer Beobachtungen von Fixsterntrabanten, Mannheim.
Melcher,H. 1974, Relativitätstheorie, Berlin, Deutscher Verlag der Wissenschaften.
Michell,J. 1767, Phil.Trans.London 57, 234.

Michelson,A.A. 1881, Amer.J.Science (3) 22, 120-129.
Michelson,A.A., Morley,E.W. 1886, Amer.J.Science (3) 31, 377-386.
Mohorovičić,St. 1928, in: E.Gehrke, Handbuch der physikalischen Optik 2, 917 ff., Leipzig, J.A.Barth.
Nyrén,M. 1888, Bull.Acad.Imp.St.Petersburg 32, 402-412.
Osten,H. 1925, Astron.Nachr. 224, 66-67 (Nr.5356).
Pauli,W. 1921, Enzyklopädie der mathematischen Wissenschaften V/2, S. 563.
Penrose,R. 1959, Proc.Camb.Phil.Soc. 55, 137.
Sommerfeld,A. 1959, Vorlesungen, IV. Optik, 2.Aufl., Leipzig, Geest & Portig.
Poincaré,H. 1891, Elektrizität und Optik I (Vorlesungen, Berlin, J.Springer.
Rindler,W. 1986, Essential Relativity, Heidelberg, Springer.
LaRosa,M. 1924, Ann.d.Physik 75, 195-200.
Ruder,H., Ruder,M. 1994, Die Spezielle Relativitätstheorie, Vieweg Braunschweig.
Schmidt,Th. 1964, Z.Astrophys. 60, 106-111.
Schneider,M. 1979, Himmelsmechanik, BI Mannheim.
Schröter,J.H. 1792, Astronomisches Jahrbuch für das Jahr 1795, 108-110.
Soldner 1800, Astronomisches Jahrbuch für das Jahr 1803, 185-194.
Seeliger,H. 1884, Astron.Nachr. 109, 275-280 (2610).
deSitter,W. 1913, Phys.Z. 14, 429.
Spencer,D.E., Shams,U.Y. 1996, Physics Essays 9, 476-483.
Stokes,G.G. 1845, Phil.Mag.(3) 27, 9-15.
Stokes,G.G. 1846, Phil.Mag. 28, 76-81.
Strömberg,G. 1931, Publ.Astr.Soc.Pacific 43, 266.
Terrell,J. 1959, Phys.Rev. 116, 1041.
Tomaschek,R. 1924, Ann.d.Physik 74, 136-145.
Tomaschek,R. 1925, Z.Physik 32, 397-402.
Toretti,R. 1984, Relativity and Geometry, Oxford, Pergamon.
Treder,H.J. 1985, Ann.d.Physik 42, 71-72.
Turner,H.H. 1909, MNRAS 69, 403-414.
Varičak 1910, Phys.Z. 11, 93-96.
Varičak 1910, Phys.Z. 11, 287-294.
Varičak 1910, Phys.Z. 11, 586-587.
Veltmann,W. 1870, Astron.Nachr. 75, 145-160 (1786).
Veltmann,W. 1870, Astron.Nachr. 76, 129-144 (1809).
Veltmann,W. 1873, Ann.d.Physik u.Chemie 150, 497-535.
Wiener,O. 1919, Ber.Sächs.Akad.Wiss. 71, 249-254.
Young,T.Y. 1800, Phil.Trans. 90, 106-150.
Young,T.Y. 1804, Proc.Roy.Soc.London 94, 1-16.
Zurhellen,W. 1914, Astron.Nachr. 198, 1-10 (4729).

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