Arago's experiments on the speed of light (1810)

by James Lequeux, honorary astronomer at the Paris Observatory, curator of the Arago exhibition to mark the 150th anniversary of his death (2003)

Appointed secretary-librarian of the Paris Observatory in 1805, Arago immediately began experimenting on the refraction of gases, overseen by Biot, and participated in the Observatory's astronomical activities proper: measurements of the positions of stars to calculate the latitude of Paris, and data reduction to determine orbits of comets.

He also turned his attention to the speed of light, perhaps at the instigation of Laplace. He sought to find out if the speed of light differs from one star to another. At the same time, he tried to detect a possible variation in the speed of light when the earth moves closer to or further away from a given star. In the latter case, he made the implicit hypothesis, which at the time seemed obvious to everyone, that the speed of the Earth is simply added to or subtracted from the speed of light (special relativity has proven that this is false, as the speed of light in a vacuum is constant). In the first case, Arago thus had to find out if the angle of deviation undergone by light from a star when it passes through a prism changes from one star to another, and, in the second, if for the same star that angle varies at different periods of the year, given that the speed of the Earth is then oriented differently from that of the star.

Arago's work is described in a memoir presented to the Institute on 10 December 1810, but which was not published; he found it again shortly before his death in 1853 and had it published by the Academy of Sciences, "without changing a single word".[1] In it he writes:

> *If one recalls that the deviation experienced by light rays obliquely penetrating diaphanous bodies is a determined function of their primitive velocity,[2] one will see that the observation of the total deviation to which*

1. *CRAS* 36 (1853) p. 38–49; *OC* t. 7, p. 548–568.

2. In the corpuscular theory of light on which the article is based, to explain refraction it was thought that "light corpuscles" abruptly accelerate when they enter a refringent body, and that this acceleration is constant, and independent of their primitive velocity. As a consequence, it was thought that the relation between the velocity

they are subject when traversing a prism provides a natural measurement of their velocity.

In 1805–1806, Arago experimented with a 45′-angle prism, the dispersion of which was sufficiently small to allow him to work with white light. Both with and without a prism, he observed artificial sources of light, stars, the Sun, the Moon and the planets. He observed that the deviation of their light by the prism was always equal to 25′, with variations of 5 seconds of degree at the most, which he rightly interpreted as being due to errors of measurement. From this he deduced that variations in the speed of light do not exceed 1/480°. The existence of significant variations in the speed of light from one star to another was therefore strongly cast into doubt. This result caused quite a stir because it seemed to contradict the corpuscular theory of light.

Arago was then sent to measure the Barcelona meridian on the Balearic Islands, and the affair was put on hold until his return in 1809. At this point, the memoir in which he had described his initial observations in 1806 had not yet been examined by a referee. Then Delambre hastened to present a report on this memoir to the First Class of the Institute (the provisional name of the Academy of Sciences) on 4 September 1809: Arago's work was certainly one of the reasons favouring his election to the Institute two weeks later. Arago thus decided to take new measurements using a prism with a larger angle; most of these measurements were made in 1810. As the dispersion of the prism was now becoming troublesome for an observation in white light, but he nevertheless needed this light to take precise measurements, Arago had an achromatic prism made, i.e. one with minimal dispersion, so as to be able to work with white light (Fig. 1).

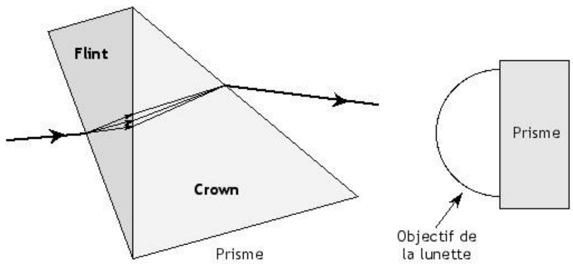


***Figure 1**: Arago's achromatic prism.*

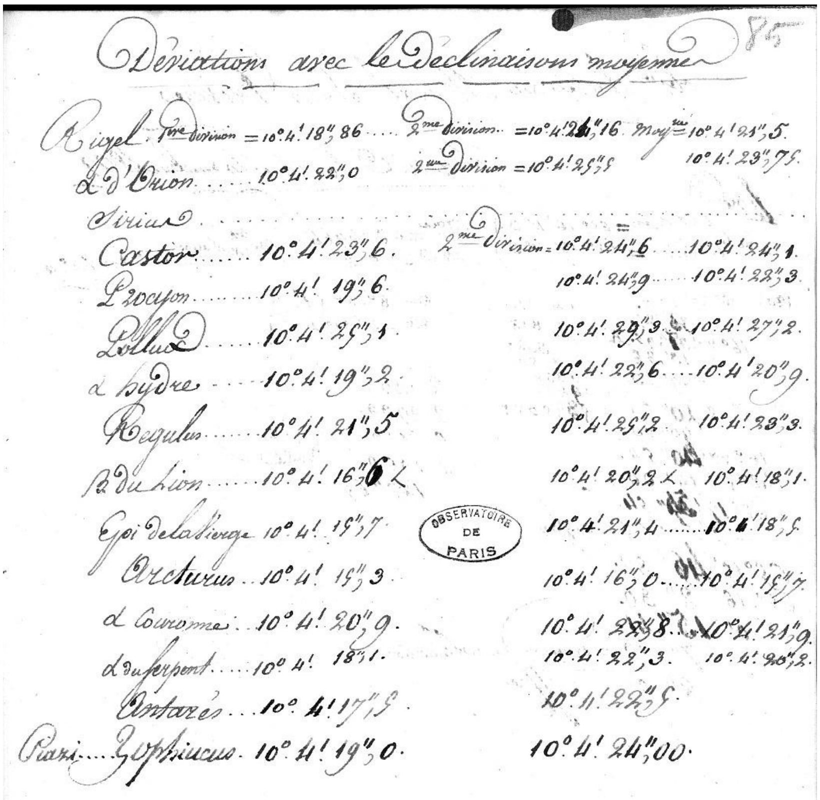
The light enters a flint glass prism, where it is dispersed differently depending on its colour, and then a crown glass prism affixed to the previous one, which corrects the

before and afterwards was not independent of the initial velocity, and that the angle by which the ray is deviated therefore depends on this velocity. It was therefore believed possible to measure the initial velocity of the light by observing the deviation produced by the prism.

dispersion of the flint glass. In the end, the angle by which the light is deviated is the same regardless of its colour, which makes it possible to observe white light. We do not know how the prism was oriented with regard to the incident light. In his last series of observations, Arago placed a set of two achromatic prisms affixed together in front of half of the lens of a telescope, as shown on the right.

The achromatic prism, which gave a deviation of just over 10°, was attached in front of the lens of the telescope of a meridian mural circle, which meant that the stars were observed when they passed through the meridian. The prism could rotate and be moved sideways. Arago took measurements, both with and without the prism, of the angular distance to the zenith of various stars as they transited the meridian (Fig. 2). He repeated these measurements at different times of the year. He found that the deviations produced by the prism presented only very slight differences from one star to another, which he attributed to errors of measurement. To reduce their effect, he nevertheless had another prism constructed.

Once again, no significant difference was found from one star to another. The speed of light did not seem to depend on the properties of the star from which the light was emitted. Furthermore, had the speed of light simply interacted with that of the Earth, Arago would have easily been able to detect the effect of this movement on the speed of light: at two opposite periods of the year, for stars close to the ecliptic, it would have produced a deviation reaching 6″ with the single achromatic prism and 14″ with the double prism. He observed nothing of the sort.


Déviations avec les Déclinaisons moyennes — 85

Rigel. 1re division = 10°4'18",86 .... 2me division = 10°4'24",16 Moy = 10°4'21",5
α d'Orion .... 10°4'22",0 — 2me division = 10°4'25",5 — 10°4'23",75
Sirius ....
Castor ..... 10°4'23",6. — 2me division = 10°4'24",6 ..... 10°4'24",1
Procyon .... 10°4'19",6 — 10°4'24",9 ...... 10°4'22",3
Pollux ..... 10°4'25",1 — 10°4'29",3 ... 10°4'27",2
α hydre .... 10°4'19",2 — 10°4'22",6 .... 10°4'20",9
Regulus ...... 10°4'21",5 — 10°4'25",2 — 10°4'23",3
β du Lion ...... 10°4'16",6 — 10°4'20",2 — 10°4'18",1
Epi de la Vierge 10°4'15",7 — 10°4'21",4 ...... 10°4'18",5
Arcturus .. 10°4'15",3 — 10°4'16",0 .... 10°4'15",7
α Couronne .. 10°4'20",9 — 10°4'22",8 ... 10°4'21",9
α du serpent ..... 10°4'18",1 — 10°4'22",3 — 10°4'20",2
Antarès ... 10°4'17",5 — 10°4'22",5
Paris .... α Ophiucus 10°4'19",0 — 10°4'24",00

Figure 2: *Page from one of Arago's handwritten notebooks in which he records the final result of his initial measurements with the achromatic prism. In it he indicates the difference in declination of various stars measured with and without a prism with the two opposite divisions of a mural circle, and then their mean, that is to say the deviation of this prism. As we can see, the differences between one star and another are of an order of only a few seconds of degree, due simply to errors of measurement.*

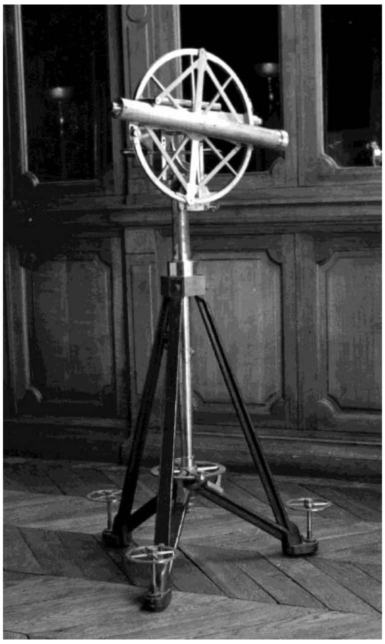


***Figure 3*: Fortin's repeating circle at the Paris Observatory.**

Arago and Laplace were perplexed by these results. They wavered between two explanations: either Newtonian theory was false and the speed of light was constant, or the eye can perceive only "speckles of light" with a given speed. They opted for the second hypothesis.

Indeed, Arago writes:

> *It seems [that] … one can only explain the observation by assuming that luminous bodies emit rays with all sorts of velocities, provided one also admits that these rays are visible only when their velocities fall between specific limits. In effect, in this hypothesis the visibility of the rays will depend on their relative velocities, and, as these same velocities determine the quantity of the refraction, the visible rays will also always be refracted in the same way.*

From this they draw a rather unexpected consequence, but one which shows that they suspected infrared and ultraviolet rays to be of the same nature as light. This was far from obvious at the time:

> *It may be useful to note that the observations that I have related and the supposition which explains them are connected in a quite remarkable manner to the experiments of Herschel, Wollaston and Ritter. As we know, the first one found that there are invisible rays outside the prismatic spectrum, and on the red side, but which have a heat-producing property to a greater degree than light rays; the two other physicists recognised, at more or less the same time, that on the violet side there are invisible and heatless rays, but whose chemical action on silver muriate* [chloride] *and several other substances is very discernible* [these are of course the infrared and the ultraviolet]*. The latter rays could make up the class of those which lack only a small increase in velocity in order to become visible, and the calorific rays could be those that too great a velocity has already deprived of the property of emitting light.*

Either way, Arago's observations sowed confusion among advocates of Newtonian theory. Arago was still one of them, but not for long. This was evoked by Alexandre de Humboldt in his preface to Arago's *Œuvres complètes*:[3]

> *By applying a prism to the lens of a telescope, [Arago] had proved not only that the same refraction tables can serve for the light that the Sun emits and that which comes to us from the stars [here is at least one practical application of Arago's observations], but moreover – and which already cast much doubt on the theory of emission – that the rays of the stars towards which the Earth moves, and the rays of the stars from the Earth moves away, refract in exactly the same quantity. To reconcile this result, obtained after very delicate observations, with the Newtonian hypothesis, one would have had to acknowledge that luminous bodies emit*

3. *OC* t. 1, p. I–XXXII.

rays of all speeds, that only the rays with a certain velocity are visible, and that they alone produce a sensation of light in the eye.

Arago mentions other suggestions for aberration-related experiments designed to seek the differences in the speed of light, which consisted in observing the position of the stars using a telescope filled with water. Initiated by Rudjer, then by Alexander Wilson, and resumed in the second half of the 19th century by the English astronomer Airy and others, they did not yield more results than Arago's own observations.

Disconcerted by his result, Arago, who was increasingly convinced of the validity of undulatory (wave) theory, turned to his friend Fresnel to ask him to try to interpret his observations in the framework of this theory. Fresnel's work was published in 1818 in the *Annales de Chimie et de Physique*[4] in the form of a letter to Arago. Fresnel understood that the speed of light in Arago's prism did not simply add up with the speed u of the Earth: to some extent this prefigures special relativity. He expressed this by saying that the ether in the moving prism did not attain the velocity u, but was dragged only partially with the velocity $u\times(1-1/n^2)$, n being the index of refraction of the prism glass.

Yet Arago's interest in the problem waned because he was now working with Ampère on electromagnetism. One might have expected him to say a few words about it when he presented his article of 1810 in 1853, but this was not so. The hypothesis of the "partial drag" of ether, put forward by Fresnel to explain the result of Arago's experiment of 1810, would have been completely forgotten had Fizeau not alluded to Fresnel's text in relation to his experiment of 1849.

Be that as it may, although they were conducted in the framework of the corpuscular theory of light, and even though they were not related in writing until 1853, Arago's experiments of 1810 remain a fundamental milestone in our understanding of the nature of light and in the validation of the theory of special relativity of 1905.

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(September 2008)

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4. *ACP* 19 (1818) p. 57, reproduced in Fresnel (1866, 1868, 1870) t. 1, p. 627–636.