
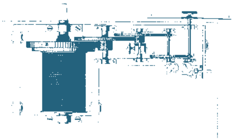
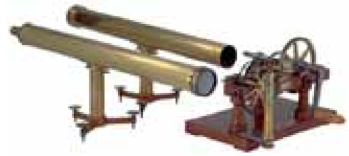

SCIENCE & HISTORY

Hippolyte Fizeau

Physicist of the light

James Lequeux

EDP Sciences

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THE French physicist Hippolyte Fizeau was the first to have directly measured the velocity of light in 1849. He discovered the shift in wavelength produced by the relative velocity of a light or sound source and an observer independently from Doppler. But it is not generally known that he was also a pioneer of photography, that he performed with Léon Foucaults magnificent interference experiments, in particular in the infrared, and also that several of his other experiments put his successors on the track to Relativity. Fizeau also imagined, in 1851, that the apparent diameter of stars could be measured by interferometry, opening the way for developments that are presently experiencing enormous success. This book is the very first devoted to the scientific work of this great physicist.

Most of the experimental notes of Fizeau have been preserved as well as many of his instruments, making it possible to reconstruct the processes of his research in an exceptionally precise and detailed manner. The book, illustrated with numerous autographs and featuring important unpublished texts, is written in a lively and easily accessible way.

James Lequeux is an astronomer emeritus of the Paris Observatory. He has published scientific biographies of Arago and Foucault in English, and many textbooks and popular books in French and in English. He has been awarded an important prize for the history and philosophy of science by the French Academy of sciences.

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Hippolyte Fizeau, physicist of the light

James Lequeux

Emeritus Astronomer at the Paris Observatory

17, avenue du Hoggar
Parc d'Activité de Courtabœuf, BP 112
91944 Les Ulis Cedex A, France

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Introduction

The first half of the nineteenth century saw the emergence in France of physicists and astronomers of extraordinary quality, who established classical physics to a large extent and even created astrophysics. The preceding century had seen great precursors like Lagrange, Laplace, Lavoisier or Monge, while prestigious institutions had promoted science and education; but, thanks the social promotion made possible by the Revolution, by the creation of the Polytechnic school by the Convention, and by the Egyptian campaign, new talents of the highest order emerged. The revolutionary and romantic enthusiasm allowed them all boldness. The most important physicists and astronomers of this generation were undoublty Ampere, Arago, Carnot, Fourier, Fresnel and Malus. Scientific biographies have been published on each of them, at least in French. A second, no less brilliant generation includes Fizeau, Foucault and Le Verrier. The last two have been, too, the subjects of recent scientific biographies in English. Only Fizeau remained little studied, which is why I wrote the present book. Later, in the second half of the nineteenth century, French science was on the decline, and it would be difficult to quote physicists and astronomers with as much genius as the preceding ones, with the exceptions of Poincaré, Langevin and the Curie. The reasons for this decline, at a time when science flourished in Germany, England and the United States, remain to be studied in detail.

Fizeau's life was that of a wealthy bourgeois, safe from material concerns, who was able to concentrate fully and without hindrance on science. He was generally described as a "landlord" or "annuitant" in official documents. The private part of his life offers no particular interest, and is certainly not the focus of this book. As for his scientific career, until 1849 it merged with that of Leon Foucault, with whom he worked almost constantly. They had much in common: the same age, medical studies, considerable manual skill and peerless inventiveness. In 1849, Fizeau carried alone his famous measurement of the velocity of light; then, the following year, the two men fell out with each other after their competition to measure the difference in the velocities of light in air and water. They now followed divergent paths, often harsh and unexpected in the case of Foucault who died young, in 1868, of what was likely multiple sclerosis. For his part, Fizeau made other brillant experiments, then became an established and considered scientist, well inserted in his time, which did not prevent him from having occasionally some bright and innovative ideas. He died in 1896 after a long career, and a particularly long service as a member of the Academy of Sciences, which he had entered on January 2, 1860.

I want to thank my wife Geneviève and my friend William Tobin for their careful reading of the French text and their numerous suggestions for correcting and improving it. William Tobin also communicated or showed to me unpublished documents. I thank Florence Greffe for her warm welcome to the Archives of the Academy of Sciences and for allowing me to reproduce and publish numerous autograph documents from the Fizeau funds. Similarly, the Mayor of Suresnes and Mrs. Marie-Pierre Deguillaume, director of the Museum of Urban and Social History of this city, have authorized me to publish other autograph documents as well as photographs of instruments that belonged to Fizeau: many thanks to them and to the museum staff. Marie-Christine Thooris kindly provided photographs of the replica of the Fizeau apparatus that belongs to the museum of the Ecole Polytechnique. Finally, I thank my colleagues of the Library of the Paris Observatory, who are always ready to make available to users images from their collections.

Contents

Chapter 1
The beginning of a scientific life

On 1839 August 19, Arago presents to the Academy of Sciences and the Academy of Fine Arts the photographic process of Daguerre. Bibliothèque de l'Observatoire de Paris.

Armand-Hippolyte-Louis Fizeau, sixth in a family of nine children, several of whom died in infancy, was born in Paris, 7 rue Thibautodé in the Louvre district, on the 23rd of September 1819. He was baptized on September 29th in the Saint-Germain l'Auxerrois church. His sister Gabrielle, a religious person, died in 1862. The two other sisters and the two younger brothers remaining died in 1854, 1880, 1880 and 1885 respectively (see Appendix 1). Little is known about his mother, Béatrix (or Béatrice) Marie Petel. His father, Louis-Aimé Fizeau (1776-1864), had married her on 20th June 1809. A few years after the birth of Hippolyte, in 1823, his father was appointed a professor at the Faculty of Medicine of Paris, during the reorganization of the faculty which resulted in the expulsion of several of its members for political reasons (some of the excluded people are famous in France: Pelletan, Pinel, Vauquelin). He was himself dismissed for similar reasons in 1830, during the July Revolution[1]. Linked to Laennec (1781-1826), he held the chair of internal diseases; he was one of the first adept of auscultation of patients.

Hippolyte studied as a non-resident at Collège Stanislas and was supposed to succeed his father as a physician. But his health, affected by severe headaches, forced him to interrupt his medical studies. Soon, he recovered sufficiently to be able to follow his scientific tastes. An autograph sheet[2], unfortunately difficult to read, indicates the course of his studies and the name of his teachers (the boxes are in the original):

1835: Rhetoric

1836: Also philosophy

1837: Chemistry (Dumas, Boussingault, Orfila), Physics (Dulong)

1838: Travel; [illegible]

1839: [illegible] Sickness; Geology courses, physical studies, dissections, hospitals, chemistry, Mr Magendie; Good work; Ideas on a Memoir on the shape of drops.

1840: Trip to Le Havre; Gold salts; Lectures by Mr Élie de Beaumont; [illegible]; Course of Dr. Blainville. Daguerreotype.

1841: Travel in Anjou; Bromine; electroplating; Lectures by Mr. Blainville, Regnault, Élie de Beaumont.

1842: Travel; Note on bromine; Course of Regnault; Mathematics.

1 Corlieu, A. (1896) *Centenaire de la Faculté de Médecine de Paris*, Paris, Imprimerie nationale.

2 Académie des Sciences/Institut de France, fonds 64 J,Hippolyte Fizeau, dossier 9.28.

The teachers[3], who are almost all still famous today, were the best of the time. Alfred Cornu (1841-1902), a disciple of Fizeau that we will encounter later, said[4] that Fizeau also attended the course of Popular Astronomy of François Arago (1786-1853). Although we have found no other trace of this, it should not surprise us because all the intelligentsia of the time pressed for these courses, whose success was enormous. They were given at that time in the College de France, then from February 1841 in the amphitheater of 800 seats that Arago had built at the Observatory. Always generous with young people, Arago remarked Fizeau and closely followed his first works, which he often mentioned in an eulogistic way at the Academy of Sciences. However, the course that had most intrigued Fizeau was that of Regnault, who taught optics at the *Collège de France*. There is no doubt that it confirmed Fizeau's choice of research career.

1.1 The daguerreotype

We have just seen that in 1839, while he was continuing his studies, our young man began to think about research. A first Memoir on the shape of drops of water came to nothing, but he now embarked in a completely new field: photography. On the 7th of January 1839, Arago, who was the *Secrétaire perpétuel* (permanent secretary) of the Academy of Sciences, presented to the Academy the process of Louis Mandé Daguerre (1787-1851), an invention soon to be known as the daguerreotype[5]. Working with Nicéphore Niepce (1765-1833) until the latter's death, Daguerre submitted a copper plate covered with a thin, polished layer of silver, to iodine vapor, forming silver iodide on the surface of the plate. Upon exposure to light, the silver iodide was more or less reduced to metallic silver in exposed areas. The plate was developed in mercury vapor at 60-80 °C. The excess silver iodide was dissolved in a sodium thiosulfate solution, and the plate was washed and dried. The positive image was formed by silver-mercury amalgam grains that scattered light in the most exposed areas,

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[3] Jean-Baptiste Dumas (1800-1884) and Jean-Baptiste Boussingault (1802-1887), famous chemists; Mathieu-Joseph-Bonaventure Orfila (1787-1853), chemist, toxicologist and medical examiner; Pierre-Louis Dulong (1785-1838), physicist; François Magendie (1783-1855), physiologist; Léonce Élie de Beaumont (1798-1874), chemist and geologist; Henri-Marie Ducrotay de Blainville (1777-1850), zoologist and anatomist; Victor Regnault (1810-1878), chemist and physicist.

[4] Cornu (1897), p. C2. See this reference in the bibliography.

[5] *Arago, F. (1839), *Comptes rendus hebdomadaires de l'Académie des sciences (CRAS)* 8, p. 4-7.

giving the whites and grays, while the specular reflection on the bare polished silver gave the blacks.

During his presentation, Arago, who had just listed the immense possibilities of photography, proposed that it fell into the public domain. His request was heard: on the 9th of July 1839, the Chamber of Deputies voted an annual pension of 8,000 francs to Daguerre and 4,000 francs to the heirs of Niepce, and on August19th the details of the process were disclosed by Arago during a joint session of the Academy of Sciences and the Academy of Fine Arts. Immediately, scientists, engineers and enthusiasts worldwide started making daguerreotypes. Daguerre took the opportunity to sell the necessary equipment, while the optician Charles Chevalier (1808-1895) manufactured cameras.

However, the results were somewhat disappointing: while the images were beautiful, they were also very fragile, and the exposure times were so long that there was almost no question of photographing living characters. Then our young Fizeau, who was just twenty, intervened. He brought decisive improvements to the daguerreotype. To fix the image and make it more brilliant, he prepared a solution of sodium and gold thio-sulfide, by mixing solutions of gold chloride and of sodium thio-sulfide. He coated the plate with this product and heated it: gold replaced silver in the amalgam of the grains, and the bare silver that formed the base of the plate was covered with a thin layer of gold that browned it, making deeper blacks. Most daguerreotypes that remain today were treated by this method, that Fizeau published in 1840 in the *Comptes Rendus* (Proceedings) of the Academy of Sciences[6].

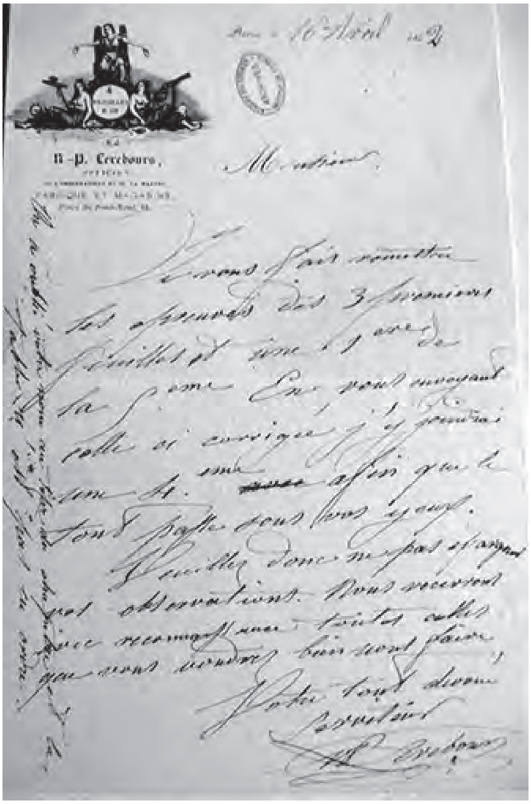
Somewhat later, he thought to expose the plate to vapors from a very dilute solution of bromine for a few moments, before exposure[7]. The silver iodide was then replaced by silver bromide, more sensitive to light: the exposure time was reduced to twenty seconds in bright light, allowing portraits of living people to be taken. Fizeau also remarked that one could reduce the exposure time further by increasing the aperture ratio of the photographic objectives, which was only f/15 in those sold by Daguerre or Chevalier; indeed, the objectives

[6] *Fizeau, H. (1840) *CRAS* 11, p. 237-238. Soon after, Arago presented a daguerreotype obtained in this way to the Academy, "which differentiates from all other similar trials by its remarkable perfection and also by the no less remarkable fact that the daguerrian image was not at all altered."

[7] *Fizeau, H. (1841) *CRAS* 12, p. 1189-1190.

with several lenses built by various opticians soon reached a larger aperture ratio.

Fizeau worked with Noël Paymal Lerebours (1807-1873), the optician of the Observatory of Paris, who was also a great photographer: he made many daguerreotypes, and he was the author of a treatise of photography that had at least five editions. The fifth edition[8] has as a co-author his collaborator Marc Secretan (1804-1867), who also became a famous optician and succeeded him. They inserted notes by Fizeau (Fig. 1.1). With Fizeau's bromination process and very open objectives, Lerebours said that he could obtain poses of less than one second.


N.-P. Lerebours,
Opticien
Fabrique et Magasins

Monsieur,

Je vous fais remettre les épreuves des 3 premières feuilles et une 1ere de la 4eme. En vous envoyant celle-ci corrigée j'y joindrai la 5eme afin que le tout passe sous vos yeux.

Veuillez donc ne pas épargner vos observations. Nous recevrons avec reconnaissance toutes celles que vous voudrez bien nous faire.

Votre tout dévoué serviteur

N. P. Lerebours

FIGURE 1.1 – Letter from Lerebours to Fizeau about inserting an article by the latter in his treatise of photography, on the use of bromine to sensitize daguerreotypes. Académie des sciences-Institut de France, Fonds 64 J, Hippolyte Fizeau, dossier 8.02.

[8] Lerebours & Secretan (1846).

As there was a lot of money to earn with daguerreotypes, competition was fierce, especially between Lerebours and Chevalier, who also had published a treatise of photography in 1841[9]. They did not fail to inveigh against each other by interposed writings, in particular about a new development that looked promising: the reproduction of photographic images. Indeed, the daguerreotype was a unique item, and it would have been interesting to replicate it. Fizeau developed an electroplating method that implied electro-deposition of a copper layer on the daguerreotype[10]. His contemporaries said that the layer came off pretty easily. Then Fizeau obtained another layer in the same way from the negative plate, which was a copy of the original[11].

Fizeau was not the only one to have this idea and to put it into practice: a man named Krasner claimed the priority as early as the 2nd of November 1840[12], and Chevalier said in his treatise (Chevalier, 1841, p 60-66) that he had obtained conclusive results in January of 1841; the weekly journal *L'Artiste* also mentioned his success on February 7th[13]. As for Fizeau, he made his presentation to the Academy of Sciences in March 1841.

In 1843-1844, Fizeau used another method to replicate the daguerreotypes, a work undertaken for a competition run by the Society for the Encouragement of National Industry, with a prize of 2,000 francs[14]: he attacked with an acid the daguerreotype plate, which was then sacrificed until it was sufficiently excavated. A fairly complex treatment allowed him to obtain "a considerable number of copies"[15]. Three plates in an important book entitled *Excursions daguerriennes* were obtained by this process from daguerreotypes by Lerebours[16].

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9 Chevalier (1841).

10 *Fizeau, H. (1841) *CRAS* 12, p. 401-402.

11 *Fizeau, H. (1841) *CRAS* 12, p. 509.

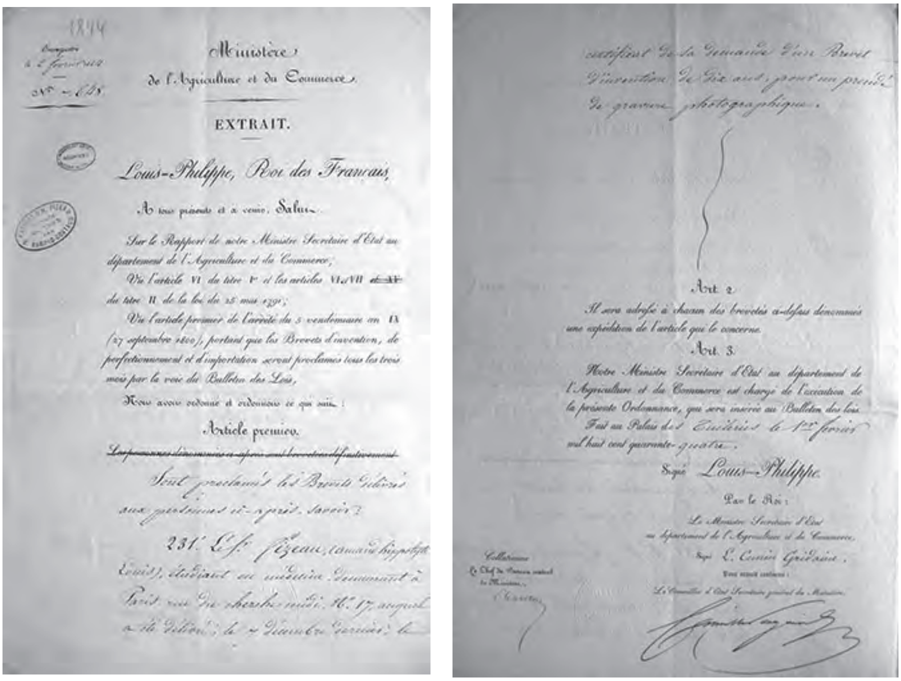
12 *(1840) *CRAS* 11, p. 712.

13 **L'Artiste* (1841) 2d Series, t. 7, 6, p. 94. One reads: "The galvano-plastic instrument was made with much care by two optical engineers, MM. Chevalier and Lerebours, who rival in talent and skillfulness [...]. M. Charles Chevalier obtained a result in his first trials [...], the application of the metal was so exact that a daguerreotype plate was reproduced in spite of its light and shallow lines."

14 Fizeau did not obtain the prize, and 1,000 francs went to MM. Choiselat and Ratel: *Bulletin de la Société d'Encouragement pour l'Industrie Nationale*, 52e année (1853) p. 297, accessible via http://cnum.cnam.fr.

15 *(1843) *CRAS* 16, p. 408; *Fizeau, H. (1844) *CRAS* 19, p. 119-121.

16 *Anonymous (1840-1843) *Excursions daguerriennes : vues et monuments les plus remarquables du globe,* t. 2, Paris, Rittner & Goupil.


Ministère
de l'Agriculture et du Commerce.
EXTRAIT.
Louis-Philippe, Roi des Français,
A tous présents et à venir, Salut.
Sur le Rapport de notre Ministre Secrétaire d'État au département de l'Agriculture et du Commerce;
Vu l'article VI du titre Ier et les articles VI, VII du titre II de la loi du 25 mai 1791;
Vu l'article premier de l'arrêté du 5 vendémiaire an IX (27 septembre 1800), portant que les Brevets d'invention, de perfectionnement et d'importation seront proclamés tous les trois mois par la voie du Bulletin des Lois,
Nous avons ordonné et ordonnons ce qui suit :
Article premier.

Art. 2
Il sera adressé à chacun des brevetés ci-dessus dénommés une expédition de l'article qui le concerne.
Art. 3.
Notre Ministre Secrétaire d'État au département de l'Agriculture et du Commerce est chargé de l'exécution de la présente Ordonnance, qui sera insérée au Bulletin des lois.
Fait au Palais des Tuileries le 1er février mil huit cent quarante-quatre.
Signé Louis-Philippe.
Par le Roi :
Le Ministre Secrétaire d'État au département de l'Agriculture et du Commerce,
Signé L. Cunin Gridaine.

FIGURE 1.2 – A patent issued to Fizeau for reproduction of daguerreotypes by electroplating (front and back). Académie des sciences-Institut de France, Fonds 64 J, Hippolyte Fizeau, dossier 8.02.

Facing the competition, Fizeau filed a patent that was recorded on the 2nd of February 1844 (Fig. 1.2). It is therefore likely that some priority was acknowledged to him, because he was the only one to have published in the *Comptes rendus*; Arago, who held him in high esteem, was perhaps no stranger to this. Taking a patent proved an unnecessary precaution, because the process was complicated and risky, especially since "most often, the original piece is in relief; so it is necessary to produce a counter-proof and to submit it to the same operations [electroplating] to produce a relief plate" (Chevalier 1841, p. 66). It was soon abandoned: after William Henry Fox Talbot (1800-1877), "its use was abandoned because of the large uncertainties that it included, who used the patience of the experimenters."[17] The future was in the neg-

[17] Article by Fox Talbot in Atheneum, dated the 4th of April 1853, accessible via http://foxtalbot.dmu.ac.uk/letters/transcriptFreetext.php?keystring=Fizeau&keystring2=&keystring3=&year1=1800&year2=1877&pageNumber=13&pageTotal=15&referringPage=0

ative-positive process by contact onto paper invented by Fox Talbot, that he patented in 1841 under the name of *calotype*. Fizeau himself congratulated Fox Talbot for this progress[18]. The daguerreotype then had only ten years to live[19].

1.2 A decisive encounter

The young Fizeau was now famous, and many photography enthusiasts came to ask for his advice. This was the case of a young man of the same age, Léon Foucault (Box 1.1 and Fig. 1.3), who was doing experiments on the daguerreotype on the side. The two young men probably had known each other at the Stanislas College or at the School of Medicine. Everything brought them together: a social environment of good bourgeoisie, parallel studies of medicine, and especially the love of science.

FIGURE 1.3 – Léon Foucault around 1862. Bibliothèque de l'Observatoire de Paris.

18 Letter from Fizeau to Fox Talbot dated the 7th of August 1844, accessible via http://foxtalbot.dmu.ac.uk/letters/transcriptFreetext.php?keystring=Fizeau&keystring2=&keystring3=&year1=1800&year2=1877&pageNumber=5&pageTotal=15&referringPage=0

19 For an history of photographic reproduction, see Daniel (1995).

Box 1.1. Léon Foucault (1819-1868)

Léon Foucault was sort of a double of Fizeau: they were born five days apart, they both began medical studies but turned to physics, and both had a huge imagination and great experimental skill. The difference was that Foucault was basically a mechanic while Fizeau had more of a taste for and skills in mathematics. Both started their first scientific experiments at their own expense, but Foucault's resources were more limited so he had to make a living by writing scientific articles for the *Journal des débats* from 1842, indeed with great erudition and critical sense. Made famous by the work done in common with Fizeau or by himself, and especially by the famous pendulum experiment, which dates from 1851, Foucault became a protégé of Napoléon III who imposed his appointment as "Physicist of the Observatory" to Le Verrier in 1855. He quarreled with Fizeau and continued his first-class scientific work alone: the design and construction of the first modern telescopes with a silvered glass mirror from 1857, then in 1862 the first accurate measurement of the velocity of light, with a rotating mirror. Rapidly weakened by a disease that was probably multiple sclerosis, he died in 1868.

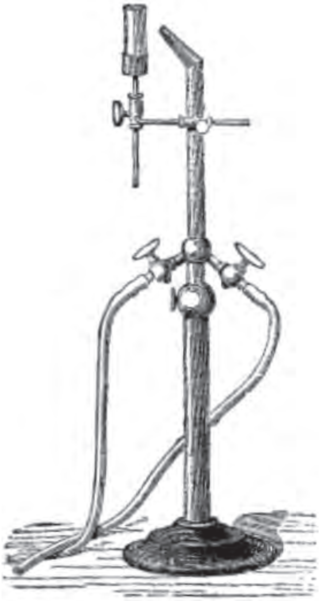


FIGURE 1.4 – The Drummond's light (limelight). The light is produced by a piece of chalk heated by a torch which burns a mixture of hydrogen and oxygen. This light source was still used at the end of the nineteenth century: the image is taken from a catalog of scientific instruments dating back to 1891. Conservatoire Numérique des Arts et Métiers.

Foucault probably contacted Fizeau for details on his method of bromination of plates. He perfected it and described his process in a booklet of ten pages, immediately published in the practical guide of Charles Chevalier[20]. This note ends with a compliment to Fizeau:

> *"But I must say in closing, that the important idea, the capital idea belongs to Mr. Fizeau,: to renew the solution [of bromine in water] for each plate."*

The two men worked separately until the second half of 1843, when they decided to collaborate. Their first collaboration was about the application of the daguerreotype to photometry, that is to say, the measurement of the intensity of light. This project had already been proposed by Arago in 1839, when he described what could be expected of photography before the Academy of Sciences[21]:

> *"The physicists succeed quite well in determining the comparative intensities of two lights adjacent from each other and perceived simultaneously; but there are only imperfect means to make this comparison, when the simultaneity condition does not exist. [...] I don't hesitate to say, that the reagents [sic] discovered by Mr. Daguerre will hasten the progress of one of the sciences that honor most the human spirit. With their help, the physicist will now proceed by way of absolute intensities; he will compare the lights by their effects. If useful, the same table will give him the prints of the dazzling rays of sunlight, of the rays three hundred thousand times fainter of the moon, and of the light of the stars. These impressions, he will equalize them either by weakening the stronger lights with excellent means, the result of recent discoveries[22], or by letting the brightest rays act only for a second, for example, and the others for up to half an hour when needed."*

Fizeau and Foucault attempted to compare the intensity of sunlight with that of two other light sources. The purpose was utilitarian: what was the best source of light to be used for laboratory experiments? Was it the sun, or the electric arc invented by Humphry Davy (1778-1829) in 1801, or the oxy-hydrogen light of Thomas Drummond (1797-1840), actually invented by Goldsworthy Gurney (1793-1875)[23] (Fig. 1.4)? To

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20 Chevalier (1841).

21 *Arago, F. (1839) Le Daguerréotype, *La France littéraire* 35, p. 404-420.

22 This obviously is for Arago the attenuation achieved by turning relative to each other two polarizers crossed successively by the light.

23 For Drummond's light, see Lauginie, P. (2013) *Drummond's Light, Limelight: a Device in its Time,* accessible via http://www.scientificinstrumentsociety.org/bulletin-127/

do this, they produced the image of the three sources on daguerreotypes plates successively with an achromatic lens. In order that these images were just at the threshold of sensitivity of the plate after development under mercury vapor, they played with different parameters: the distance from the source to the lens, the focal length of the lens, a diaphragm limiting the useful diameter of this lens, and even the exposure time.

The result[24] was that the brightness of the incandescent chalk of Drummond's light was fainter than that of the positive carbon electrode of the arc, which was itself weaker than the Sun. If the Sun, taken as the reference in good conditions, had a brightness of 1,000, that of the arc went from 136 to 385 according to the difference in potential applied to the electrodes, and that of Drummond's light only 0.5 to 6.85 according to the gas pressure in the torch. This referred to the luminance in the blue-ultraviolet light to which the daguerreotype is sensitive: this is what Fizeau and Foucault called the *chemical intensity*, because these are the wavelengths that produce the chemical reaction of the reduction of silver salts, which is the basis of photography. They realized that the relationship between the brightnesses could be different for the light to which the eye is sensitive, and they decided to measure visually the ratio of the brightnesses of the Drummond's chalk and the arc, comparing the images formed on a screen by differently diaphragmed lenses. They found that this ratio was not much different from that obtained with the daguerreotype. They concluded mistakenly that "the measures of chemical intensity [...] relative to sunlight, to the electrodes of the arc, and to a mixture of oxygen and hydrogen projected on lime, would also be the measures of the optical intensities of these light sources." This was approximately true when comparing the electric arc to the Drummond light, but not for the Sun whose temperature is much higher. At the end of the communication of Fizeau and Foucault, Arago reminded of his "experiments, already very old, in which he compared, by direct photometric means, the light of the Sun with that of the arc."[25]

This measurement does not seem very remarkable to us, but it was a first, and it required significant financial means to produce the oxy-hydrogen light and especially the electric arc: no less than 138 Bunsen batteries were purchased for this purpose.

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24 *Fizeau, H. & Foucault, L. (1844) *CRAS* 18, p. 746-755 and p. 860-862.

25 We have not found in the Memoirs on photometry of Arago any reference to these experiments, which could have been performed in 1815, a year when Arago made various photometric experiments.

Was it then that Arago told Fizeau and Foucault about a problem that preoccupied him: the darkening of the edge of the solar disk? Indeed, he wrote that he had obtained a daguerreotype of the Sun on which he found "that the rays that come from the central part of the disc of the Sun have a stronger photogenic action than those from the edges."[26] This referred perhaps to the first successful astronomical photograph, that of the partial solar eclipse of the 15th of March 1839, which had long been present at the Paris Observatory but is lost today. The question was of importance, because the edge darkening necessarily implied that the Sun's light came from a glowing gas and not from a liquid or a solid: the brightness of an incandescent solid or liquid depends very little on the angle of incidence, only the polarization of the emitted light, while that of a gas whose temperature varies with depth, as is the case for the solar atmosphere, depends on the incidence while there it is no polarization. Arago had already concluded that the Sun was an incandescent gas in 1811, noting the absence of polarization of the light from the edges of the solar disk. Yet the very existence of the darkening of the edges was controversial, the measurements apparently giving conflicting results. Fizeau and Foucault worked to obtain daguerreotypes of the Sun. For this, the solar light was reflected horizontally by a heliostat to a lens, at the focus of which the daguerreotype was placed. But the Sun is so bright that the exposure time was to be between 1/60 and 1/100 of a second: it was not possible to use the usual method of a cover removed and replaced manually on the lens. Fizeau and Foucault imagined an "original enough" shutter consisting of a plate with a horizontal slit of appropriate width, which they dropped in front of the camera: this was the ancestor of the curtain shutter.

Many daguerreotypes were obtained in this way. All show a darkening of the solar edge. The only large one that is preserved is in the reserves of the French *Musée des Arts et Métiers/CNAM*. The image, which shows several sunspots, is 91.5 mm in diameter and was obtained at the focus of an achromatic lens with a focal length of 9.88 m. This is probably the first beautiful photograph of the Sun. A reproduction was later engraved in Arago's *Astronomie populaire* (Fig. 1.5).

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[26] *Arago, F. (1854-1862) *Œuvres complètes*, t. 10, p. 231-250.

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