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THEN & NOW

Fraunhofer and his spectral lines

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This year marks the two-hundredth anniversary of Joseph von Fraunhofer's essay on the dark lines of the solar spectrum, which bear his name.[1] With this essay the hitherto unknown Bavarian optician and skilled artisan revolutionized optical glass production, which in turn either gave rise to or greatly advanced a large variety of nineteenth-century disciplines, including spectroscopy and planetary and stellar astronomy (Fig. 1).

"Bestimmung des Brechungs- und Farbenzerstreuung-Vermögens verschiedener Glasarten in Bezug auf die Vervollkommnung achromatischer Fernröhre" ("Determination of the Refractive and Dispersive Indices of Differing Types of Glass in Relation to the Perfection of Achromatic Telescopes") was the culmination of Fraunhofer's experiments on perfecting the manufacture of achromatic lenses. Its sole purpose was to publish his method for improving the construction of achromatic lenses for telescopes [1]. It was certainly not an attempt to explain theoretically the nature of the solar dark lines (later to be called absorption lines) or the lamp lines (later to be called emission lines).

Ever since Isaac Newton's work on the spectrum during the late seventeenth and early eighteenth century, experimental natural philosophers and opticians alike had attempted in vain to determine the refraction of each colored ray. But since the colors of the spectrum seemed to be continuous, no precise methods could be generated for choosing which colors to measure.

Initially Fraunhofer, as many others before him, attempted to circumvent this problem by focusing his attention on colored glasses and prisms filled with colored liquids. He hoped to determine the refractive index of a glass sample for the color of light supplied by these filters, which, he originally thought, would permit only homogeneous light to pass. Despite various attempts to produce such a glass or fluid, however, the emergent light never proved to be truly monochromatic; a mixture of spectral colors always resulted. Fraunhofer also used colored flames produced by burning alcohol and sulfur; however, these flames also produced a spectrum when viewed through one of his prisms.

After giving up on colored glasses and liquid-filled prisms, Fraunhofer decided that he wanted to view the spectrum produced when the light of a burning lamp was refracted by a prism and then viewed through a telescope mounted on a modified theodolite, an ordnance surveying instrument originally designed to measure angles for the production of maps. The modified theodolite could measure the angle of emergence from the subject prism for each colored ray. Unfortunately, the rays of light falling onto the subject prism would not be parallel, so that the angle of incidence would not be the same for each one, rendering

Figure 1 Joseph v. Fraunhofer (1787–1826). Portrait by R. Wimmer. Reprinted with permission from Deutsches Museum Munich, Germany.

[1] This article is based on Myles W. Jackson. 2000. *Spectrum of Belief: Joseph von Fraunhofer and the Craft of Precision Optics*. Cambridge, MA: MIT Press, translated by Hans Günther Holl, *Fraunhofers Spektren: Die Präzisionsoptik als Handwerkskunst*. Göttingen: Wallstein Verlag, 2009.

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the modified theodolite's measurement useless. In order to ensure that the rays striking the subject prisms would be parallel, Fraunhofer substantially increased the distance between the lamp and the prism. But, he noted, although the rays now all had measurably the same angle of incidence, the increased distance resulted in some of the refracted rays missing the prism altogether, producing an incomplete spectrum. To ensure that rays incident on the subject prism remained parallel, that an entire spectrum would be generated, and that the light would be intense enough to be seen through minute slits at such a large distance, Fraunhofer used six lamps.[2] (Fig. 2)

Fraunhofer placed the six lamps behind a shutter, 1.5 Bavarian inches (36.0 mm) high and 0.07 of a Bavarian inch (1.68 mm) thick, which was pierced by six narrow slits less than 1.5 inches high and 0.05 of a Bavarian inch (1.20 mm) wide. Each lamp was placed .58 of a Bavarian inch (13.92 mm) apart and directly behind a slit. The light from the lamps would travel 13 Bavarian feet (3.7 m) to a prism, which was made of flint glass with an angle of approximately 40^0, where it would be refracted and decomposed into colors. The dispersed light then traveled through a second slit placed directly behind the prism, which accordingly blocked a portion of the emergent beam. Some of the rays were channeled to the site of a theodolite located in Fraunhofer's laboratory at the very great distance of approximately 692 Bavarian feet (199 m) from the six lamps.

The six-shutter mechanism controlled the angles at which light from each lamp struck the surface of prism A, thereby determining the locus of the corresponding spectrum.

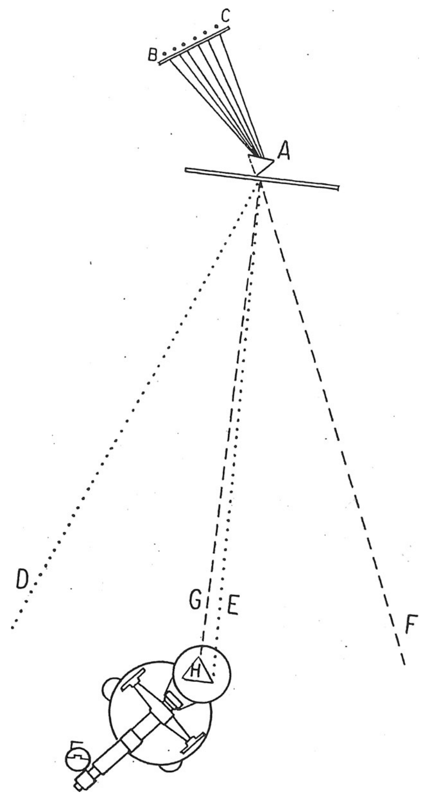

Figure 2 Fraunhofer's experimental setup for detecting the dark lines of the solar spectrum as described in his "Bestimmung des Brechungs- und Farbenzerstreuung-Vermögens verschiedener Glasarten in Bezug auf die Vervollkommnung achromatischer Fernröhre."

For example, from the lamp at C, red rays refracted to E and violet rays to D. From lamp B the red rays traveled toward F and the violet toward G. On the theodolite Fraunhofer placed a prism H whose index of refraction for the different colored rays was to be determined. He then adjusted the distances of the six-shutter mechanism from prism A, of A from the single shutter, and of the single shutter from prism H in such a manner that prism H received only the red rays from lamp C and only violet rays from lamp B. The intermittent lamps supplied the other colors of the spectrum. The spectrum of rays passing through the small aperture below A and then through prism H appeared in the modified theodolite's telescope as depicted in the figure; each spectral color appeared at a unique locus. Fraunhofer ground down the angle of prism H until all the rays from the six lamps emerged from H at a single point (though, of course, each colored ray exited from that point at a unique angle with respect to the face normal there). The object lens of the modified theodolite's telescope was aimed at that point, thereby enabling Fraunhofer to see the entire spectrum and measure each color's dispersion. Since the incident angle could be measured by the modified theodolite to the nearest arc second, Fraunhofer could now determine the index of refraction to six decimal places for each colored ray for teach type of refracting substance.

To see whether other sources of light produced the same sort of lines as the sodium lamps had (the so-called sodium couplet lines), Fraunhofer decided to use the sun as his source.[3] He placed his modified theodolite and prism in a darkened room with a window that was covered by a shutter. He cut a vertical slit in the window shutter 15 arc seconds wide and 36 arc minutes high (approximately 0.6 mm wide by 80 mm high) with respect to the center of the theodolite, allowing the solar rays to fall on a flint glass prism with an angle of 60^0 mounted on the theodolite 24 Bavarian feet (6.9 m) from the window. The prism was placed in front of the telescope's objective lens in such a manner as to ensure symmetric passage. Fraunhofer remarked: "In looking at this spectrum for the bright [sodium] line, which I had discovered in a spectrum of artificial light, I discovered instead an infinite number of vertical lines of

2 see [1], pp. 197–199.

3 see [1], pp. 201–205.

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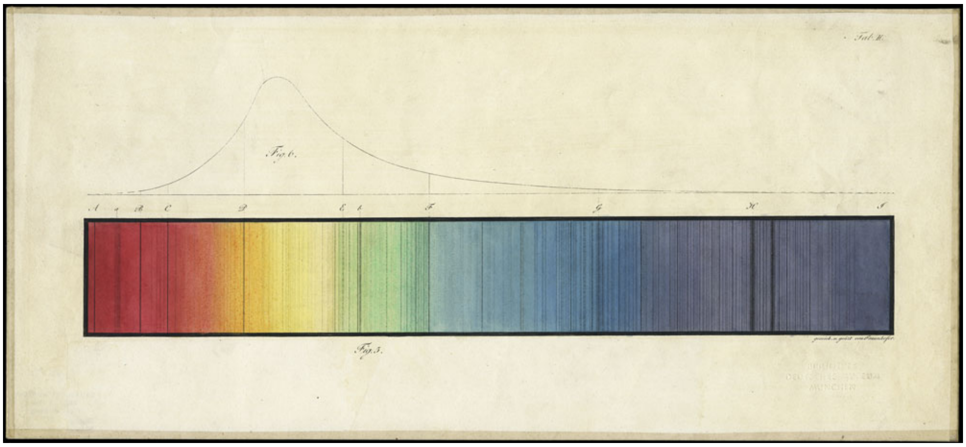

Figure 3 The dark lines of the solar spectrum as depicted by Fraunhofer in his "Bestimmung des Brechungs- und Farbenzerstreuung-Vermögens verschiedener Glasarten in Bezug auf die Vervollkommnung achromatischer Fernröhre." Reprinted with permission from Deutsches Museum Munich, Germany.

different thicknesses. These lines are darker than the rest of the spectrum, and some of them appear entirely black."[4] Fiddling with the window-shade aperture and varying the distance of the theodolite from the window did not obliterate the lines. Between B and H, Fraunhofer counted 574 dark lines.[5] (Fig. 3) Because the lines persisted no matter how he rearranged the distances, Fraunhofer became convinced that these lines were not an experimental artifact, but were an inherent property of solar light.

Fraunhofer was clever enough to use those dark lines as a natural grid that demarcates minute portions of the spectrum. Refractive indices could now be obtained for an extraordinarily precise portion of the spectrum. He then chose the most obvious (i.e., the thickest and clearest) lines for his determination of the refractive indices of a glass prism. They could easily be aligned with the cross-hatchings on his theodolite. Fraunhofer would simply read off the angle from the instrument's vernier. The calculation Fraunhofer used was as follows:

If σ is the angle of incident solar ray, ρ is the angle of the emergent ray, ψ is the angle of the prism, and n is the index of refraction, then

$$n = \frac{\sqrt{(\sin\rho \pm \cos\psi \sin\rho)^2 \pm (\sin\psi \sin\sigma)^2}}{\sin\psi}$$

As mentioned above, Fraunhofer devised his experiments such that the angle of the incident ray (for the D line) was equal to that of the emergent ray (i.e., symmetric passage). If μ (the angle of deviation) is the angle between the incident and emergent rays, then, under these circumstances,

$$n = \frac{\sin_{1/2}(\mu \pm \psi)}{\sin_{1/2}\psi}$$

The angle μ was measured by the modified theodolite, as were the arc *BC*, *CD*, *DE*, *EF*, *FG*, and *GH*. If n_E is the refractive index for the ray *E*, then

$$n_E = \frac{\sin_{1/2}(\mu \pm \psi \pm DE)}{\sin_{1/2}\psi},$$

$$n_F = \frac{\sin_{1/2}(\mu \pm \psi \pm DE \pm EF)}{\sin_{1/2}\psi},$$

$$n_G = \frac{\sin_{1/2}(\mu \pm \psi \pm DE \pm EF \pm FG)}{\sin_{1/2}\psi},$$

and so on.[6]

Fraunhofer created scores of tables listing the refractive indices of the rays (each ray corresponding to a line) for different substances- flint glass, crown glass, oil of turpentine, and water, to name just a few. He then created tables of indices for combinations of refracting media in order to determine the combination that would correct chromatic aberration for the red and violet rays of the spectrum.[7]

Fraunhofer had now provided opticians and experimental natural philosophers with a vastly more precise method for determining the refractive indices of glass samples than had ever before been attained. Previously, Fraunhofer himself had determined the relative dispersive and refractive indices of two kinds of glass by cementing them together, forming a single prism. If the two spectra produced by this compound prism appeared at the same place, without any reciprocal displacement, he concluded that their dispersive and refractive

4 see [1], p. 202.
5 see [1], p. 204.
6 see [1], pp. 208–209.
7 see [1], pp. 223–226.

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powers were the same and equal to the arithmetic average of the two extreme rays: red and violet. After the discovery of the solar lines, however, he quickly realized that two pieces of glass, which appeared to have the same refrangibility when employing the early method of testing, could actually have slightly different powers, as revealed by the existence of an overlap region of two sets of lines where there should only be one.

The dark lines of the solar spectrum, then, provided Fraunhofer with a tool for gauging the efficacy of achromatic-lens production. If the refractive indices determined by aligning the dark lines with the modified theodolite indicated that the glass was not suitable for constructing an achromatic lens (i.e., if another lens could not correct the first lens's chromatic aberration efficiently enough), Fraunhofer and his apprentices would alter the recipe by adding more or less lead oxide in the form of red lead, or by increasing or decreasing the time of stirring or cooling, or by changing how the glass blanks were cut and ground down into lenses. Hence, Fraunhofer's measurement of the refractive and dispersive was connected to the production of optical glass in an unprecedented way. By convincing experimental natural philosophers that his method of calibration (based on the spectral dark lines) was the most accurate for producing lenses, and by demonstrating with that particular method that his lenses were indeed of superior quality, Fraunhofer immediately increased the market for his products. By neither publishing the technique nor the recipes for glass making, nor permitting access to his glass hut in Benediktbeuern, Fraunhofer ensured that the ever-increasing market would be compelled to purchase only his Institute's lenses; he guaranteed the market's fidelity.

Great Britain was the world's purveyors of optical lenses until the first decade of the nineteenth century, after which Fraunhofer usurped the market. In order to do so, he needed to convince British experimental natural philosophers of the importance of the dark lines for measuring refractive indices with unprecedented accuracy. In September 1821, one of Britain's leading scholars, John Herschel, travelled to Benediktbeuern in order to observe Fraunhofer's technique of optical glass manufacture. While Fraunhofer would not disclose his technique, he did show Herschel how one could use the dark lines in order to construct superior optical glass.

We are told of Herschel's replication of these dark lines in Charles Babbage's *Reflections on the Decline of Science in England and on Some of Its Causes* of 1830.

> A striking illustration of the fact that an object is frequently not seen, *from not knowing how to see it*, rather than from any defect in the organ of vision, occurred to me some years since, when on a visit at Slough. Conversing with Mr. Herschel on the dark lines seen in the solar spectrum by Fraunhofer, he inquired whether I had seen them; and on my replying in the negative, and expressing a desire to see them, he mentioned the extreme difficulty he had had, even with Fraunhofer's description in his hand and the long time which it had cost him in detecting them. My friend added, "I will prepare the apparatus, and put you in such a position that they shall be visible, and yet you shall look for them and not find them: after which, while you remain in the same position, I will instruct you how to see them, and you shall see them, and not merely wonder you did not see them before, but you shall find it impossible to look at the spectrum without seeing them."
> On looking as I was directed, nothwithstanding the previous warning, I did not see them; and after some time I inquired how they might be seen, when the prediction of Mr. Herschel was completely fulfilled [2].

Fraunhofer's technique became incorporated into British optical textbooks by the late 1820s. One of the most widely used university textbooks on optics was Reverend Henry Coddington's *Elementary Treatise on Optics*, published in 1823 [3]. Six years later, he published a revised edition [4]. Coddington wrote in his preface to that later edition:

> The Science of Optics having of late years assumed almost a new form, it has appeared desirable that a Treatise should be drawn up, by which Students might be led, with the least possible difficulty, to the comprehension of those important Theories which have expended all, and superseded many points of the subject as contained in former works written for their use. [8]

One of the reasons for the transformation in optics was Fraunhofer's research. Coddington wrote of Fraunhofer:

[8] see [4], p. i.

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> These [spectal] interruptions, first observed imperfectly by Dr. Wollaston, and afterward independently, and with great precision, by Professor Fraunhofer of Munich, and by him termed the *fixed lines* in the spectrum, are one of the most important discoveries in the whole range of Optical Science.[9]

Coddington incorporated Fraunhofer's alphabetical designation of the spectral lines as well as his calculations of refractive indices of differing substances at those particular fixed lines.[10]

The Edinburgh natural philosopher David Brewster included Fraunhofer's contribution in his *Treatise on Optics*, published in 1831:

> One of the most important practical results of the discovery of these fixed lines in the solar spectrum is, that they enable us to take the most accurate measures of the refractive and dispersive powers of bodies, and by measuring the distances of the lines *B*, *C*, *D*, etc. Fraunhofer computed the table of the indices of refraction of different substances. ... From the numbers in the table here referred to we may compute the ratios of the dispersive powers of any two of the substances, by the method already explained in a preceding chapter [5].

Nearly thirty years later, Gustav Kirchhoff and Robert Bunsen famously demonstrated that a number of Fraunhofer lines corresponded with emission lines generated in the spectra of heated elements [6]. The Fraunhofer lines now entered into the domain of spectral analysis, spectroscopy, and analytical chemistry.

In short, Fraunhofer's unparalleled skilled techniques of optical glass manufacturing work fundamentally changed optics and optical glassmaking. In addition, his technique of using the dark lines of the solar spectrum became the preferred method of calibrating refractive indices with a view to test the quality of optical lenses. His work was a prime example of the contributions of skilled artisans to the scientific enterprise.

[9] see [4], pp. 237–238, italics present in the original. It turns out that William Hyde Wollaston had detected several dark lines of the solar spectrum back in 1802.

[10] see [4], p. 239.

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[2] C. Babbage, *Reflections on the Decline of Science in England, and on Some of Its Causes*; B. Fellows, London, pp. 210–211 (1830), italics present in the original.

[3] H. Coddington, *Elementary Treatise on Optics*; J. Smith, Cambridge, UK (1823).

[4] H. Coddington, *A Treatise on the Reflexion and Refraction of Light, Being Part I of a System of Optics*; J. Smith, Cambridge, UK (1829).

[5] D. Brewster, *Treatise on Optics*; Longman, Rees, Orme, Brown and Green and John Taylor, London, pp. 87–88 (1831).

[6] G. Kirchhoff, R. Bunsen, Chemische Analyse durch Spectralbeobachtungen, *Annalen der Physik* **110**, 161–189 (1860); G. Kirchhoff, Ueber die Fraunhoferschen Linien, *Annalen der Physik* **185**, 148–150 (1860); G. Kirchhoff, Ueber das Verhältnis zwischen dem Emissionsvermögen und dem Absorptionsvermögen der Körper für Wärme und Lichte, *Annalen der Physik* **185**, 275–301 (1860).

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