

The Master of Dispersion

Daniel Kleppner

If your literary heritage happens to encompass the writings of James Thurber, you will recall Walter Mitty, a shy fellow with a fantasy life in which he assumed heroic roles—heart surgeon, explorer, private eye, and ace pilot, among others. I think there is something of Walter Mitty in most of us, for who has not had some fantasy such as conquering a great mountain peak or winning at Wimbledon or dancing like Fred Astaire (or perhaps Ginger Rogers) or painting like Picasso, or [insert your favorite fantasy]. This thought occurred to me not long ago as I thumbed through a short monograph printed in 1815. Turning the pages of the antique document triggered a fantasy of being an ace historian of science. Fortunately, one does not need to be an ace historian to enjoy the pleasures of history. Also fortunately, we seem to be in a golden age of the history of science in which merely reading the current literature could be a full-time occupation.

The monograph that inspired these musings came my way while I was exploring the origins of the diffraction grating. The monograph's author was Joseph Fraunhofer, who is generally given credit for the invention. Tracking down the story of how he actually invented the diffraction grating, however, turned out to be difficult. By good luck, MIT is the home of the Dibner Institute and its Burndy Library, a glorious collection of antique scientific books. In response to my request for anything by Fraunhofer, the librarian disappeared into the vault and reappeared with a monograph he wrote on the dispersive power of glass, printed in Munich and dated 1814–15. Unfortunately, that was several years before Fraunhofer invented the diffraction grating, so the monograph did not shed much light on my question. Nevertheless, it contained a treasure: Fraunhofer's engraving of the sharp absorption lines in the solar spectrum—the Fraunhofer lines—that he discovered in 1814.

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The main body of Fraunhofer's monograph is a series of tables of refractive indices of various glasses. Fraunhofer was a genius at producing optical glasses that were clear and, what is most important, uniform. To take full advantage of these glasses it was essential to know precisely how their refractive index varies with wavelength—their dispersion. To measure dispersion, Fraunhofer invented an intricate differential refractometer that used colored lamps as wavelength standards. In the search for better standards, he dispersed sunlight through a high-quality prism and discovered the intricate series of sharp dark lines that now bear his name. Unknown to Fraunhofer, in 1802 William Hyde Wollaston had observed several absorption features in sunlight, but with a prism that lacked the ability to resolve the lines.

Fraunhofer identified more than 570 lines, though not all are shown in the engraving in his monograph. One might mistake that engraving for a modern spectrum except that the abscissa lacks units, but merely bears the labels *Red, Orange, Gold, Green, Indigo, Purple*. In the original copy of the engraving preserved in the Deutsches Museum (shown on page 11) Fraunhofer omitted the labels and simply painted the colors he had seen. He gave the prominent lines across the spectrum alphabetical labels that remain in use today. The C line is the hydrogen Balmer α line, and the D lines (they form a doublet) are due to sodium. Armed with the absorption lines that provide a dense array of wavelength markers, and with his genius at measuring refractive indices, Fraunhofer could determine dispersion with unprecedented precision. In a class by himself, he was the world's master of dispersion.

The tables in Fraunhofer's 1814 monograph display not only his technical virtuosity but also his skill at protecting proprietary information. Although he published the refractive indices to six figures, he concealed the makeup of his glasses. To convince possible skeptics that his measurements were as precise as he claimed, without revealing the recipes for his glasses, he

presented data for the dispersion of water that anyone could check.

A wretched childhood

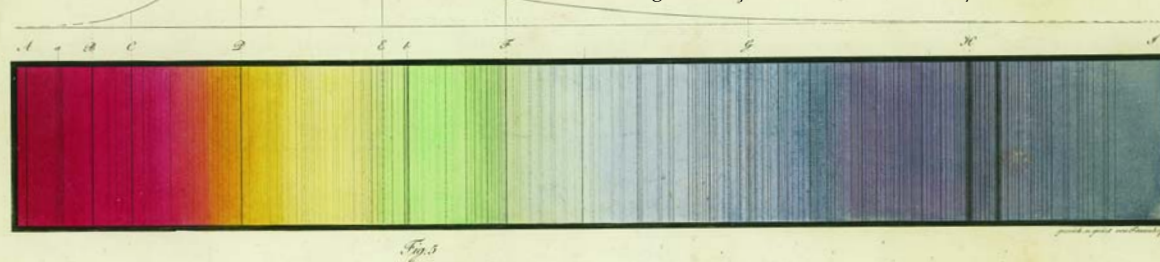
How Fraunhofer acquired his formidable skills is a story of rags to riches worthy of a plot by Charles Dickens. Born in 1787, Fraunhofer was orphaned at the age of eleven and apprenticed to a harsh glassmaker by the name of Philipp Anton Weichelsberger. One night in 1801, a providential event occurred—providential, at least, for Fraunhofer: Weichelsberger's house collapsed causing grave injury to Weichelsberger's wife but miraculously leaving Fraunhofer unscathed. Then came a second providential event: the Prince Elector, Maximilian Joseph IV, rushed to witness the miracle and was so impressed by the young man that he bestowed a handsome dole and assigned his privy counselor, one Joseph von Utzschneider, to look after the boy's welfare. Weichelsberger, however, evidently unmoved by these divine omens, continued to treat his apprentice harshly, forbidding him to attend a school for working-class boys and even denying him oil for night-time study. Fraunhofer finally rebelled and sought advice from Utzschneider, who had by then forsaken government service in favor of a management position in the optics industry. He advised Fraunhofer to use the Prince's dole to buy out his apprenticeship, learn a little math and optics—with tutoring to be provided—and then work for him at his Optical Institute. That was in 1806. At the age of 19, Fraunhofer set off on a career, starting with a cram course in applied optics.

Utzschneider provided Fraunhofer with books and tutors in physics, optics, and mathematics. After eight months of study, Fraunhofer left Munich to work at the Optical Institute at Benediktbeuren, a secularized Benedictine monastery devoted to glass-making. He discovered how to make the world's finest optical glass and invented methods for measuring dispersion with incredible precision. Within a few years, the world's best achromatic lens systems all came from Benediktbeuren.



DONNA COVENEY/MIT

Dark lines in the solar spectrum were discovered in 1814 by Fraunhofer, who immediately employed them as wavelength standards. He labeled the most prominent lines with letters that remain in use today. They are barely visible in the upper drawing. He observed more than 570 lines and displayed 288 in the engraving (lower drawing). Lacking knowledge of wavelengths, he painted in the colors. Small script in the lower right corner translates as "Made and engraved by Fraunhofer." (Courtesy of Deutsches Museum.)



In 1818, Fraunhofer was elevated to the directorship of the Optical Institute. The market for fine optical instruments was enormous because, in the early decades of the 19th century, Europe, for the first time, was being accurately surveyed. For triangulation, the better the lens systems, the longer the range and the easier the job. Also, then as now, the military had a great appetite for optics. The center of the optics industry, previously in England, moved to Bavaria, which helped to transform Bavaria from one of the most underdeveloped German states to one of the most prosperous. The loss of its optics industry was a serious blow to England, and the English made a number of unsuccessful attempts to regain it. Michael Faraday, among others, took up the challenge of producing glass that could rival Fraunhofer's, but he failed. Some years later the British government attempted to obtain the secrets by bribery, and that, too, failed.

Wonderment and delight

In studying the diffraction of sunlight through a narrow slit, Fraunhofer discovered that the slit was naturally dispersive: The diffraction pattern consisted of blurred colored fringes with the spread of colors increasing with each fringe. Apparently unaware of Thomas Young's ideas on interference that had been published in 1802, or Augustin Fresnel's mathematical analysis of single-slit interference published in 1819, Fraunhofer laboriously measured the angles for the intensity zeros of various light sources and empirically deduced the elementary law of diffraction for a single slit. Because narrow slits transmit little light, his experiments were plagued by faintness. Then he hit upon the happy idea of increasing the brightness by using many slits. For this he mounted parallel fine-thread screws on a frame and wrapped fine wire across them. To his wonderment and delight, Fraunhofer discov-

ered that the blurred fringes had been replaced by a series of bright, sharp, and highly resolved spectral lines.

In modern notation, Fraunhofer found that the angle of deviation θ for a spectral line of wavelength λ is given by $\sin \theta = n \lambda / d$, where d is the center-to-center distance between the wires and $n = 0, 1, 2 \dots$ is the order of diffraction. Because angle and distance can be measured with high accuracy, Fraunhofer had discovered how to determine the absolute wavelength of light. In his first attempt, he measured the wavelength of the D lines, estimating the uncertainty to be one part in a thousand. He was correct to within that uncertainty. Fraunhofer went on to construct an engine for ruling grooves in a grating, and even studied the effects of the shape of the grooves and groove imperfections on the quality of the spectra.

Fraunhofer had a number of scientific advances to his credit in addition to discovering the solar absorption spectrum and inventing the diffraction grating. He transformed spectroscopy from a qualitative art into a quantitative science by showing how to measure the wavelength of light accurately. He studied the spectrum of starlight, observing that the spectra of Sirius and a number of other first-magnitude stars differed from each other and from the Sun; thus Fraunhofer founded the field of stellar spectroscopy. He studied the spectra of flames and electrical discharges and discovered that flames display a bright doublet at the same position as the solar D lines.

However, all of Fraunhofer's discoveries were reported with little or no comment: His true passion was not for science but for making the world's best optics. He let nothing divert him for long. For example, when he discovered the mysterious dark lines in the solar spectrum, he did not stop to dwell on their origin, but noted, "In all

my experiments I could, owing to lack of time, pay attention to only those matters which appeared to have a bearing upon practical optics."

Fraunhofer's meteoric career culminated in his becoming director of the Optical Institute and earning numerous honors, including knighthood and membership in the Royal Academy of Sciences, Munich. Throughout his career, however, Fraunhofer never lost his love for glass-making, often tending the furnaces himself. In the 18th and 19th centuries, glassmakers usually died young due to poisoning from heavy-metal vapors. Fraunhofer died in 1826 at the age of 37 years. He, his father, and grandfather were all glassmakers and they all died young.

Unfortunately for Bavaria, Fraunhofer also never lost his passion for protecting proprietary information, and his most precious recipes for glass are said to have gone to the grave with him. But perhaps he actually wrote them in secret notebooks that have been lying hidden for nearly two centuries. Benediktbeuren remains a charming spot, and one can think of worse pastimes than combing its ancient grounds while fantasizing about amazing notebooks that wait to be unearthed by the deft touch of an ace historian of science.

I thank Myles W. Jackson and Herbert Walther for helpful comments.

Further reading

► A fascinating account of Fraunhofer's accomplishments and his role in the artisanal tradition in 19th-century Germany is presented in M. W. Jackson, *Spectrum of Belief: Joseph von Fraunhofer and the Craft of Precision Optics*, MIT Press, Cambridge, MA (2000).

► Fraunhofer's paper on the diffraction grating is reprinted in J. S. Ames, *Prismatic and Diffraction Spectra: Joseph von Fraunhofer, and William Hyde Wollaston*, Harper and Bros., New York (1898). ■