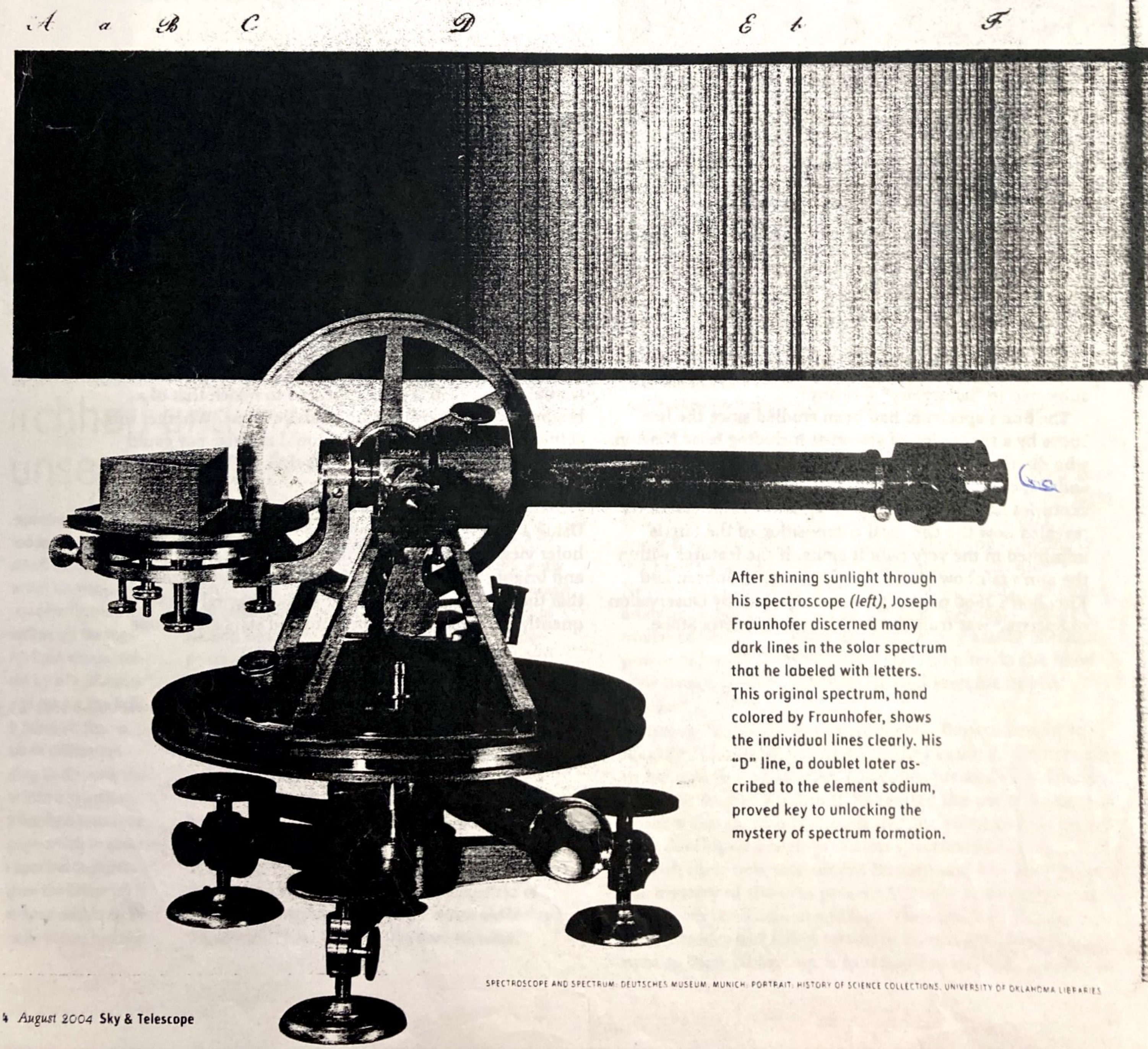
Starlight Detectives

The Birth of Celestial Spectroscopy

By Alan W. Hirshfeld



After shining sunlight through his spectroscope *(left)*, Joseph Fraunhofer discerned many dark lines in the solar spectrum that he labeled with letters. This original spectrum, hand colored by Fraunhofer, shows the individual lines clearly. His "D" line, a doublet later ascribed to the element sodium, proved key to unlocking the mystery of spectrum formation.

SPECTROSCOPE AND SPECTRUM: DEUTSCHES MUSEUM, MUNICH; PORTRAIT: HISTORY OF SCIENCE COLLECTIONS, UNIVERSITY OF OKLAHOMA LIBRARIES

By analyzing starlight, astronomers opened the door to a new field of inquiry: astrophysics.

Joseph Fraunhofer (1787–1826), raised in poverty and with little formal education, became an accomplished instrument maker and an astronomical pioneer. His analyses of solar and celestial spectra were unprecedented for his time. and made him a hit with the ladies.

AS THE INDUSTRIAL AGE kicked into full swing, so too did the infant field of astrophotography. Astronomers around the globe quickly realized the power and scientific benefit one could achieve by using photographic plates and telescopes together, and by the mid-1800s they were gathering exposures of the Moon, Sun, and stars (April issue, page 36). While pictures allowed an unprecedented analysis of astronomical objects, they told only part of the story. The chemical and physical properties of the stars remained an enigma. Could the distant stars and nebulae — once characterized by French philosopher August Comte as too remote to ever yield up their chemical secrets — be subjected to "laboratory" scrutiny?

The Sun's spectrum had been studied since the late 1600s by a succession of scientists including Isaac Newton, who directed a narrow sunbeam into a darkened room and dispersed it with a glass prism. But it wasn't until two centuries later that Robert Bunsen and Gustav Kirchhoff revealed how the chemical composition of the Sun is imprinted in the very light it emits. If the features within the Sun's rainbow were hieroglyphs, then Bunsen and Kirchhoff's 1860 paper, "Chemical Analysis by Observation of Spectra," was truly the astronomer's Rosetta Stone.

Spectral ABCs

The first major breakthrough in celestial spectroscopy came in 1802 when English chemist William Hyde Wollaston observed several dark lines cutting across the Sun's otherwise continuous spectrum; Wollaston mistakenly supposed that the lines were natural divisions between the colors. A decade later, in an effort to test lenses he had made, master optician Joseph Fraunhofer magnified the Sun's spectrum with a small telescope and tallied 574 dark lines. He labeled the most prominent of these A, and then B, C, D, and so on — designations still in use today. Fraunhofer noted that the position of the D line (actually a very close pair) appeared to match that of a bright yellow line emitted by a candle flame. Whether this coincidence was significant he could not say, nor could he explain why the solar line was dark and its laboratory counterpart bright.

Fraunhofer later focused his attention beyond the Sun. Using a 4-inch refractor equipped with a prism, Fraunhofer viewed the spectra of the Moon and several planets and bright stars, including Sirius and Castor. He found that the relative prominence of stellar spectral lines frequently differed between the Sun and stars and among the stars themselves. At this point Fraunhofer returned to his regular activity — telescope making — and the new field of celestial spectroscopy slumbered for 40 years.

After Fraunhofer, chemists throughout Europe studied the spectra of light emitted by various flames and electric arcs. Experimental data accumulated, and spectroscopic theories abounded. There were even hints that each chemical element or compound might possess its own unique spectral pattern, and that spectroscopic examination of matter — even the identification of new elements — might be feasible. The "ringer" in these lofty aspirations was Fraunhofer's troublesome D line, which confounded explanation; like an uninvited guest, the yellow line showed up in the spectrum of virtually every substance. Why would elemental spectra, if presumed to be unique, all share a common line? The answer eventually came from two German scientists.

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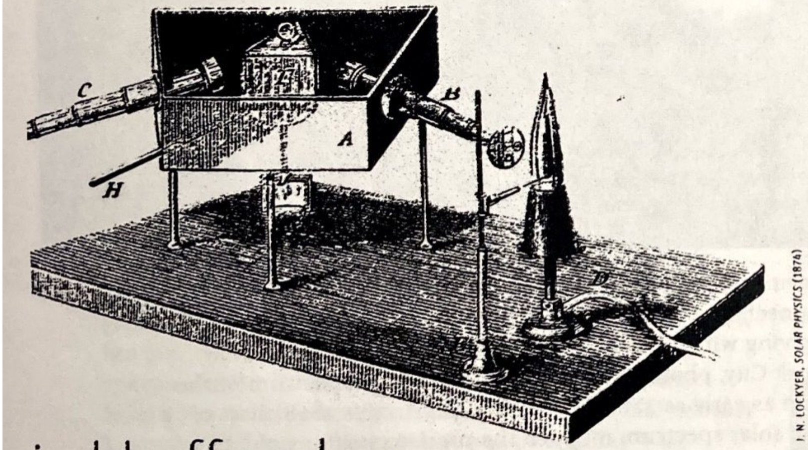
Two spectroscopic pioneers, **Robert Bunsen (1811–99)**, right, and **Gustav Kirchhoff (1824–1887)**, developed the most sensitive spectrometer of their time and used it to revolutionize the field of spectroscopy. They confirmed that Fraunhofer's D line was due to sodium, discovered the elements cesium and rubidium, and were the first to explain the mechanism that gives rise to emission and absorption spectra.



J. N. LOCKYER, SOLAR PHYSICS (1874)

irchhoff and unsen's Spectroscope

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(A). A sample is held in place (E) and combusted in a Bunsen burner or similar flame (D). The light passes through the slit and lens (B) to a prism, which can be moved by the handle (H). The resultant spectrum is observed with the telescope (C).

It is important to realize that each spectral line is an image of the linear slit through which light enters the spectroscope. If the slit were shaped like a squiggle, the spectral "lines" would likewise appear as squiggles. In fact, if the slit were sufficiently widened, the lines would morph into an array of singly colored renderings of the celestial body being studied. The reason Isaac Newton never saw the dark lines in the Sun's spectrum is that he used a hole instead of a slit to direct sunlight to his prism; as a result, the projected spectrum consisted of overlapping disks of color, which obliterated the dark features.

Spectroscopic Pioneers

Robert W. Bunsen was fearless in the laboratory, even after a chemical explosion in 1843 cost him the sight in his right eye. He routinely investigated toxic substances such as arsenic, whose smell "produces instantaneous tingling of the hands and feet, even giddiness and insensibility." Nevertheless, Bunsen rose to become Germany's foremost analytic chemist. His eccentricity was legendary. Bunsen, observed one of his students, "had a very salamanderlike power of handling hot glass tubes, and often at the blowpipe have I smelt burnt Bunsen, and seen his fingers smoke!"

Among his numerous experiments, Bunsen sought to identify substances by the color they emitted when set afire in his eponymous burner. His colleague and close friend, physicist Gustav Kirchhoff, suggested the use of a prism to observe the spectrum of each flaming substance. Together they developed a high-precision spectroscope.

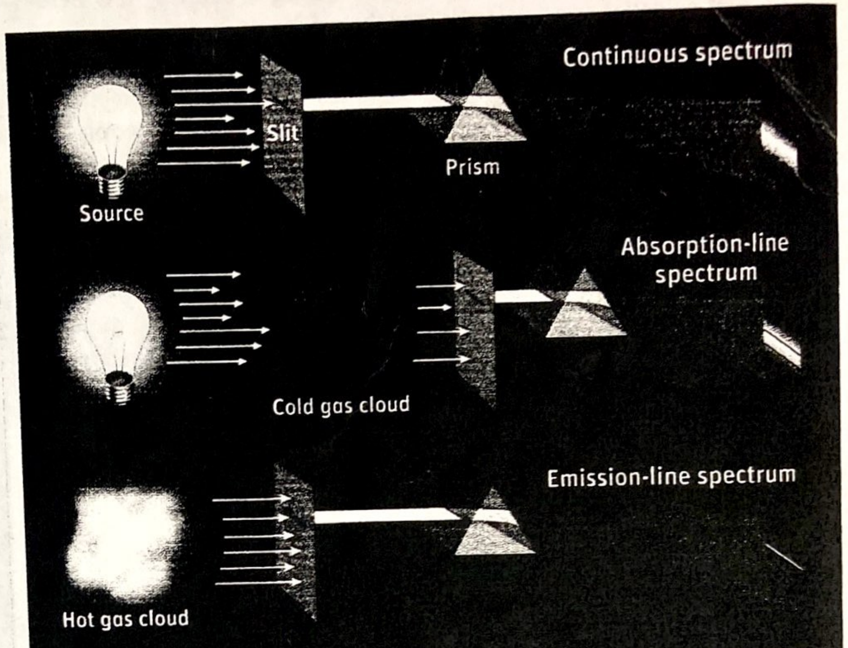
With their new instrument Bunsen and Kirchhoff solved the mystery of the ever-present D line — known today to arise from the element sodium. They realized that their predecessors had fallen victim to an unanticipated contaminant in their laboratories: salt! Sodium chloride, or salt, is ubiquitous on Earth's surface and, if due care isn't taken, infiltrates chemical samples. As 19th-century historian Agnes M. Clerke described it, "[Salt] floats in the air; it flows with water; every grain of dust has its attendant particle; its absolute exclusion approaches the impossible."

The resolution of the D-line issue revealed not only Bunsen's superior laboratory technique but also the incredible sensitivity – and scientific potential – of spectroscopic analysis. As if to underscore the latter, Bunsen and Kirchhoff used their prowess in the laboratory to discover a pair of new elements, cesium and rubidium, by spectral observations alone.

Next, the two Heidelberg scientists confirmed that the various bright-line sequences seen in laboratory spectra coincide precisely with the corresponding dark-line sequences in the spectrum of sunlight. Thus, Fraunhofer's dark D line reveals the presence of sodium in the Sun, while the rest of the Fraunhofer lines indicate the presence of different chemical elements, including the Sun's major constituent, hydrogen.

Their groundbreaking experiments also suggested a physical basis for the different types of spectra: the spectral lines of a tenuous gas might appear either in emission, like that seen in the laboratory, or as dark absorption bands if viewed against an incandescent background, like those in the spectrum of the Sun.

The ramifications of Kirchhoff and Bunsen's work were profound and numerous. At one point the two scientists pointed their spectroscope out the window and analyzed the chemical constituents of a raging fire 10 miles away. If they could identify the composition of an earthly fire, mused Bunsen, might astronomers not someday do the same for the stars?



Spectra come in three flavors: continuous, absorption, and emission. A white-light source emits across all visible wavelengths; the result is the classic rainbow of light, a continuous spectrum. Absorption occurs when an absorbing medium, such as a cool gas, veils incoming light and removes energy at specific wavelengths. As a result, gaps appear in the spectrum. Emission lines arise from a hot, tenuous gas.

Solar Spectroscopy and Beyond

Bunsen's vision was fast realized. Lewis M. Rutherfurd, observing with an $11^{1}/_{4}$-inch refractor from downtown New York City, photographed a high-dispersion spectrum of the Sun as early as 1864. Andreas J. Ångström's 1868 chart of the solar spectrum mapped the precise positions of 1,200 absorption lines, many of which could be attributed to common elements. Late in the century some 50 elements had been identified in the Sun, including one — helium — that had not yet been detected on Earth.

After learning of Bunsen and Kirchhoff's work in 1862, self-taught amateur astronomer William Huggins, at Upper Tulse Hill outside London, set his sights — and a spectroscope — on the wider universe. He stocked his personal observatory with the trappings of the Victorian spectroscopist — prisms, batteries, electrical spark coils, Bunsen burners, chemical powders — until it resembled Frankenstein's laboratory. Beginning with an Alvan Clark 8-inch refractor, Huggins observed the spectra of stars and nebulae visually, first with the assistance of his friend, chemist William A. Miller, and subsequently with his astronomically inclined wife, Margaret — a "capital scientific housemaid," in her own words. An 1863 attempt to photograph the spectral lines of Sirius and Capella failed; not until the mid-1870s, with a better clock drive and the introduction of faster dry-plate photography, did Huggins succeed.

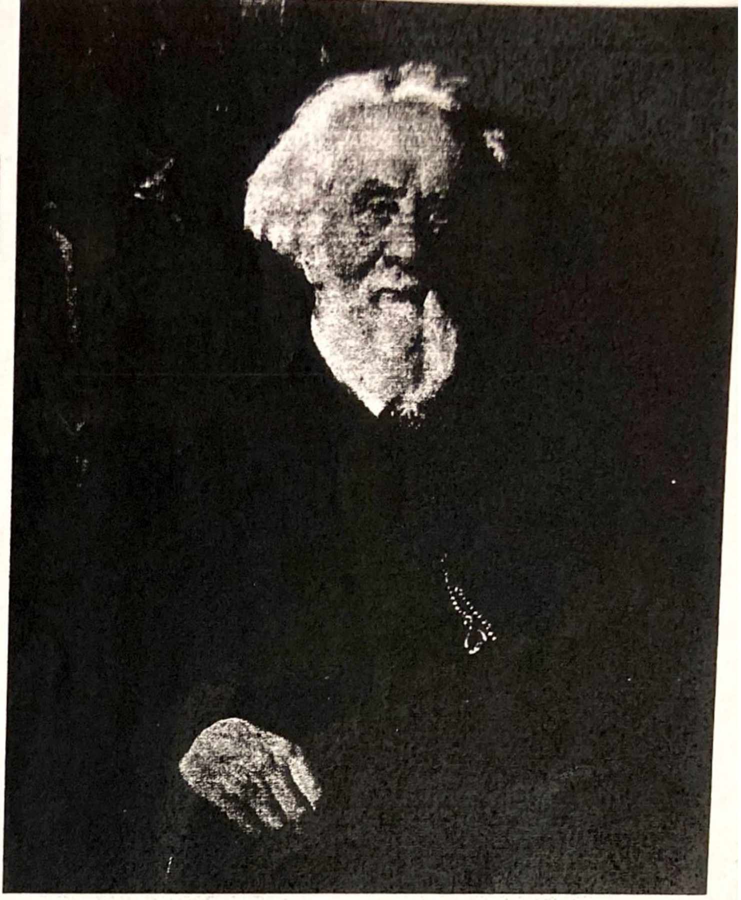
Huggins's observations confirmed those made by Fraunhofer a half century earlier: stars exhibit largely the same spectral-line patterns as the Sun, though their relative prominence often differs. Such variation among stellar spectra would go unexplained until the 20th century, when the physics of stars was elucidated.

Still, astronomers now had evidence that the elemental makeup of the universe — and by extension, its physical laws — was uniform throughout. In 1864 Huggins also made a key discovery about the nature of the enigmatic nebulae: the spectra of some of them contain only emission lines. In other words, they resemble the signature of a hot gas. However, spiral "nebulae" display continuous spectra like the Sun's, as though their feeble light arises from a myriad of unresolved stars. Might the spiral nebulae be distant "island universes" like our own Milky Way, whose stars are rendered indistinct by distance? This question too would not be answered until the 20th century, when larger telescopes, improved photography, and an astronomer named Edwin Hubble came on the scene.

Sorting Spectra

While Huggins launched his pioneering investigations in England, Henry Draper was grinding telescope mirrors along the banks of the Hudson River, 20 miles north of New York City. Although he was a physician by training, astronomy ran in Henry Draper's blood; his father, John W. Draper (April issue, page 38), took the first photograph of the Moon when Henry was three and recorded the Sun's spectrum a few years later. Inspired by the sight of Lord Rosse's 6-foot speculum-metal reflector in Ireland, Henry constructed his own 15-inch and later 28-inch silvered-glass reflectors. In 1872 he used the larger instrument to photograph, albeit crudely, Vega's spectrum, the first of a star other than the Sun. With his adoption of faster dry-plate photography in 1879 (at the suggestion of Huggins), Draper began the wholesale recording of celestial spectra.

Within three years he had obtained 80 exquisite spectra of stars, planets, a comet, and the Orion Nebula. Only his premature death at age 45 prevented him from embarking



William Huggins (1824–1910) was a leader in spectroscopy and was among the first to look at deep-sky objects with spectroscopes. In doing so he observed that some nebulae display the characteristics of hot, tenuous gas, while others exhibit faint continuous spectra — research that later paved the way for the recognition of spiral "nebulae" as galaxies. Before **Margaret Lindsay Huggins (1848–1915)** met her husband, she was already an accomplished instrument builder, astronomer, and spectroscopist. Together they published many joint papers. She was most noted for her observations of the Orion Nebula.

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on an extensive project to classify stellar spectra — a field pioneered by Jesuit astronomer Angelo Secchi in the 1860s in Rome. Draper's widow, Anna Mary Palmer, endowed the Harvard College Observatory with funds to continue the classification work. Key to the success of this time- and labor-intensive project was the development of an objective prism, which fits over a telescope's main lens and creates a spectrum of every star in the field of view. When finally completed in the 1920s, the resultant *Henry Draper Catalogue* contained spectral classes of more than 200,000 stars.

Shifted Focus

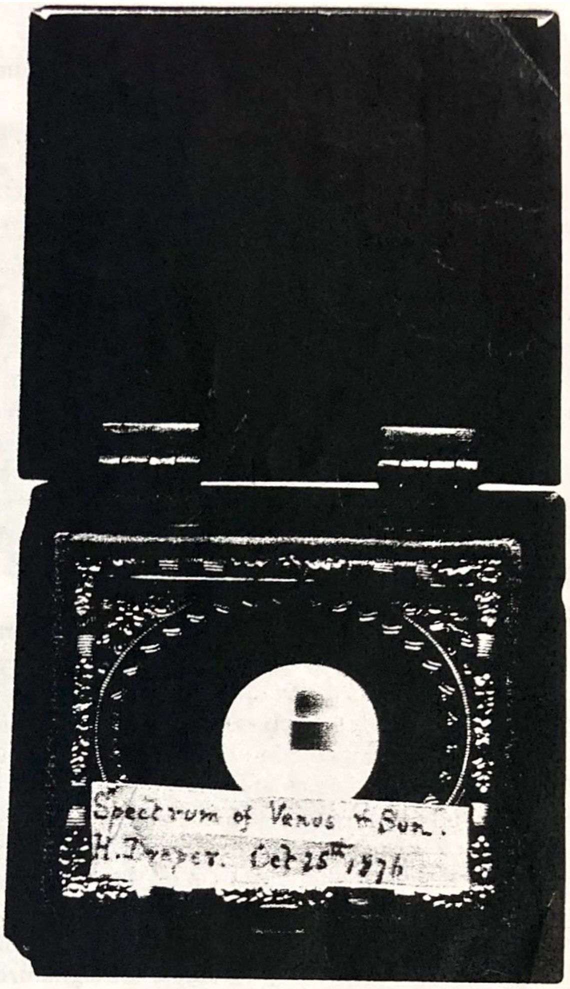
Even before Huggins and Draper began to investigate celestial spectra, astronomers had realized that spectral lines might provide a measure of a star's line-of-sight movement through space. In the 1840s Austrian mathematician Christian Doppler and French physicist Armand Fizeau independently laid the foundation for what became known as the Doppler effect. A sound wave alters its pitch when the source of sound approaches or recedes from the listener; similarly, a light wave alters its frequency when the source of light approaches or recedes from the viewer. In the case of a star hurtling through space, the star's spectral lines appear shifted slightly from their normal places: redward, if the star is receding from the Earth, and blueward, if approaching. With a sufficiently precise spectroscope, such a shift is measurable, and the star's line-of-sight, or radial, velocity can be computed.

William Huggins detected spectral-line shifts visually in several bright stars as early as 1868, though his estimated radial velocities were far off the mark. Two decades later, German astronomer Hermann C. Vogel obtained definitive stellar-velocity measurements using photographed spectra. By the 1890s William Wallace Campbell and his colleagues at Lick Observatory in California published the radial velocities of thousands of stars. Their conclusion: stars in the Milky Way — our Sun included — are streaking through space at hundreds of thousands of miles an hour.

The Doppler effect also proved key to the discovery of unresolved, or spectroscopic, binary stars. English inventor William Henry Fox Talbot predicted in 1871 that the orbital motion of a binary star — even one whose components are too close together to be seen individually — might reveal itself in the periodic oscillation of its spectral lines. In 1887 Harvard astronomer Edward C. Pickering found that the spectral lines of the brightest member of the double star Mizar in Ursa Major sometimes appear double. Further study by Pickering's colleague, Antonia C. Maury, revealed that the lines shift in precise rhythm, subsequently pegged at every 20.5 days, first toward the blue end of the visible spectrum and then toward the red. Later, the fainter member of the Mizar double was also found to be a spectroscopic binary, as were well-known stars like Polaris, Spica, Capella, and Algol. Along with stellar radial velocities, the computation of binary-star orbits was an area where the interests of classical astronomers overlapped those of their astrophysically inclined counterparts.

As the 19th century drew to a close, celestial spectroscopy had been utilized to extraordinary effect within both the solar system and the extrasolar realm of the Milky Way. A wealth of spectroscopic data had accumulated, with more being added every day. A new publication, *The Astrophysical Journal*, came into existence in 1895 to deal with the deluge. Yet the impact of these spectroscopic observations on the fledgling science of astrophysics was mitigated by the shaky theoretical basis on which the field rested. Astronomers had gotten ahead of themselves. In truth, the "astro" part of astrophysics had outrun the "physics" part.

One major hindrance was the lack of proper instrumentation — specifically, large telescopes. It was the observational imperatives of the budding astrophysicists that drove the creation of gargantuan reflectors. These larger-than-life light buckets would channel more photons into cameras and spectrographs than ever before and would ultimately yield the greatest triumph yet of celestial spectroscopy: the discovery of the expanding universe. ∗



HARVARD COLLEGE OBSERVATORY

Henry Draper was among the first to photograph the spectra of Venus and the Sun, in 1876. Draper recorded the spectra of 80 diverse celestial objects before his untimely death; subsequent work funded by his widow resulted in the 200,000-star catalog that carries his name.

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