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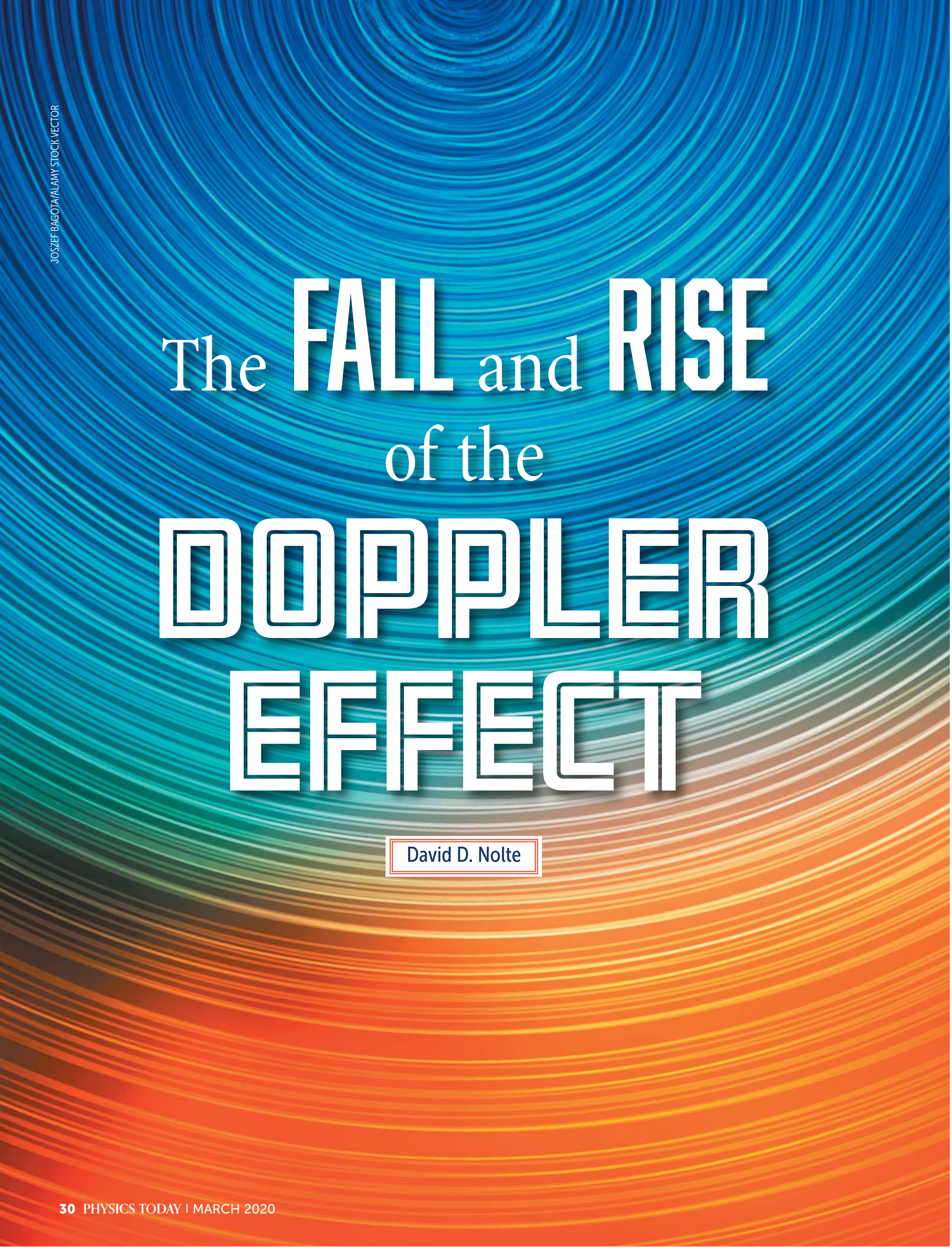

JOSZEF BAGOTA/ALAMY STOCK VECTOR

The FALL and RISE of the DOPPLER EFFECT

David D. Nolte

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The phenomenon is so pervasive that we stake our lives on it, but Doppler's idea faced fierce criticism that took half a century to overcome.

Of all the eponymous discoveries that emerged from 19th-century physics—Young's fringes, the Biot–Savart law, the Fresnel lens, the Carnot cycle, the Faraday effect, Maxwell's equations, Michelson's interferometer, and many more—only one is heard daily on the evening news: the Doppler effect.[1] The effect, which describes the change in a wave's frequency heard by an observer moving relative to the wave source, is shown in figure 1. You experience the effect as you wait by the roadside for a train to pass by or a jet to fly overhead. Albert Einstein may have the most famous name in physics, but Christian Doppler's is probably the most commonly used. That's ironic because Doppler was hounded by a pompous nemesis, ridiculed for his effect, stripped of his university position, and forced to abandon Vienna in public disgrace and declining health. He finally retreated to Venice and died a few months later.

Despite Doppler's ignominious end, today his effect tells scientists of Earth's motion across the universe, allows physicists to cool atoms in laser traps to a fraction of a degree Kelvin, and is used to detect alien planets orbiting distant stars. With Doppler light scattering, scientists can see the flow of blood in arteries, and they are beginning to personalize chemotherapy by measuring tiny Doppler shifts from the motion of components inside living cells.[2] So why did his peers reject his idea, even years after his death, and how has it been rehabilitated so thoroughly that we now stake our lives on it? The answer begins with a troubled career that almost failed to launch.

Doppler's vision

Doppler was born in 1803 in Salzburg, Austria, to a long-standing family of stonemasons. By the age of 30, he was at the end of a temporary mathematics assistantship at the Imperial and Royal Polytechnic Institute (now TU Wien) in Vienna and could not find work except as a bookkeeper at a cotton factory. The Austrian empire in the early 19th century was a sprawling bureaucratic state with layers of regulations and armies of able applicants for any position. Doppler was lost in that environment despite his advanced education. His applications for permanent technical posts were denied, and he despaired of ever finding a suitable life, so he decided to emigrate to the US. He sold most of his possessions to pay for his journey and visited the US consulate in Munich to obtain the necessary paperwork. But on his return to Austria, on the eve of leaving Europe for an uncertain future, he received an offer for a teaching position in Prague, which he took in 1835.

He began to publish scholarly papers and in 1837 was appointed supplementary professor of higher mathematics and geometry at the Prague Polytechnical Institute (now Czech Technical University); in 1841 he was promoted to full professor of applied geometry. There he met Bernard Bolzano—a political agitator and a mathematician who developed rigorous concepts of mathematical limits. He is famous today for his part in the Bolzano–Weierstrass theorem in functional analysis. Bolzano presided as chairman over a meeting of the Royal Bohemian Society of Sciences on 25 May 1842, the day Doppler read a landmark paper on the color of stars to a meager assembly of only five regular members of the society.

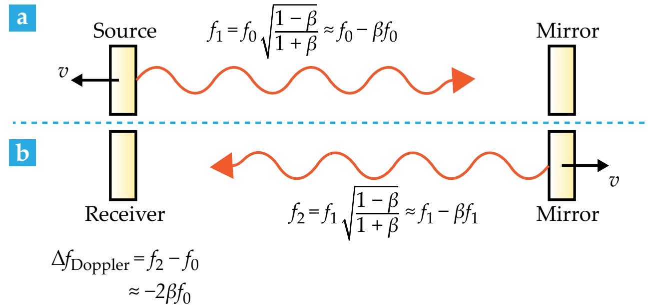


FIGURE 1. THE DOPPLER EFFECT in light backscattering is a relativistic effect that involves two different frames. The mirror in the first frame **(a)** sees a redshifted photon emitted from a receding source. The moving mirror in the second frame **(b)** re-emits the photon, which is redshifted again relative to the receiver, and produces twice the effect. The source frequency is f_0, the Doppler frequency shift on backscattering is $\Delta f_{\text{Doppler}}$, and the ratio of velocity v to the speed of light is β. (Image by David Nolte.)

Doppler had become fascinated by astronomy and by the phenomenon of stellar aberration. It was discovered by James Bradley in 1727 and could be explained by Earth's motion around the Sun combined with the finite speed of light, which causes the apparent position of a distant star to change slightly through a year. As Doppler studied Bradley's work, he wondered how Earth's relative motion would affect the color of the star. By making the simple analogy of a ship traveling with or against a series of ocean waves, he concluded that the frequency of the wave peaks hitting the ship's bow was no different from the peaks of light waves impinging on the eye. He concluded that the color of light would be shifted slightly to the blue if the eye was approaching towards, and to the red if it was receding from, the light source.

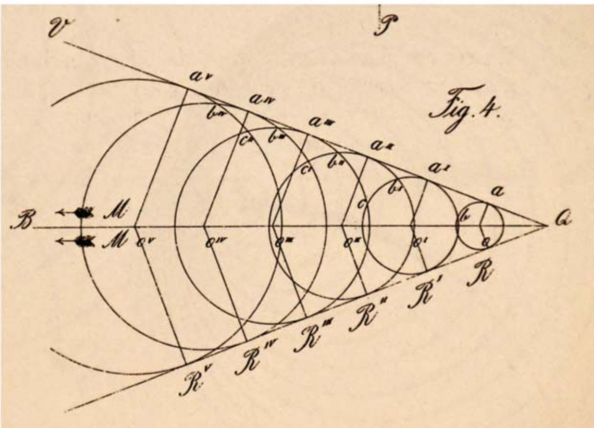
His interest in astronomy had made Doppler familiar with binary stars in which the relative motion of the light source might be large enough to cause color shifts. In fact, the star catalogs included examples of binaries that had complementary red and blue colors. Therefore, his paper, published in the *Proceedings of the Royal Bohemian Society of Sciences* a few months after he read it to the society, was titled "Über das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels" ("On the colored light of the double stars and certain other stars of the heavens").[3] Although Doppler was mistaken in his assumption that stellar motion would cause a change in the broad-spectrum color of a star, his derivation of frequency shifts was correct. Figure 2 shows Doppler's own drawings of his effect at high speeds.

Many who heard of Doppler's theory did not believe it. Subsequently, on a cold February morning in 1845, Dutch scientist Christoph Buys Ballot, who had recently received his doctorate from the University of Utrecht, loaded an open train car with seasoned musicians and sent them blowing their horns down the railroad line between Utrecht and Maarssen. Buys Ballot did not think that stars would change color by moving, but having no means to test the effect on light, he decided to test it on sound. Unfortunately, the musicians were pelted with hail and snow, which prevented them from blowing their horns properly, so the experiment was reconvened in the milder month of June. That time, with Buys Ballot riding the footplate of the locomotive and the car of trumpeters holding a steady note, musicians standing beside the tracks could hear the approaching note a half-tone higher and the receding note a half-tone lower. The experiment validated Doppler's theory for sound.[1] Buys Ballot published a paper describing the experiment,[4] but he still refused to acknowledge that light could change color despite the close analogy between sound and light.

Petzval's attack

Doppler's prolific scientific output, combined with influential supporters who valued the importance of his work, brought him to the attention of the emperor of Austria, Franz Joseph, newly crowned after his uncle was forced to abdicate during the revolutions of 1848. Reforming education was a top priority for some of the emperor's advisers, and they persuaded him to found Austria's first institute of physics and to name Doppler as its first director. Excited by the prospects and full of ideas, Doppler threw himself into his new position. As a member of the Austrian Academy of Sciences, he proposed a prize for the development of photography to advance scientific inquiry. Unfortunately, photographic lenses were the specialty of another member, Joseph Petzval. His supporters in the academy quashed Doppler's prize proposal, possibly at Petzval's instigation.[1] More trouble from Petzval awaited Doppler and his effect.

At a meeting of the academy on 22 January 1852, Petzval read a paper criticizing Doppler's theory. At a later meeting on 21 May 1852, about 60 members and guests assembled to hear both sides of the argument. The large audience for the mock trial of the Doppler effect stands in ironic contrast to the mere five members of the Bohemian Society who first heard Doppler's ideas 10 years earlier. Petzval's speech, which was published later, attacked Doppler's theory for both sound and light. Petzval thought that no great science could come from a few simple lines of algebra: In his view, all natural phenomena were the manifestations of underlying differential equations. From that premise, he proposed a principle for the conservation of oscillation time in undulatory phenomena. Although he was a mathematician of some talent, he was adrift as a natural philosopher. Petzval conflated a source and receiver in relative motion with a stationary source and receiver embedded in a moving medium. He argued that the pure notes of a well-tuned orchestra would be just as harmonious to an audience on a blustery day as on a calm one; the notes would be unaffected



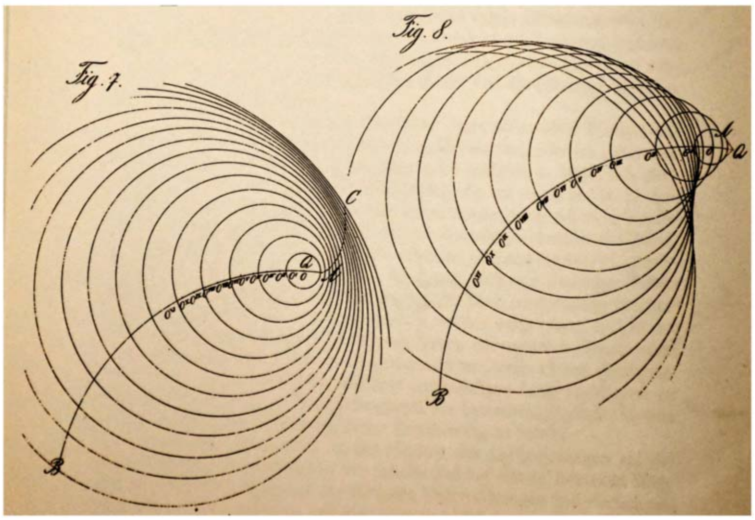


FIGURE 2. THESE DRAWINGS, from Doppler's 1847 paper,[17] illustrate his effect at high speeds and anticipate the Mach cone, which was predicted and photographed by Ernst Mach 40 years later. They also show shock-wave focusing for sources with angular velocity. (Harvard University Biodiversity Heritage Library, public domain.)

by the wind's motion. Ernst Mach later said that Doppler would agree but quipped that if the orchestra were falling from a great height, the audience would hear the piece in F major rather than E major.[5]

Doppler was nonplussed by Petzval's attack. His principle already had been verified for acoustic waves by Buys Ballot and by John Scott Russell, a UK railroad and naval engineer who later discovered solitons propagating in a canal. Furthermore, Hippolyte Fizeau in France had proposed the same theory for light in 1848. Unaware of Doppler's work, he had made the insightful prediction that the effect would be observable in shifts of narrow emission lines from stars in motion rather than from their overall change in color. Fizeau presented his results in a lecture to the Philomatic Society of Paris on 29 December 1848. Hence, the effect is sometimes called the Doppler–Fizeau effect.

Doppler defended himself against Petzval's onslaught simply by asking his opponent whether an observed phenomenon must be deemed nonexistent if it cannot be derived from differential equations. As reasonable as that argument is, a majority of the academy sided with Petzval, and only a few others, including Andreas von Ettingshausen, put up a defense for Doppler.

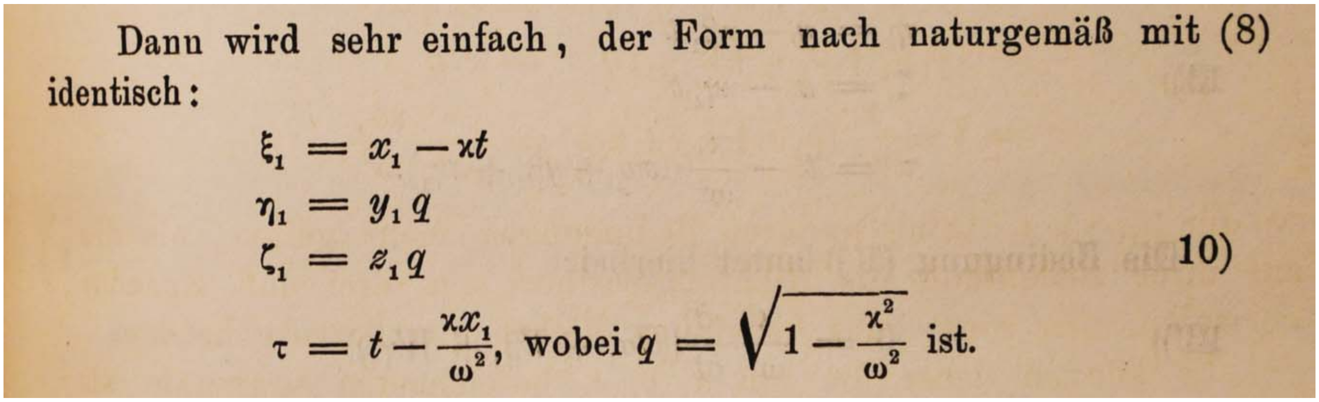
The academy's final decision was scheduled to take place during a meeting on 21 October 1852; once again Petzval was allowed to make his case. Doppler was unable to attend: The stress and disappointment of the Petzval affair had taken its toll on his health, which collapsed after years of battling tuberculosis. When academy members learned that he was making arrangements for a trip to Venice to improve his health, some mistakenly viewed it as a retreat from the fray and a concession of defeat. Members found in favor of Petzval and pronounced that Doppler's theory must be "abandoned, since it is false, as has been demonstrated."[1] Ten days later Doppler was officially stripped of his directorship of the Physics Institute of Vienna and replaced by Ettingshausen, but Doppler was already en route to Venice where he would die of his disease only four months later.

That might have been the end of the affair at the Physics Institute of Vienna, but Ettingshausen wasn't ready to abandon the Doppler effect just because a committee said it didn't exist. Several years later, he suggested to his student Ernst Mach that he construct a laboratory apparatus to directly demonstrate the acoustic Doppler effect. Mach built and tested a rotating-reed system with tubing that delivered air to the reed, causing it to vibrate at its natural frequency while directing its sound to a stationary observer. As the device spun, the reed approached and receded from the observer, who could hear the rapidly rising and falling tones.[6] Petzval continued denying the effect and accused Mach of youthful foolishness and of throwing away his chances at a career by pursuing an abandoned theory.[1] In response, Mach devised an even more ingenious apparatus, which allows one to listen in one direction to the rising and falling tones and in an orthogonal direction, in which the reed and observer are relatively stationary, to a constant pitch. That arrangement demonstrates even Petzval's preferred principle of frequency conservation. Despite such demonstrations, Petzval was never satisfied, and over the succeeding years Mach had to contend with persistent confusion and disbelief by many others until he finally refused to discuss the effect further.

Vogel's spectrum

Although experimental support for the acoustic Doppler effect accumulated steadily, corresponding demonstrations of the optical Doppler effect were slow to emerge. The breakthrough came in 1868 from William Huggins. He was an early pioneer in astronomical spectroscopy and was famous for discovering that some bright nebulae—planetary nebulae in our own galaxy—consist of atomic gases whereas others consist of unresolved emitting stars. Huggins corresponded with James Clerk Maxwell to confirm the soundness of Doppler's arguments, which Maxwell corroborated using his new electromagnetic theory. In May 1868 Huggins read a paper to the Royal Society of London reporting on observed shifts in the star's spectral lines.[7]

The importance of Huggins's report on the Doppler effect from Sirius was more psychologically important than scientifically accurate because it convinced the scientific community that the optical Doppler effect existed. Only one year later, Joseph Norman Lockyer, codiscoverer of helium, observed a


Dann wird sehr einfach, der Form nach naturgemäß mit (8) identisch:

$$\xi_1 = x_1 - \varkappa t$$
$$\eta_1 = y_1 q$$
$$\zeta_1 = z_1 q \qquad 10)$$
$$\tau = t - \frac{\varkappa x_1}{\omega^2}, \text{ wobei } q = \sqrt{1 - \frac{\varkappa^2}{\omega^2}} \text{ ist.}$$

FIGURE 3. THE TRANSFORMATIONS that keep the wave equation for light invariant were stated in 1887 by Woldemar Voigt.[12] His factor q is the inverse of the Lorentz factor $\gamma = 1/q$. Voigt's equations are identical to the Lorentz transformation if each equation is divided by q. (Image from ref. 12.)

shift in the spectral lines of solar prominences—the high-speed motion of luminous gases ejected from the Sun.[8] Lockyer didn't mention the associated Doppler effect, and because there was no method to confirm the speed of the prominences, his observations were not a definitive demonstration of the optical Doppler effect.

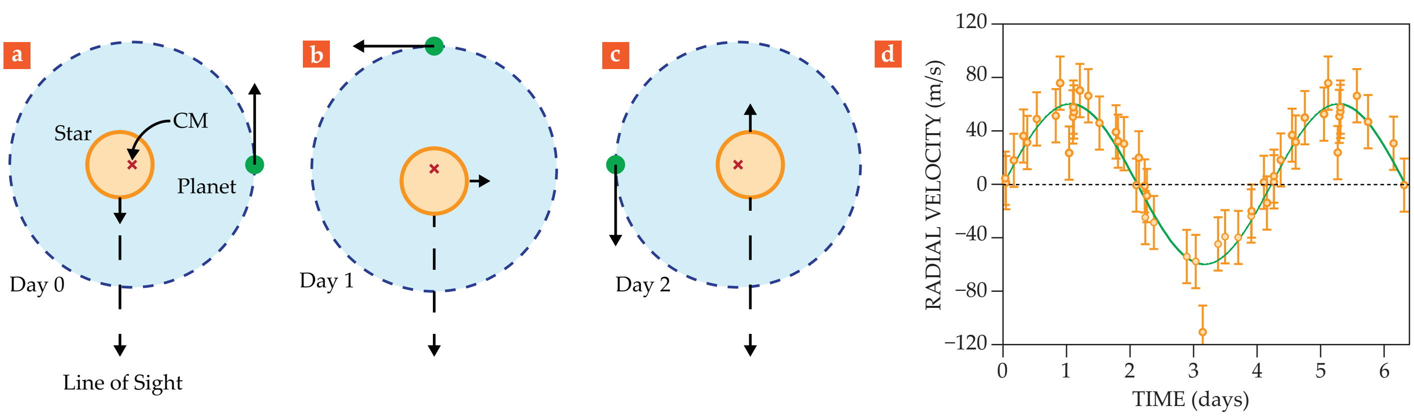
A German astronomer, Hermann Vogel, began working with a new spectrograph that optically projected the spectrum from one side of the Sun next to a reversed spectrum from a point on the opposite side. That doubled the visible effect of the Doppler shift on sharp spectral lines, and Vogel was able to calculate an equatorial rotation speed of the Sun that closely matched the value obtained from the motion of sunspots. Vogel's results were published in 1872 as the first conclusive demonstration of the optical Doppler effect.[9]

Vogel was also working to improve the measurements of the radial velocity of stars—the speed along the line of sight—and was acutely aware that the many values quoted by Huggins and others for stellar velocities were nearly the same as the uncertainties in the measurement process. Using the human eye to observe the spectral lines was the chief problem. Astronomers had begun using photographic plates on telescopes, and Vogel adapted that new technology to the radial velocities problem. He installed photographic capabilities in the telescope and spectrograph at the Potsdam Observatory in 1887 and made observations of Doppler line shifts in stars through 1890. Vogel published an initial progress report in 1891, and his definitive paper in 1892 provided the first accurate stellar radial velocities.[10] Fifty years after Doppler read his paper to the Royal Bohemian Society of Sciences, the Doppler effect had become an established workhorse of quantitative astrophysics. Aristarkh Belopolsky, a Russian astronomer, finally achieved a laboratory demonstration of the phenomenon in 1901 by constructing a device with a narrow-linewidth light source and rapidly rotating mirrors.[11]

Voigt's transformation

At the January 1887 meeting of the Royal Society of Science in Göttingen, Germany, Woldemar Voigt delivered a paper in which he derived the longitudinal optical Doppler effect in an incompressible medium. He was responding to results published in 1886 by Albert Michelson and Edward Morley on their measurements of the Fresnel drag coefficient using an improved version of the 1851 Fizeau experiment that propagated light through moving water. Voigt pointed out that the wave equation for light is invariant under his transformations, shown in figure 3. From a modern vantage point, physicists immediately recognize, to within a scale factor, the Lorentz trans-

FIGURE 4. THE ORBITAL MOTION of the star 51 Pegasi was detected by the Doppler wobbles of the star and its Jupiter-mass planet relative to the system's center of mass (CM) **(a–c)**. The velocity modulation is 60 m/s **(d)**. (Panels a–c by David Nolte; panel d is adapted from ref. 14.)



formation of relativity theory. Of particular note is the last equation,[12] which introduces a position-dependent time as an observer moves with speed κ relative to the speed of light ω. Therefore, Voigt derived the longitudinal Doppler effect by considering relativistic effects a few months prior to the epic Michelson and Morley experiment of 1887 on ether drift and two years before George Fitzgerald proposed length contraction.

Voigt's derivation takes a classic approach that is still used in today's textbooks to derive the Doppler effect. Twenty years later, Einstein completed the relativistic description of the Doppler effect by predicting the transverse Doppler effect for a source moving along a line perpendicular to an observer's line of sight.[13] That effect had not been predicted by either Doppler or Voigt.

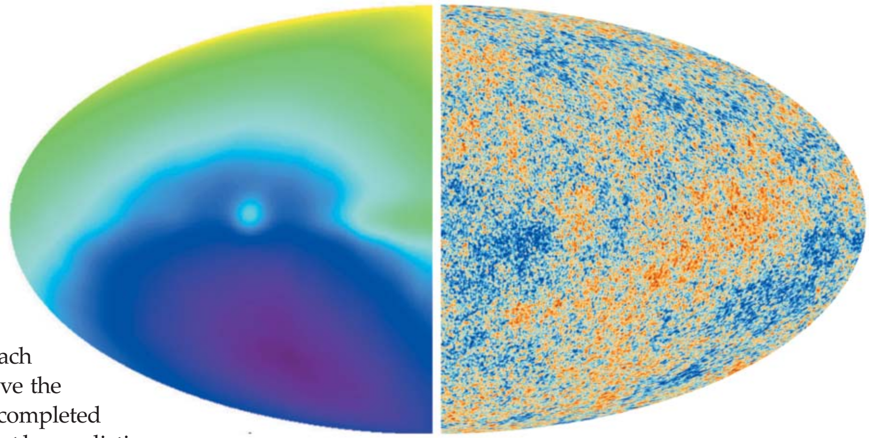


FIGURE 5. ANISOTROPY IN THE COSMIC MICROWAVE BACKGROUND. The Doppler dipole anisotropy (left) is caused by the motion of Earth. The small-angle anisotropy (right), after subtracting the dipole, is caused partly by Doppler scattering of photons in the early universe. (Images courtesy of NASA.)

Doppler spectroscopy

Almost two centuries have elapsed since Doppler published his simple idea using the analogy of a ship plowing through a series of ocean waves, and the idea now underlies our most sensitive forms of optical metrology of dynamical systems. Far beyond Doppler weather radar, the effect's applications extend from the ultrasmall, using Doppler cooling of atoms in the laboratory, to the ultralarge, using Doppler measurements of stellar wobble in the search for exoplanets. Until the launch of the *Kepler* satellite in 2008, most exoplanets had been discovered by detecting the Doppler shifts caused by small radial velocity variations as a star and an exoplanet orbit the system's center of mass. Using the Doppler wobble technique they reported in 1995, shown in figure 4, Michel Mayor and Didier Queloz discovered the first exoplanet, orbiting the star 51 Pegasi.[14] They received the 2019 Nobel Prize in Physics for their work (see PHYSICS TODAY, December 2019, page 17). Radial velocities as small as 3 m/s are resolved if measured over many years.

On a larger scale, the velocity curves of stars within galaxies, which provide some of the most compelling evidence for the existence of dark matter, are observed by Doppler spectroscopy. The relative velocities of the galaxies themselves, such as the streaming of the Virgo cluster of galaxies toward the Great Attractor, are also determined through the Doppler effect. At the largest scale, the Hubble effect is a cosmological redshift caused by the expansion of space rather than an actual Doppler effect. But the motion of Earth, 370 km/s relative to the local cosmic microwave background (CMB), is observed as the large-scale Doppler dipole anisotropy, as shown in figure 5. Doppler fluctuations caused by local motions in the early universe contributed to the small-scale CMB anisotropy that helps to determine the early uniformity of mass distributions and the fraction of dark matter in the universe.

In the life sciences, the acoustic Doppler effect is used in ultrasound imaging, first demonstrated in the 1960s for blood flow measurement,[15] and is now used routinely for Doppler imaging of internal motions, including the Doppler fetal monitor that detects a newborn's heartbeat in prenatal care. The optical Doppler effect is a major feature of dynamic light scattering to detect the directed motion of blood in optical tomography. The intracellular motions in living tissues produce Doppler signatures down to 10 mHz for speeds of several nanometers per second.[16] Subtle changes in intracellular speeds may eventually help doctors select the best treatments for cancer patients. Thus Doppler's eponymous effect has achieved a form of immortality he could never have imagined as he retreated from Vienna on his final journey to Italy, watching St. Stephen's steeple receding into the distance at a redshift of several MHz, though he could not perceive it.

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