What Light Through Yonder Window Breaks?

More Experiments in Atmospheric Physics

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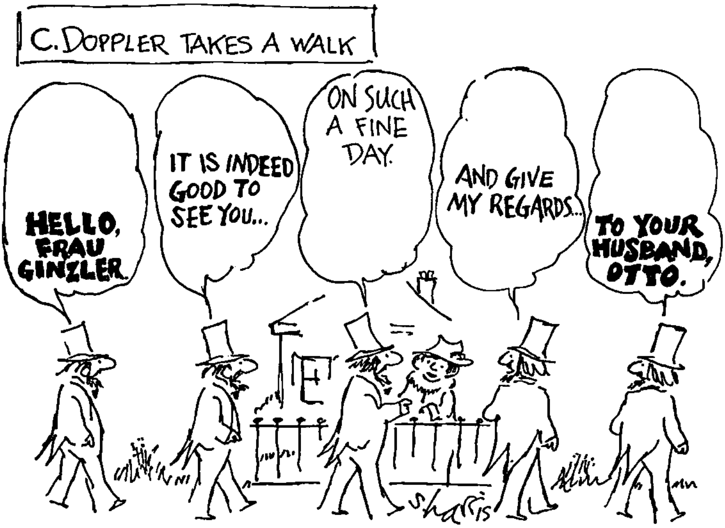
The Doppler Effect



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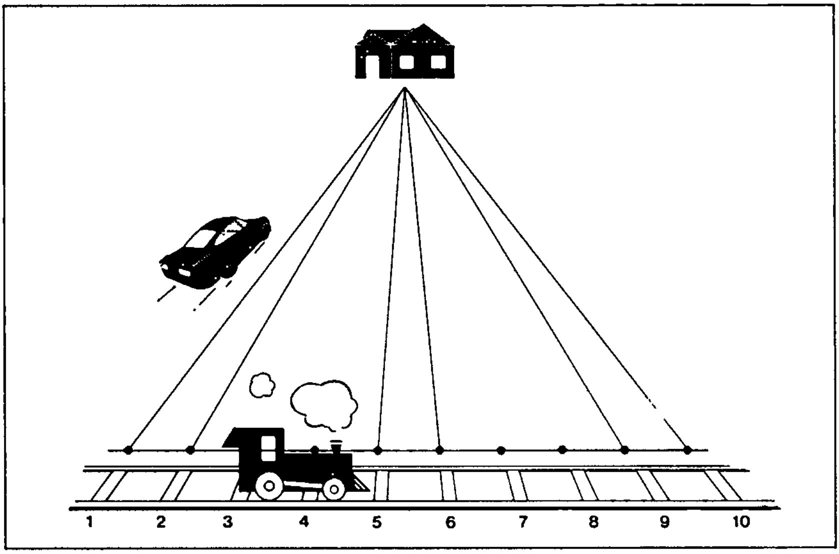
Doppler radar is all the rage in meteorology these days. I am told that it is even mentioned on television. Lest *Doppler radar* become yet another bit of unassimilated jargon that everyone can mouth but few understand, I offer the following.

A Train of Thought

T. P. Gill's book *The Doppler Effect* is too advanced to be recommended for the general reader, but its introduction contains insights I have found enlightening. In particular, Gill's definition of the Doppler effect is succinct and clear: "By the Doppler effect is meant the change in the apparent time interval between two events which arises from the motion of an observer together with the finite velocity of transmission of information about the events." He then goes on to suggest an example: "One might think of a Doppler effect arising when letters are posted from successive railway stations on a long train journey." This hint inspired me to develop the following arguments.

Consider a train moving at constant speed on a stretch of straight track alongside of which stations are regularly spaced. At each station, a car is waiting with its engine running. As the train passes a station, someone on board throws a letter to the car's driver, who immediately heads for a distant house to deliver the letter (see Figure 14.1). The time interval between posting letters is constant; it is the distance between stations divided by the train's speed. But what about the interval between the times they are received? Your immediate response might be that these two intervals are equal. You would be correct if the car's speed were infinite, in which instance it would travel a finite distance in zero time. But because of its finite speed, the two time intervals are unequal. An observer on the train drops letters off at a certain frequency, one every fifteen minutes, say, whereas an observer

Figure 14.1
A train moving at constant speed has an observer on board who tosses letters to the drivers of cars waiting at each station. These cars are driven to a distant house where the letters are delivered. Although the frequency of posting letters is constant, that of delivering them is not: it is greater when the train is moving toward the house, less when it is moving away.



at the house receives them at a different frequency in general. Which frequency is greatest depends on whether the train is moving away from or toward the house. It is easiest to explain why by examining special cases.

Consider first the letters posted at stations 1 and 2 (Figure 14.1). Suppose that the first car arrives at the house just as the train passes the second station. That is, the time it takes the train to go between stations is the time it takes the first car to travel to the house. At the instant the first letter arrives, the second car begins its journey. But this journey is shorter than the first. Hence if the two cars have the same speed, the time between the two deliveries is less than that between the two postings, and the letters are received at a greater frequency than they are sent. Between stations 1 and 2 the train was moving toward the house. What if the train is moving away from it, between stations 9 and 10, for example? Again, assume that the speeds of train and car are such that the ninth car arrives at its destination just as the train passes the tenth station. The journey from this station is longer than that from the ninth. Hence if the two cars have the same speed, the time between the two deliveries is greater than that between the two postings, and the letters are received at a lesser frequency than they are sent. These results imply that when the train is neither moving away from nor toward the house, the frequencies of posting and receiving are the same. That this is so is evident from Figure 14.1, which shows equal distances from stations 5 and 6 to the house.

To make my point as simply as possible, I chose special cases. But my conclusions are valid in general. They can be stated succinctly thus: Signals (letters) transmitted (posted) at a given frequency are received at a different frequency depending on the relative motion of transmitter and receiver. If the transmitter is moving toward the receiver, the frequency of reception is greater than that of transmission; if the transmitter is moving away from the receiver, the frequency of reception is less than that of transmission. The degree to which these two frequencies are different depends on the speed with which the signals are transmitted (the speed of the car for the example chosen). The higher this speed, the closer these frequencies are to each other (in the limit of infinite speed of transmission, they are identical). But notions of what is large (or small) are not absolute. Large (or small) relative to what? It is *ratios* of speeds that determine frequency differences. Such a ratio is the speed at which transmitter and receiver approach or recede divided by the speed of signal transmission; the smaller this ratio, the closer the frequencies of transmission and reception.

If the track were a circle with its center at the house, there would be no difference between the frequencies of transmission and reception of letters regardless of the ratio of the train's speed to that of the car's. In this instance the train is neither moving toward nor away from the house. Stated another way, there is no motion along the line joining transmitter and receiver.

A Smattering of History

Christian Doppler, an Austrian, was the first (1843) to explain the effect that carries his name. He was also the first to misapply it. Doppler recognized that the frequency of a source of sound or light moving relative to an observer must increase or decrease according to whether it is approaching or receding. And he also gave a quantitative relation between the transmitted and received frequencies as a function of the signal velocity and relative velocity of source and observer. He first applied his relation to sound, showing that to raise the pitch of a pure note from C to D requires the source to be moving toward the observer at about 40 meters per second (90 miles per hour). But this was only illustrative. The primary purpose of his paper in the *Proceedings of the Royal Bohemian Society of Learning* is evident from its title: "On the Colored Light of the Double Stars."

Suppose that a star emits a continuous spectrum of light, visible and invisible. If the star is moving away from us, its spectrum will be shifted toward lower frequencies (i.e., toward the red); if it is moving toward us, its spectrum will be shifted toward higher frequencies (i.e., toward the blue). Doppler mistakenly believed that the spectrum of light emitted by stars ends abruptly at the violet and red ends of the spectrum (he seems to have been unaware of light beyond the visible, either ultraviolet or infrared); thus he concluded that a star would become invisible if it were moving at a sufficiently high speed. He did not realize that ultraviolet radiation emitted by a receding star, say, would be shifted into the visible part of the spectrum to take the place, at least partly, of the visible light that had been shifted into the infrared.

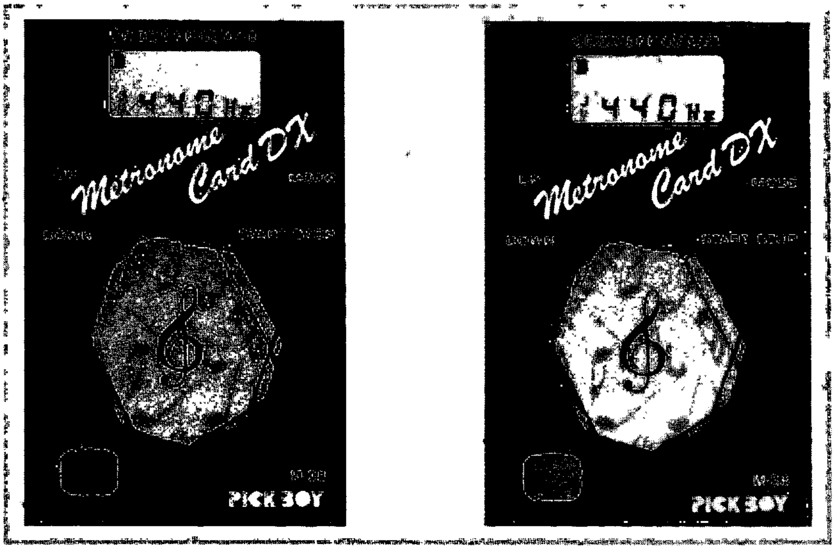
Doppler explained incorrectly the colors of stars by invoking an effect he enunciated correctly. He could not have known that the extremely high velocities (appreciable fractions of the speed of light) stars must have for their color to be markedly affected by their motion are rare. Indeed, it is by making use of his effect that the relative velocities of stars are determined, but not in the way he envisioned. My admiration for him is not diminished a whit by his failures, which are eclipsed by his successful exposition of a simple but universal property of signals that had escaped the attention of all his predecessors.

It is fitting that I invoked a train to explain the Doppler effect, for a train played an important role in its experimental verification. This was undertaken by the Dutch meteorologist Buys-Ballot about two years after the appearance of Doppler's paper. Buys-Ballot obtained for a few days the use of a train pulling an open car along a straight stretch of track. The source of sound was trumpets played by skilled musicians, and musicians were also the observers. He alternated sources and observers, placing them in the moving train and by the side of the track. A moving musician would play a given note, and a stationary musician would record its apparent pitch. What was C for the player might be D for his listener (this easily detectable shift does not require astonishing speeds). Buys-Ballot's results confirmed the correctness of Doppler's ideas. When Buys-Ballot first told the musicians about the effect he was trying to verify, they denied that it could exist. They reasoned that the *noise* of approaching trains is no different from that of receding trains. And they were correct: noise is not sound of a single frequency but rather a broad range of frequencies. It is only when a pure note is sounded that changes in pitch can be detected easily. It is to pure notes that we now turn for a demonstration of the Doppler effect.

A Doppler Effect Demonstration

A few years ago Alistair Fraser and I devised a Doppler effect demonstration at the cost of horrifying our colleagues. They had thought they were inured to our inanities until the day we roared up and down the halls of our building carrying blaring instrument tuners.

Figure 14.2
These tuners are used by musicians to determine whether their instruments are in tune. They also can be used to demonstrate the Doppler effect.



Two tuners, like those shown in Figure 14.2, are required. We originally used Alistair's bagpipe tuners (an oxymoron if there ever was one), but subsequently much less expensive tuners have become available. These tuners produce the notes of the musical scale.

With these tuners, an exciting classroom demonstration of the Doppler effect can be obtained at the price of sweat and a red face (or possibly a heart attack). Set both tuners to the same note. Then, after having cleared the aisles, grab one of the tuners and run the length of the room as if pursued by demons. The students listen for the *beat frequency* and estimate its value, from which your speed can be estimated.

What exactly is a beat frequency? When two sources of sound with different frequencies are superposed, the result contains four components: two with the frequencies of the individual sources, one with their difference, and one with their sum. The beat frequency is the *difference* of frequencies.

Let me give an example of a beat frequency. One summer, on a trip west in my 1969 pickup truck, I would hear a low-frequency hum at certain speeds. This unnerved me because the more than 170,000 miles on the truck's odometer kept me ever alert for the precursors of catastrophic failure. The frequency of the hum was so low that I could estimate it, perhaps a few hertz (the hertz, abbreviated Hz, is the unit of frequency: one hertz is one cycle per second). The rotational frequency of the engine at 45 mph is perhaps 50 Hz (i.e., 3000 rpm); that of the wheels about a fourth of this. Both of these frequencies were appreciably higher than what I was hearing, which puzzled me. When I got to San Francisco I discovered the source of the hum. Because of worn kingpins, each of the two front tires was scalloped, and the scalloping was not quite the same on both. Hence the frequencies of the sound generated by them were slightly different. The low-frequency hum I was hearing was the difference between these two frequencies, the beat frequency.

In the classroom it is easy for students—at least most students—to hear the beat frequency as you run with tuner in hand. It is a low-frequency tone superposed on the much higher frequency of the tuner. To help the class measure the runner's speed, it is convenient to pick a particular frequency for the pure note emitted by the tuner. The speed of sound is about 330 meters per second. The fractional shift in frequency of a moving source is approximately the ratio of its speed to that of sound. Hence, if you set the tuner to emit sound of frequency 330 Hz (close to E above middle C), the beat frequency gives the runner's speed directly in meters per second. When I have done this demonstration in class, we have measured beat frequencies of about 5 Hz, which corresponds to a speed of 5 meters per second (11 mph). This is a reasonable figure. Olympic sprinters can average twice this over much greater distances than the length of a classroom.

This classroom demonstration has been quite successful, perhaps as much for its scientific content as for the spectacle it presents of a middle-aged, sweating, red-faced professor who—so the students can hope—just might keel over from his exertions. When I am in an especially theatrical mood, I take off my shoes and run in stocking feet.

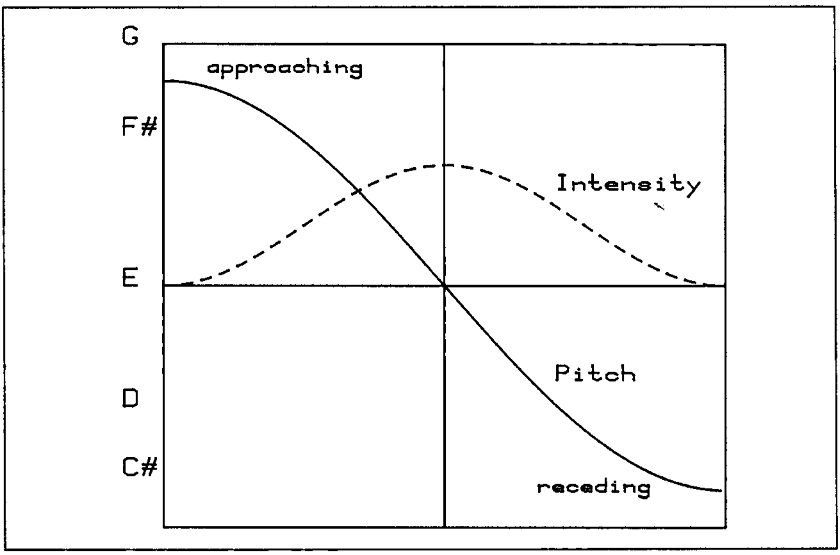
A Misconception Dispelled

The cartoon by Sidney Harris at the head of this chapter gave me a chuckle when I first glanced at it. But it embodies a misconception, namely, that the apparent frequency of a moving source of sound goes through a maximum (or minimum) rather than changing steadily from high to low.

Given that Doppler is the character in this cartoon, the changing boldness of the letters in the balloons was surely meant to convey a changing frequency (or pitch), not intensity, of the sound received from an object as it moves past an observer. I'll assume that the bolder the letters, the lower the pitch (although it is largely irrelevant if the bolder letters were intended to convey higher pitches); the steady rise of the position of the words in the balloons is consistent with this assumption. The cartoon therefore shows a rising, then falling, pitch as Doppler passes by Frau Ginzler. In reality, the pitch only falls steadily. For example, Figure 14.3 shows the pitch perceived by a stationary observer as a 125-mph train (common in Britain but not, alas, in the United States) with its whistle blowing approaches and then recedes.

To an observer standing by the tracks, the apparent whistle frequency is shifted by an amount proportional to the component

Figure 14.3
The pitch heard by a stationary observer from a whistle on a 125-mph train changes from high to low as the train approaches and then recedes. Simultaneously, the whistle grows louder as the train approaches, reaches a maximum when the train is closest to the observer, then fades as the train recedes into the distance.



of the train's velocity along the line between it and the observer. When the train is far away and moving toward the observer, the frequency he hears is greater than that heard by the engineer. As the train moves closer, the apparent whistle frequency decreases. Just as the train passes the observer, both he and the engineer hear the same frequency. As the train recedes, the apparent frequency heard by the observer, now less than that heard by the engineer, continues to decrease. Thus a plot of frequency heard by the observer as a function of time shows a steadily decreasing value rather than, as the cartoon implies, a transition from low to high back to low (or from high to low back to high).

Many students think that the pitch of the sound from a moving object rises, then falls (or vice versa). My guess is that the origin of this misconception lies in the changing intensity, which is also shown in Figure 14.3. It seems fairly easy to be confused about changing pitch when intensity is also changing. The cartoon correctly conveys the changing intensity (if we take higher, less-bold letters to indicate greater intensity) but not the changing pitch of Doppler's greetings to Frau Ginzler as he strolls past her.

Doppler Radar

Our demonstration of the Doppler effect makes use of sound waves. Doppler radar relies on electromagnetic waves. My first encounter with Doppler radar occurred when I was a student at the University of Arizona. From the newspapers, I had learned about a new gadget used by the police to catch speeders, but I had never seen one. Then one day, while riding my bicycle to the university, I saw a policeman with a strange object in his hand. So I stopped, approached him, and asked if his gadget was what I thought it was. He was quite proud of it and needed no coaxing to give me a demonstration. "Do you want to see how it works?" he grinned. "See that car coming toward us? Point this at the car, and its speed appears on this display. Oops, I'll see you later." The car was speeding, so off he went after it.

Because the speed of all electromagnetic waves (that of light) is about a million times that of sound, the Doppler effect for light is proportionately less than for sound. Thus to measure my running speed by the change in frequency of electromagnetic waves requires measuring beat frequencies much less than a millionth of the frequency of the radiation used. With modern electronics this can be done readily.

A Doppler radar can measure the motions of storms along the direction of the beam its antenna transmits. Scatterers in the atmosphere (raindrops, hail, snowflakes, insects, etc.) are illuminated by this beam. Because they are moved by the wind, the frequency of the radiation illuminating them is slightly different from that transmitted. They scatter radiation of this shifted frequency back to the antenna. Because of the relative motion of the scatterers (which themselves can be looked upon as small transmitters) the radiation received by the antenna is shifted in frequency again. The relative difference between the transmitted and received frequencies is equal to twice the speed (along the beam) of the scatterers divided by the speed of light.

Doppler radar can determine wind speeds within a radius of only about 50 km. Such radars are expensive, so dense national or international networks of them are out of the question. During the past few years, however, a project (to which I am contributing in a small way) to measure the global winds from satellites has been hatching. This project is simple in conception (although it may not be in execution): A beam from an infrared laser mounted on a satellite sweeps the atmosphere below it, illuminating atmospheric particles moving with the wind. Because of their motion, the frequency of the infrared radiation scattered back to the satellite by the particles is shifted by an amount proportional to the wind speed (along the beam).

At present, measurements of wind speeds over the globe are sparse. Yet to know where the atmosphere is going one must know how fast and in which direction it is going there. Thus by making use of the Doppler effect, the global winds may some day be determined to an extent that will have a major impact on weather forecasting.

readers. An even more advanced text is Earle H. Kennard's *Kinetic Theory of Gases* (McGraw-Hill, 1938), from which I learned that the thermal conductivity of water vapor is slightly less than that of both nitrogen and oxygen (p. 180).

Chapter 14

A brief, but good, history of the life of Christian Doppler and the effect that bears his name, together with some of its modern applications, was given by Kurt Toman in "Christian Doppler and the Doppler Effect," *Eos, Transactions, American Geophysical Union*, Vol. 65, 1984, p. 1193.

An entire chapter of Hans Christian von Baeyer's *Rainbows, Snowflakes, and Quarks* (McGraw-Hill, 1984) is devoted to the Doppler effect, especially to its history and significance.

A short biography of Doppler is given in *Dictionary of Scientific Biography*, the 15 volumes of which are an excellent source for anyone seeking biographical information about scientists.

Chapter 15

I have learned much from Herschel W. Leibowitz's *Visual Perception* (Macmillan, 1965), a book filled with the insights of one of the leading authorities on perception. About half of this book is a collection of classic papers on visual perception.

Hermann von Helmholtz's *Popular Lectures on Scientific Subjects* are well worth reading, especially his lecture "The Eye as an Optical Instrument," in which he avers that "if an optician wanted to sell me an instrument which had all these defects [of the human eye], I should think myself quite justified in blaming his carelessness in the strongest terms, and giving him back his instrument."

Yves Le Grand's excellent book *Light, Colour and Vision* (2d ed., Chapman and Hall, 1968) is the first place I look for information on how the human eye responds to light.