CHAPTER 5

ETHER DREAMS

You've just seen how Maxwell's electromagnetism leads to electromagnetic waves, including light, and predicts that these waves should move with speed *c*, about 186,000 miles per second. But 186,000 miles per second relative to what? In the preceding chapter we asked the analogous question for sound, Seven hundred miles per hour relative to what?, and had an obvious answer. Sound moves at 700 miles per hour relative to air, the medium in which sound waves are a disturbance. So what's the corresponding answer for light? (When I say "light" in this context, I mean any electromagnetic wave, including visible light. I'll often use "light" and "electromagnetic wave" interchangeably.)

Before we try to answer this question, let me emphasize why it's so important. Without an answer, Maxwell's equations are on shaky ground because their prediction of electromagnetic waves moving with speed *c* is meaningless. If we can't say with respect to what that speed *c* is measured, then the statement "Light goes at speed *c*" is pretty vacuous. We're now going to explore possible answers to the question, Speed *c* relative to what? If you find you don't like those answers, then I challenge you to come up with your own! Keep in mind that we need an answer if Maxwell's electromagnetic theory—a theory that is supposed to explain a great many important physical phenomena including much of modern technology—is to have a solid grounding.

Enter the Ether

Nineteenth-century physicists, heady with the successes of Newtonian mechanics, naturally assumed that electromagnetic waves are like sound and all other known waves, namely, that they are disturbances of some medium. They called that medium the *ether*. Then, Speed *c* relative to what? had an obvious answer: Light goes at speed *c* relative to the ether. An immediate corollary is that if you're moving through the ether, then light's speed relative to you won't be *c*—just as the speed of sound waves measured by someone moving through the air is different from the 700-miles-per-hour-speed of sound relative to air.

Let's take a closer look at this ether. Ether is supposed to be to electromagnetic waves what air is to sound waves—the medium in which the waves are a disturbance. Now sound waves are possible only where there's air, which is why astronauts on the airless moon can't communicate by talking. But light reaches us from the far corners of the Universe, so ether must be everywhere. Ether must be a kind of tenuous, transparent "background" that pervades the entire Universe. It fills the space between the planets, stars, and galaxies. Because light propagates through transparent substances like air and water, ether must permeate the tiny spaces between and even within atoms.

This ubiquitous ether would need some unusual properties. It would have to be a fluid like air or water, rather than a solid, since things move through it. Further, it should be a very tenuous fluid, because it offers no resistance to the motion of planets. If it did, Earth and the other planets would lose energy and eventually spiral into the Sun. But at the same time ether would need to be very stiff, because the speed of light is so big. You can see this if you imagine a stretched spring, Slinky, or rubber band. Send a wave pulse down the spring by disturbing it briefly and then letting go. The more you stretch the spring, the faster the pulse travels. An analogous situation holds for sound waves in different media; sound travels faster in water than in air, for instance, because water is "stiffer" in the sense of the spring with more stretch. And an analogy holds for electromagnetic waves in the ether. For those waves to have the high speed of 186,000 miles per second, the ether must be very stiff

indeed. The two ether properties of being tenuous, to minimize resistance, and being stiff, to maximize wave speed, aren't easily reconciled. Ether would have to be a rather unusual material.

Don't Like the Ether? Try Another Answer

Its contradictory properties make ether an improbable substance, but so ingrained was the mechanical paradigm and so crucial is it to answer the question, Speed *c* relative to what? that nineteenth-century physicists saw no alternative to the ether. You may think you see an alternative, namely, do away with the ether entirely and let electromagnetic waves propagate through empty space. If you go down that road, then I'm going to ask you for an answer to the question Speed *c* relative to what?, and I'm going to expect a good answer that's consistent with physical experiments.

Here's a seemingly good answer: Light goes at speed *c* relative to its source. Eliminate the ether, that is, and let light propagate through empty space at 186,000 miles per second relative to whatever object emitted the light. An observer at rest with respect to that light source would measure *c* for the light's speed, but an observer for whom the source was moving would obviously measure a speed different from *c*. This idea is pretty simple. An analogy would be a baseball pitcher who can throw a 100-mile-per-hour fastball. Thrown from the pitcher's mound, the ball moves at 100 miles per hour relative to the pitcher. Since the pitcher is standing on the ground, that amounts to 100 miles per hour relative to Earth. But put the pitcher in an open car going 50 miles per hour. Again, the ball goes 100 miles per hour relative to its source, namely the pitcher. But relative to observers on the ground, it would be going 150 miles per hour. (Or so it seems; more on this later!)

So does the measured speed of light depend on the speed of its source relative to the observer? No, it doesn't. A host of experiments and observations confirm this. A particularly straightforward confirmation comes from astronomical observations of double-star systems. Unlike our Sun, about half the stars in the Milky Way galaxy are locked in a gravitational embrace with another star. These double stars orbit around each other with orbital periods ranging from hours to years. In some cases the system lies with the plane of its stars' orbits in line with our view from Earth. Then as the stars orbit, one moves toward us while the other moves away; half a period later this situation is reversed (Figure 5.1). We can analyze the stars' motions in detail by studying slight shifts in the wavelength (i.e., color) of light as we observe it. These changes arise because of the star's motions relative to Earth.

Now even the nearest stars are very far away—so far that light from them takes many years to reach us. A slight difference in the speed of light from the two stars in a double-star system would show up as a long time delay between our receiving light that was, in fact, emitted simultaneously from the two stars. We would have to compensate for this difference in light travel times to infer the stars' motions. But we need no such compensation! The stars move exactly as Newton's law of gravity says they should, based on the light as we receive it. There's no increase in the speed of light from the star that's momentarily moving toward us and no decrease for the star that's moving away from us. The speed of light simply does not depend on the motion of its source.

So what's wrong with our baseball analogy? What's wrong is that light doesn't consist of particles like miniature baseballs. Rather, as you know, it consists of waves. Think about sound waves for a

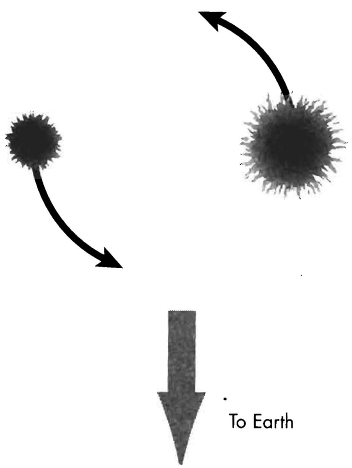

Fig. 5.1 A double-star system, showing the two stars orbiting each other. At the moment pictured, the left-hand star is approaching Earth and the right-hand star is receding. If the speed of light depended on the speed of its source, light from the left-hand star would reach Earth sooner.

minute. The speed of sound waves is 700 miles per hour relative to the medium, namely air, in which sound is a disturbance. If a source of sound—say a fire truck's siren—moves through the air at 60 miles per hour, the speed of the sound is still 700 miles per hour relative to the air. It doesn't pick up the additional 60 miles per hour of the fire truck. Apparently light is like that. It must move at c relative to the medium, namely ether, in which it is a disturbance. If a source of light moved through the ether, the speed of the light would nevertheless still be c relative to the ether.

(By the way, something about the sound from a moving source does change, namely, its pitch. When the fire truck is coming toward you, the siren sounds like it has a higher pitch. When it moves away, the pitch you hear is lower. The analogous shift for light is what lets us measure motions in double-star systems.)

In disabusing you of the notion that the speed of light might be c relative to its source alone, I reverted naturally to the language of ether—the medium in which light waves are purportedly a disturbance. Despite the problematic aspects of the ether, what else are we (or, more precisely, nineteenth-century physicists) to do? Light, after all, consists of waves, and all other known waves are disturbances of some medium. The speed of each type of wave—sound waves, water waves, stadium waves, earthquake waves, etc.—is its speed relative to its particular medium. Why not the same for light?

If you're still troubled by the all-pervasive, tenuous, light-wave-supporting ether, then again I challenge you to tell me relative to what light travels at speed c. That's a harder challenge now you know that the answer cannot be "relative to its source." So for now we'll continue to follow the nineteenth-century physicists' line of thought, picturing light waves as disturbances of an ether that pervades the entire Universe. If you really don't like the ether, though, hold on—eventually you'll be vindicated!

A Broader Question

We were led to the ether concept by questioning relative to what light travels at speed c. I want to convince you now that this question is really a special case of a more general one: In what frame of reference are the laws of electromagnetism (i.e., Maxwell's equations) valid? The two questions are related because one prediction of the laws of electromagnetism is that there should be electromagnetic waves and that they should go at the speed of light, *c*. When we answer "ether" to the question "Relative to what does light go at speed *c*?", we're saying that Maxwell's prediction of electromagnetic waves that go at *c* is really valid only in a frame of reference at rest with respect to the ether. Observers in a reference frame moving through the ether will measure some other speed for light relative to themselves; thus for them, in the context of their reference frame, the predictions of Maxwell's equations won't be valid. That's why my two questions, one about the speed of light and the other about the validity of Maxwell's equations, are essentially equivalent. Maxwell's equations predict electromagnetic waves going at *c*, so those equations can only be valid in a frame of reference where one will, in fact, measure *c* for the speed of light.

So what's the answer to our new question, In what frame of reference are Maxwell's equations valid? It's obvious: In the context of nineteenth-century physics, there's only one frame of reference in which Maxwell's prediction about electromagnetic waves is valid, and that's a frame of reference at rest with respect to the ether.

Dichotomy in Physics

In Chapter 3 we discovered the principle of Galilean relativity, which states that Newton's laws of motion are valid in all uniformly moving frames of reference. So if we ask explicitly in what frame of reference Newton's laws of motion are valid, then the answer is "in any uniformly moving frame of reference."

This question we've just asked about Newton's laws of motion is exactly the same question we asked in the previous section about Maxwell's laws of electromagnetism. But there we found quite a different answer. Maxwell's electromagnetism, it seems, isn't valid in just any frame of reference. Rather, the laws of electromagnetism should be valid only in one very special frame of reference—a frame

of reference at rest with respect to the ether. Put another way, the laws of motion obey a relativity principle but the laws of electromagnetism seem not to. So although there's no experiment we can do with the laws of motion to answer the question, Am I moving?, there should be electromagnetic experiments that can answer this question. That is, the concept of absolute motion is meaningless for mechanics, but apparently it has meaning for electromagnetism. Although there's no privileged state of motion for mechanics, there seems to be a privileged state for electromagnetism—namely, being at rest relative to the ether.

Why the dichotomy? Why should one main branch of physics (mechanics) not care about states of motion, while the other (electromagnetism) does? Wouldn't it be simpler and more coherent if both branches of physics obeyed the relativity principle, or both didn't?

Think back to the second chapter, where I asked about a tennis match played on a cruise ship, on Venus, and on a planet in a distant galaxy moving away from Earth at nearly the speed of light. You wisely and logically agreed that it made perfect sense to expect that tennis playing—a manifestation of the laws of motion—would work the same in all those contexts or, as we would now say, in all those different reference frames. That is, you intuitively accepted the principle of relativity as applied to the laws of motion. Then I asked about heating a cup of tea in a microwave oven, and you agreed that the microwave oven, like the tennis ball, should also behave the same way in the different reference frames. But it's electromagnetism, not mechanics, that governs the microwave oven. Through our exploration of the question, Relative to what does light go at speed *c*?, we've just found that the laws of electromagnetism seem not to obey the relativity principle. That is, the laws of electromagnetism should not be valid in all reference frames—and electromagnetic experiments should therefore give different results in reference frames that are in different states of motion. So the microwave oven shouldn't work the same way in that distant galaxy moving at nearly *c* as it does on Earth!

What's wrong with your intuition from Chapter 2? Again, the difficulty is with the ether. When you blithely agreed that the microwave oven should work the same way everywhere, you weren't taking the nineteenth-century view, with its unique reference frame of the ether, in which frame alone the laws governing the oven should be valid.

So why not get rid of the ether, now troublesome not only because of its improbable characteristics but because it's also the cause of an illogical and unsatisfying dichotomy between two branches of physics? That dichotomy runs counter to your good sense that the laws governing physical reality, whether tennis balls or microwave ovens, should work the same everywhere and regardless of one's state of motion. If you abandon the ether, then you could eliminate that dichotomy.

But if you abandon the ether, then I challenge you once again to answer the question, Relative to what does light go at speed c? or, equivalently, In what frame of reference are the laws of electromagnetism valid? If you give the same answer that I'll happily accept for the laws of motion—"in all uniformly moving reference frames"—then you'll vindicate your intuitive sense from Chapter 2 that the microwave oven should work the same in all states of motion. But if you give that answer, you'll find yourself on the edge of a philosophical abyss. That's because you'll be insisting on a seeming contradiction: that two different observers must each find valid the Maxwellian prediction that light waves move at speed c—*even if those observers are moving relative to each other*! Better not go there, at least not yet; instead, we'll stick for now with the nineteenth-century ether concept and explore further its implications.

Earth and Ether

Following nineteenth-century physicists, we've established ether as the medium through which light waves propagate with speed c, and we recognize therefore that Maxwell's equations of electromagnetism can only be valid in a frame of reference at rest with respect to the ether. So a logical question arises: How is our Earth moving relative to the ether?

It's pretty obvious that we aren't moving very fast through the ether, because if we were then we would see obvious differences in the speed of light coming from different directions. For example, if Earth were moving at 90 percent of c, then light from stars in the direction toward which Earth is moving would be going at $1.9c$ relative to us ($c + 0.9c = 1.9c$). But light from stars in the opposite direction would be going at only one-tenth of c ($c - 0.9c = 0.1c$). That difference would be patently obvious. But if Earth were moving much more slowly through the ether—at a tiny fraction of c—then we might not notice the difference unless we looked very carefully. So again the question: How is Earth moving relative to the ether? That is, how fast and in what direction is Earth's motion relative to the ether?

We begin with an even simpler question: Is Earth moving relative to the ether? That one has a yes-or-no answer. Either Earth is moving relative to the ether, or it isn't.

Insulting Copernicus

Consider first the possibility that Earth isn't moving relative to the ether. I can think of only two ways for this to be the case. First, the ether might be a fixed substance that extends throughout the Universe. Then Earth alone among all the cosmos would be at rest relative to the ether. I say "alone" because all other celestial objects—the Moon, Mars, Venus, the other planets, the Sun, other stars in our galaxy, and the other galaxies in the Universe—all are moving relative to Earth. So if Earth is at rest relative to the ether, then it alone is at rest. That makes us pretty special. If we're the only beings at rest relative to the ether, then Maxwell's equations are valid only for us, and only we measure c for the speed of light. Observers on other celestial bodies measure different speeds for light in different directions, and for observers moving very fast relative to Earth—like those in distant galaxies—that effect must be dramatically obvious.

Copernicus would turn in his grave! It's hard to imagine a worse insult to the Copernican revolution than to make our planet so special that one of the two main branches of physics is valid only on Earth. I spent most of Chapter 3 presenting a history of science that led steadily away from the notion of Earth being a special, privileged place in the Universe. Do you really want to return to parochial, pre-Copernican ideas? Do you really think you and your planet are so special that, in all the rich vastness of the Universe, you alone can claim to be "at rest"?

On purely philosophical grounds, we should reject the notion that Earth alone could be at rest relative to the ether. Now, philosophy isn't science, and I hasten to add that there's plenty of good scientific evidence to support this view. For example, we observe light-emitting processes in distant stars and galaxies that seem to work the same there as they do here on Earth. That suggests we don't have any special status vis-à-vis the laws of electromagnetism. So we can confidently reject the idea that Earth alone is at rest relative to the ether.

Ether Drag

It might still be possible for Earth to be at rest relative to the ether if our planet somehow "dragged" the surrounding ether with it. Presumably other planets and celestial bodies would do the same, so each would be at rest relative to its local blob of ether. Then observers everywhere and in different states of motion would find the laws of electromagnetism to be valid, and no one would have any claim to be special. Copernicus would be a lot happier with that!

So does Earth drag the ether with it? Astronomical observations dating to 1725 provide a clear answer. A simple analogy will help you understand these observations. In Figure 5.2a you're standing, holding an umbrella in the rain. Obviously the best approach to keeping dry is to hold the umbrella directly overhead. But what if you run through the rain? Now it's better to tilt the umbrella, holding it at an angle (Figure 5.2b). Figure 5.2c shows why: viewed from your frame of reference, the rain is coming down at an angle, and you want to hold the umbrella so the rain still hits the umbrella top straight on. Since the rain is falling at an angle, you should hold the umbrella at the same angle. If you run in the opposite direction, you should still hold the umbrella tilted at the same angle in front of you, but now this will be a different absolute direction.

However, suppose that somehow you drag a big blob of air with you as you run—so big a blob that rain falling into it has time for

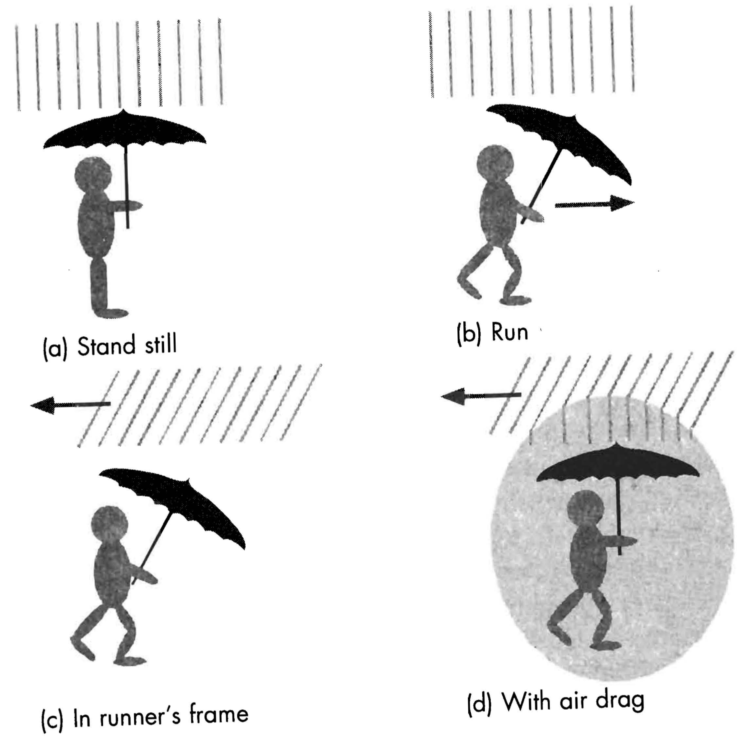

Fig. 5.2 An analogy for the aberration of starlight. (a) Standing still in vertically falling rain, you hold your umbrella straight overhead to keep driest. (b) Running, you tilt your umbrella. (c) The situation in (b), shown from the runner's frame of reference. In this frame, the rain falls at an angle. (d) If the runner drags a large blob of air, then rain entering the blob will take on the blob's motion, and thus will fall vertically relative to the runner.

the force of the moving air to accelerate it to your running speed before it hits you or your umbrella. Figure 5.2d shows the situation from your point of view. As you run through the rain, the rain outside your blob of dragged air falls at an angle as seen from your reference frame. But inside the blob, the moving air accelerates the rain until it shares the blob's motion. So now, relative to you, it's falling straight. The upshot is that you don't have to tilt your umbrella. Rather, you'll stay driest if you hold it right overhead.

You can see from the foregoing discussion that an umbrella in a rainstorm is a useful device for determining whether you drag a big blob of air when you run—as if you don't already know the answer. But let's suppose you don't. So you set out in a rainstorm to answer the question. You run through the rain and hold your umbrella first over your head, then at an angle. You find out which approach keeps you driest. If the overhead approach is best, then, as in Figure 5.2d, you can conclude that you do drag a big blob of air with you. But if tilting the umbrella works best, then from Figure 5.2c it's obvious that you don't drag the air with you.

Running in the rain with an umbrella provides an analogy for astronomical observations that answer the question, Does Earth drag a blob of ether with it? The runner moving through the air is like Earth moving through the ether. The rain is like light from a distant star "falling" on Earth. The umbrella is an astronomer's telescope. And the question is, Do we need to point the telescope at an angle to compensate for Earth's motion? Actually, the question is slightly more subtle, since we can't stop Earth and compare the telescope angles with Earth stopped or moving. But what we can do is compare the angles for different directions of Earth's motion. Relative to the Sun, Earth is right now moving in some direction. Six months later, halfway around its orbit, the planet will be going in the opposite direction. If Earth doesn't drag the ether, then we'll need to change the angle of our telescope to observe the same star at six-month intervals, just as running in different directions in Figure 5.2c requires changing the direction of the umbrella's shaft. Such a change in the apparent direction to a star is known as *aberration of starlight*. If, on the other hand, Earth does drag the ether, then we keep the telescope in the same direction for both observations. In this case there's no aberration. So what happens? In fact, the telescope angle changes—a small change, to be sure, but readily detectable with astronomical measurements as early as 1725. We conclude that Earth does not drag ether with it.

It seems we've answered the question of whether Earth is moving relative to the ether. On philosophical as well as observational grounds we first ruled out the possibility that Earth alone is at rest relative to the ether. Now aberration of starlight shows that Earth doesn't drag a blob of ether with it. Those were the only ways we could conceive of Earth's being at rest relative to the ether. So we have to conclude that Earth *is* moving relative to the ether.

Given that fact, we can now ask how fast and in what direction Earth is moving. That's the question nineteenth-century physicists set out to answer. With a variety of clever experiments, they sought to measure Earth's motion through the ether. These experiments typically involved the propagation of light through water and had the added benefit of verifying the notion that moving substances—for example, flowing water—do not communicate their motion to the surrounding ether. That is, the experiments confirmed the absence of ether drag. But, curiously, they failed to detect Earth's motion through the ether. This disappointing result was attributed to the effects of the water on light, effects that apparently just cancelled out the sought-after indication of motion through the ether. The question of Earth's motion remained ambiguous.

Wrap-up: Physics at 1880

It's now about the year 1880, and here's how things stand. Together, Newton's mechanics and Maxwell's electromagnetism seem to explain all known physical phenomena. There's a philosophically disturbing dichotomy, in that a relativity principle holds in mechanics but not in electromagnetism, but that doesn't diminish the explanatory power of these two great branches of physics. Light is understood as an electromagnetic wave, propagating with speed c through a Universe-permeating medium called ether. Astronomical observations show that the speed of light does not depend on the motion of its source and that Earth must be in motion relative to the ether. The only thing remaining to solidify the picture of electromagnetic waves in the ether is to measure Earth's motion. But as of 1880 no experiment has succeeded in doing so. Then again, the experiments are difficult, they require great sensitivity, and there are complicating effects that may obscure the desired result. What's needed is a conceptually simple experiment that's sensitive enough to measure unambiguously Earth's motion through the ether. Such an experiment should, once and for all, lay to rest any nagging doubts about the ether.