



THE UNIVERSE

Is the Universe Leaking Energy?

Total energy must be conserved. Every student of physics learns this fundamental law. The trouble is, it does not apply to the universe as a whole **BY TAMARA M. DAVIS**

ENERGY CAN NEITHER BE CREATED nor destroyed. This principle, called conservation of energy, is one of our most cherished laws of physics. It governs every part of our lives: the heat it takes to warm up a cup of coffee; the chemical reactions that produce oxygen in the leaves of trees; the orbit of Earth around the sun; the food we need to keep our hearts beating. We cannot live without eating, cars do not run without fuel, and perpetual-motion machines are just a mirage. So when an experiment seems to violate the law of energy conservation, we are rightfully suspicious. What happens when our observations seem to contradict one of science's most deeply held notions: that energy is always conserved?

Skip for a moment outside our Earthly sphere and consider the wider universe. Almost all of our information about outer space comes in the

form of light, and one of light's key features is that it gets redshifted—its electromagnetic waves get stretched—as it travels from distant galaxies through our ever expanding universe, in accordance with Albert Einstein's general theory of relativity. But the longer the wavelength, the lower the energy. Thus, inquisitive minds ask: When light is redshifted by the expansion of the universe, where does its energy go? Is it lost, in violation of the conservation principle?

Modern physics has shown that when we move far from the comfort of our everyday lives to explore the extremes of time and space, many of our basic assumptions start to crumble. We know from Einstein that simultaneity is an illusion that changes based on the observer's perspective and that notions of distance and duration are also relative. We now also suspect that the apparent continuity of time and space may be as illusory as the deceptively smooth appear-

KEY CONCEPTS

- As the universe expands and distant galaxies recede from us, their light gets redshifted, thus becoming less energetic.
- This seeming violation of the principle of conservation of energy is actually not in contradiction with accepted physical laws.
- According to the author, the proper interpretation shows that the energy of individual photons is conserved. And phenomena taking place inside the galaxy generally conserve energy.

—The Editors

WHY ENERGY SEEMS TO DISAPPEAR

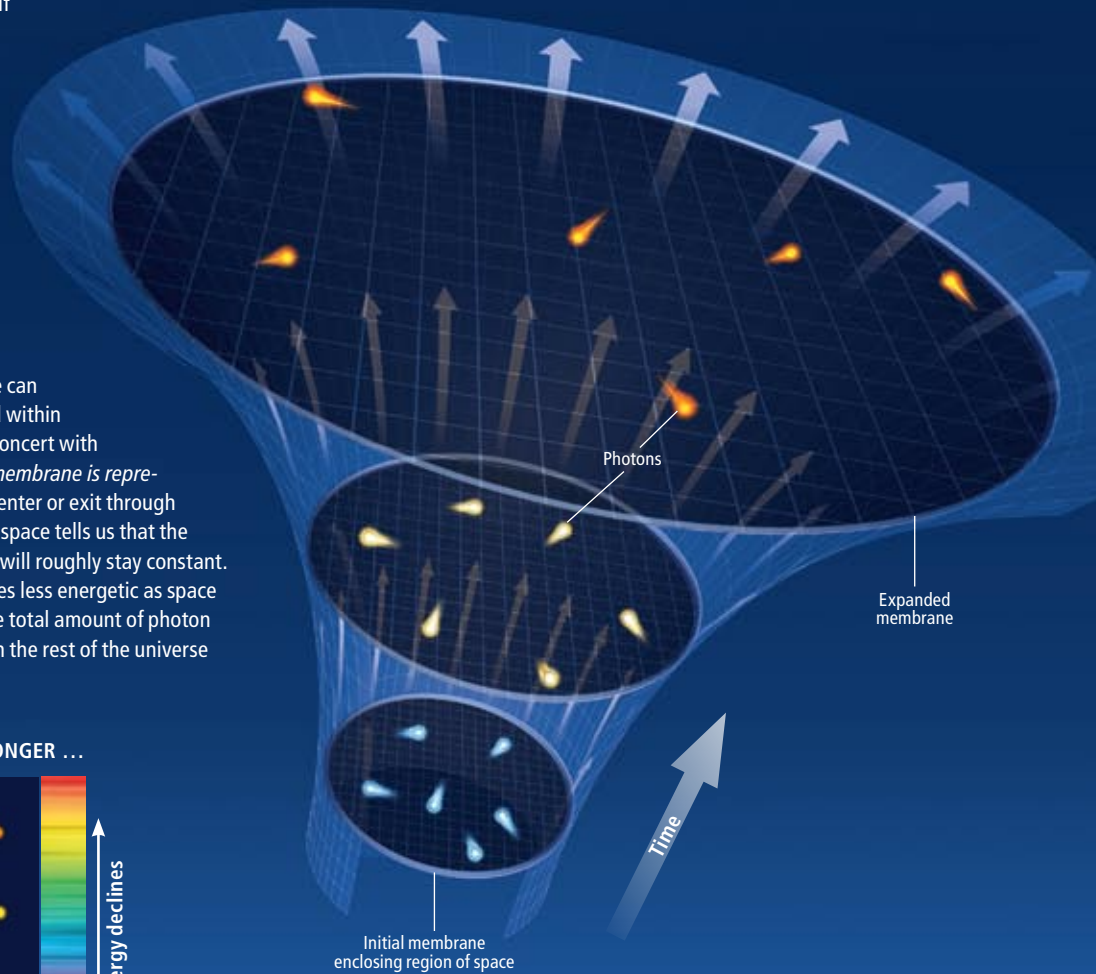
Those who argue that the universe is losing energy base their conclusion in part on the redshift of light.

The universe appears to be expanding, as if space itself were getting stretched out.

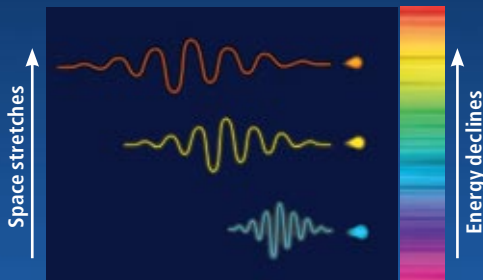
In consequence, the electromagnetic waves that compose light get stretched as well, shifting, in the case of visible light, toward the red part of the spectrum (*below*).

Photons of longer wavelength have lower energy, so logic dictates that each photon must become less energetic as it travels toward us.

But does the universe as a whole lose energy? The total energy of the photons in the universe cannot be calculated, but one can in principle calculate the energy contained within an imaginary membrane that expands in concert with the universe (*at right, the region inside a membrane is represented as two-dimensional*). Photons can enter or exit through the membrane, but the uniform density of space tells us that the number of photons in the enclosed region will roughly stay constant. Because each photon in the region becomes less energetic as space expands, this calculation suggests that the total amount of photon energy in the region and, by implication, in the rest of the universe must be going down.



ELECTROMAGNETIC WAVES GET LONGER ...



... YET THE NUMBER OF PHOTONS STAYS THE SAME; ENERGY APPEARS TO BE LOST

ance of matter. What *is* there in physics that we can rely on? Which of our deeply held principles is pulling the wool over our mind's eye and blinding us to the deeper truths? We physicists spend our days challenging what is known and striving to discover where our knowledge is inadequate or just plain wrong. And history is littered with the debris of discarded misconceptions. Is conservation of energy one of those misguided ideas?

It is not. On the scale of individual photons, energy is always conserved, even as light gets redshifted. Likewise, for phenomena that take place within our galaxy, violations are virtually impossible and our cherished law remains on a sound foundation. But on a cosmological scale, energy

becomes a subtle concept indeed, and that is where things start to get interesting.

SYMMETRY AND CONSERVATION

NOT ONLY HAS CONSERVATION of energy been empirically validated many times over, but scientists also have good theoretical reasons to believe it. Our confidence comes from German mathematician Emmy Noether, who put conservation of energy on a secure footing nearly 100 years ago, when she discovered that all conservation laws are based on symmetries of nature.

Usually you think of symmetry as something you see in a mirror, a reflection of some kind or a rotation perhaps. An equilateral triangle is

The metaphor of the universe as an expanding rubber balloon should be taken with a grain of salt.

symmetric because you can flip it sideways or rotate it one third of the way around, and you end up with exactly the same shape. A square also has symmetry, but you need rotate it only one fourth of the way around to find an identical configuration. The most symmetric of the two-dimensional objects is the circle, because you can rotate it any amount and reflect it over any axis through its center, and it remains exactly the same—it displays what is called continuous symmetry.

Physical laws, too, can be symmetric. The passage of time does not change the laws of nature; if you repeat an experiment many times—for example, making billiard balls collide at a given angle—the result is always the same. This quality is known as time symmetry. The laws of nature do not change depending on where you are—so we have spatial symmetry. Nor do the laws of nature change depending on the direction in which you look (rotational symmetry). Sure, the scenery may change depending on where you are standing, when you are standing there and the direction you are looking, but the fundamental underlying laws of physics that dictate how that scenery behaves are independent of your location, orientation and time. When a law remains unchanged regardless of the situation, it, like the circle, is said to be continuously symmetric.

What Noether discovered is that whenever nature displays a continuous symmetry, a conservation law comes along for the ride, and vice versa. In particular, spatial symmetry dictates that momentum is conserved; rotational symmetry ensures angular momentum is conserved; and time symmetry means that energy is conserved.

So, saying that energy is conserved is as solid as saying that the laws of physics are the same now as they were in the past and will be in the future. On the other hand, were time symmetry to break down, conservation of energy would fail. As we will see, this is where energy conservation may start to get in trouble in Einstein's universe.

GO WITH THE FLOW

THERE IS NO BETTER WAY to test whether the present matches the past, and thus to see if energy is conserved in the universe, than to watch the past in full live action through an astronomer's telescope. Our telescopes are now so powerful that we are able to see back to when the first galaxies were forming and beyond to the piping-hot afterglow of the big bang itself. The

light we are seeing has been traveling for billions of years, and in all that time, the first thing it has hit is the mirror of our telescope. The wavelengths of that light are our key to assessing conservation.

In the 1920s Edwin Hubble discovered that the light of most galaxies is redshifted: he found that the wavelengths of photons that were emitted or absorbed by atoms (such as by hydrogen) in all but the nearest galaxies to us appear, when they reach us, to be stretched relative to the wavelengths emitted by the same atoms at home—stretching roughly in proportion with the galaxies' distance. In fact, ever since the discovery of this phenomenon, whenever astronomers cannot measure a galaxy's distance more directly they instead give an estimate using its redshift as a proxy.

Redshifts (and blueshifts) also happen all the time here on Earth. **Imagine driving past a police radar.** As your car approached, the electromagnetic waves from the radar would look slightly shrunk to you—if you could see them—when they reached you. But after you passed, the waves would look a bit stretched. This is the Doppler effect: it is the electromagnetic equivalent of the familiar change in acoustical pitch you would hear in a siren as it passes by. (The police officer can tell if you are speeding by measuring a Doppler shift in the reflection of the radar.) Although in this case the waves are not in the visible spectrum, physicists still call the stretching and shrinking of the waves redshift and blueshift, respectively.

Cosmological redshifts, however, are generally considered to be different from the Doppler effect. Doppler shifts are caused by relative motion. In that case, the photons are not losing or gaining energy; they just look different to you than they do to the emitter. In contrast, most general relativity or cosmology textbooks say cosmological redshifts happen because as light travels, the very space it travels in gets stretched like the surface of an inflating rubber balloon.

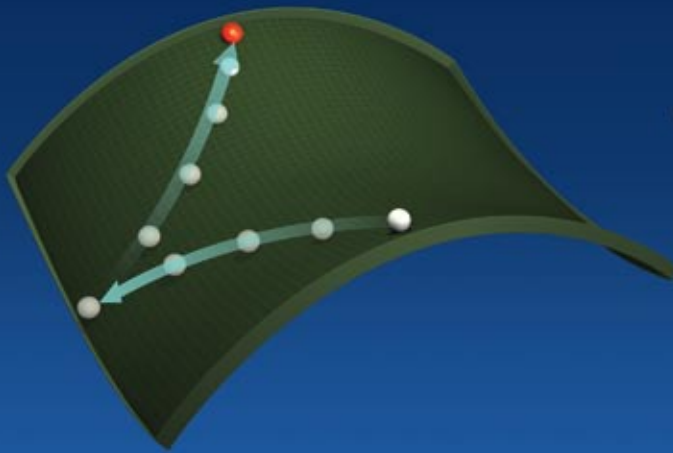
In fact, cosmological redshifts can happen even when there seems to be no relative motion at all, as the following thought experiment shows. Imagine a galaxy far, far away but connected to ours by a long tether. Relative to us, the galaxy is not moving, even as other galaxies in its vicinity recede from us. Yet standard calculations show that the light reaching us from the tethered galaxy will still be redshifted (though not quite as strongly as the light from the galaxies in its vicinity, which have not been pulled out of the

A MATTER OF CHANGING GEOMETRY

Conservation laws are intimately tied to symmetries of nature. In particular, energy is conserved when the laws of nature have “time symmetry.” Time symmetry is said to occur if any experiment gives the same results regardless of when it is performed. But if experiments can give different results at different times, energy may not be conserved. An example is playing a bank shot on a pool table that has a changing geometry. At cosmological scales, our universe has a changing geometry, which once again implies that energy may not be conserved.

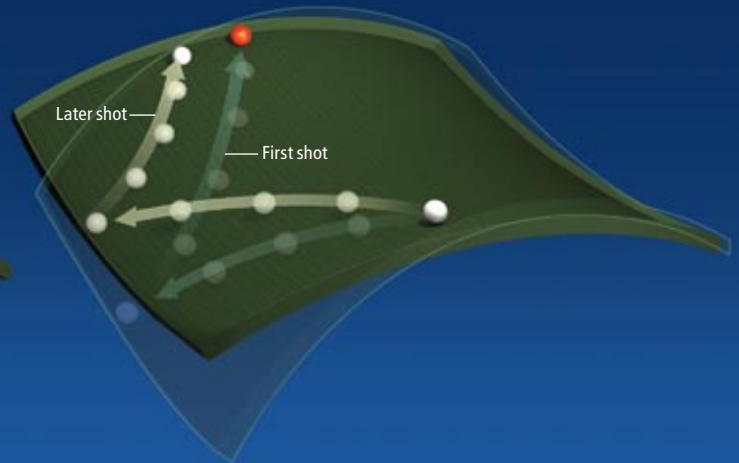
CURVED POOL TABLE

To play on a table that has curved, or “non-Euclidean,” geometry, you have to adjust your shots to the geometry. Still, if the geometry is fixed, the same exact shot will work again in the future. Because of this time symmetry, in a universe with fixed geometry energy would be conserved.



EVOLVING GEOMETRY

If the pool table has a geometry that changes in time, however, the shots that worked in the past may not work again—therefore, time symmetry is broken. Something similar can happen in the universe, because according to general relativity the motion of matter and energy changes the geometry of space. Under these conditions, energy need not be conserved.



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flow of the expansion). This redshift is usually attributed to the stretching of the space through which light travels.

PECULIAR PHYSICS

SO PHOTONS TRAVELING in an expanding universe appear to lose energy. What about matter? Does it lose energy, too? When we describe the motion of matter in the universe, we distinguish between two different types. An object can just be receding with the general flow of the universe’s expansion, just like dots painted on our balloon. In cosmology, such an object is called comoving. But an object can also have its own motion on top of the motion caused by the expansion. This second type is called peculiar motion, and it takes place when something is dragged out of the smooth flow of the expansion by local effects, such as the gravitational pull of a nearby galaxy or the thrust of a rocket.

Galaxies themselves always have at least a bit of peculiar motion, but for distant galaxies—which recede faster than near ones do—the pe-

culiar velocity is small compared with their recession. At the largest scales, the distribution of galaxies is uniform, so local effects are negligible and galaxies are essentially comoving. They can be regarded as the dots on the balloon, that is, as flag posts of the expanding fabric of space.

A comoving frame of reference such as that defined by galaxies is very handy: for example, it gives a universal convention for time, so that everyone in every comoving galaxy would agree on how long ago the big bang happened.

If an intergalactic traveler drifts for billions of light-years, he or she will pass many of these flag-post galaxies. But because the universe is expanding, the flag posts are moving away from one another, and our traveler appears to be going slower and slower relative to each subsequent galaxy he or she passes. So the traveler appears to slow down.

Thus, much as light loses energy by increasing in wavelength, matter loses energy by slowing down. At first sight those behaviors appear to be very different. But, interestingly, quantum mechanics unifies the two. In the quantum-

mechanical view of matter, particles that have mass also have wavelike properties. French physicist Louis de Broglie found that the larger the momentum of a particle, the smaller its wavelength and the greater its energy—and he won the Nobel Prize in 1929 for his discovery.

Particles of matter can have high momentum by having high mass or high velocity, or both. That feature explains, for example, why a baseball does not appear to wiggle about in wavelike motions after it leaves the pitcher's glove. Baseballs are enormously massive in quantum terms, and at the typical speed of a major-league fastball pitch (about 145 kilometers an hour) a baseball has a wavelength of 10^{-34} meter—not something a batter will have to worry about. On the other hand, an electron traveling at the same speed has a wavelength of 18 microns: still small, but 29 orders of magnitude larger than a baseball's, and very noticeable when it comes to the behavior of electrons.

When you calculate how much relative velocity massive particles lose as they pass by their receding neighbors, you find that the de Broglie wavelength of the particles increases by exactly the same proportion as a photon's wavelength does. Thus, light and matter seem to behave in exactly the same way when it comes to energy loss in the expanding universe, and in both cases it looks as if energy conservation is being violated. In the case of matter, the paradox is explained by the fact that we are measuring velocity in different frames of reference—that is, relative to the receding galaxies. As we will see, something similar happens with photons.

CREATIVE ACCOUNTING

WERE COSMOLOGICAL ACCOUNTANTS to verify that the universe is losing energy, they might attempt to tally up all the energy in the universe, rather than focusing on one object at a time. They might first add up all the energy contained simply in the mass of the matter in the universe (mass m and energy E are equivalent following Einstein's $E = mc^2$, where c represents the speed of light). Then they would add in the kinetic energy related to the matter's peculiar motion. To that sum, they would have to add the energy of light as well and then get to the complex job of counting the energy in all the gravitational fields around planets, stars and galaxies, plus the energy contained in chemical bonds and in the nuclei of atoms. (Sound and heat are just the motion of particles, so they have already been accounted for.)

A first problem they would face is that the universe may be infinitely large and contain an infinite amount of matter and energy. Thus, the accountants would need to take a shortcut. They would draw an imaginary membrane around a region of the universe and add up the energy inside [see box on page 40]. They then would let the membrane expand as the universe does, so that comoving galaxies stay inside the membrane. Light and matter can pass in and out of the membrane, but because the universe is homogeneous, the same amount leaves as enters, so the amount inside the membrane stays roughly constant. Our accountants know that the whole universe can be constructed from a series of such volumes. If the energy in the universe is to be conserved as a whole, therefore, it is enough to show that the energy in any one of those volumes is conserved.

The calculation is easy to do for matter that is at rest—just chilling out and going with the flow of the expansion. Its only energy in this case comes from its mass, and because no matter leaves or enters the membrane, we know the mass is conserved. But things are a bit more complicated for light, as we have seen, and for matter that has peculiar velocity. Although the number of photons or of matter particles within the membrane does not change, over time photon energy is lowered, as is the kinetic energy of the peculiarly moving matter. Therefore, the total energy in the membrane goes down.

The situation would be even more complicated if the accountants were to count dark energy, which is what is causing the universe's expansion to accelerate. The nature and properties of dark energy are still a complete mystery, but it appears that dark energy does not dilute as the universe expands. Thus, as the volume in our membrane increases, the amount of energy in that volume increases as well, with the additional energy seemingly coming out of nowhere! One might think that the increase in dark energy could balance out the losses in all other forms of energy, but that is not the case. Even if we take dark energy into account, the total energy within the membrane is not conserved.

How do our accountants reconcile these changing energies with Noether's theorem? In fact, they would soon realize that there is no reason why Noether's theorem should apply to our changing universe. According to general relativity, matter and energy curve space, and as matter and energy move (or spread out in an expanding space) the shape of space changes accordingly. In everyday life, these effects are

MORE COSMIC PUZZLES

Is space within our galaxy expanding?

No. Cosmic-scale expansion does not affect the dynamics inside a galaxy. Once local gravitational effects cause a galaxy to form, the expansion has no power to pull the galaxy apart.

Do photons from distant galaxies get redshifted because the universe's density has been decreasing? After all, photons get redshifted when they climb up a gravitational gradient.

True, but at any given time, the universe was uniform, so the density of matter was the same behind a photon as it was in front of it. Thus, photons had no gravitational gradient to climb out of.

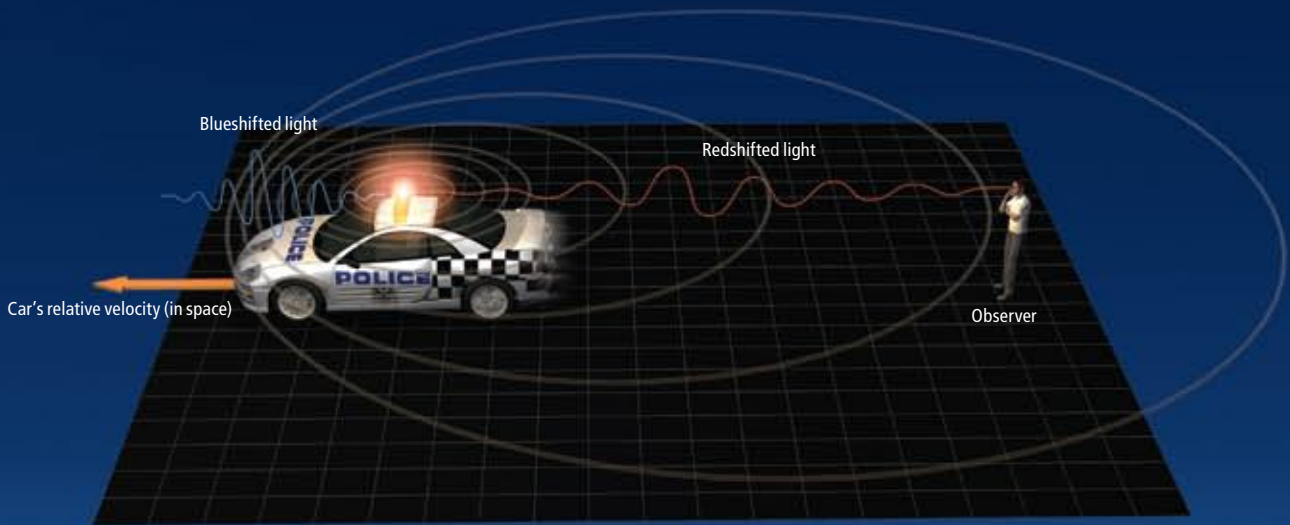
Is entropy compatible with time symmetry?

Yes. In complex interactions of particles, such as the breaking of an egg, we can tell which way a movie of the process is being played—the direction in which entropy increases, which is the direction of increasing disorder. Nevertheless, any single one of the interactions between particles could happen forward or backward, as far as the laws of physics are concerned.

HOW PHOTON ENERGY IS CONSERVED AFTER ALL

The redshift we see in distant galaxies is usually attributed to the stretching of space, but it can also be interpreted as an effect of the receding motion of the galaxies with respect to the observer. It is therefore similar to the familiar Doppler effect, which one can hear in the siren of a police car that is passing

by but that also affects the wavelengths of photons—for example, those from the car's emergency lights (*below*). In the case of the police car, energy is conserved; similarly, calculating galaxy redshift as a Doppler shift (*opposite page*) shows that photons from a distant galaxy also do not lose energy.



ORDINARY DOPPLER SHIFT

Doppler shifts arise from relative motion. The lights flashing from the top of a police cruiser appear redshifted or blueshifted—though imperceptibly to human eyes—depending on whether the car is moving away from you or toward you. The larger the car's velocity relative to an observer, the

stronger the effect will be. But the occurrence of the Doppler shift does not mean that photons change color (nor that they lose energy) along the way; they just have different colors as seen from an observer's point of view than they have from the car's own point of view.

essentially too small to detect, but at cosmic scales they can be relevant.

This malleability of space implies that the behavior of the universe is not time-symmetric. The easiest way to visualize this fact is to go back to the example of the billiard balls. If we watched several movies of a particular shot being played on a pool table of changing geometry—for example, one that starts flat and warps with time—each movie would look different from the others; you could tell when and in what order each movie was taken. Time symmetry would be broken [*see box on page 42*].

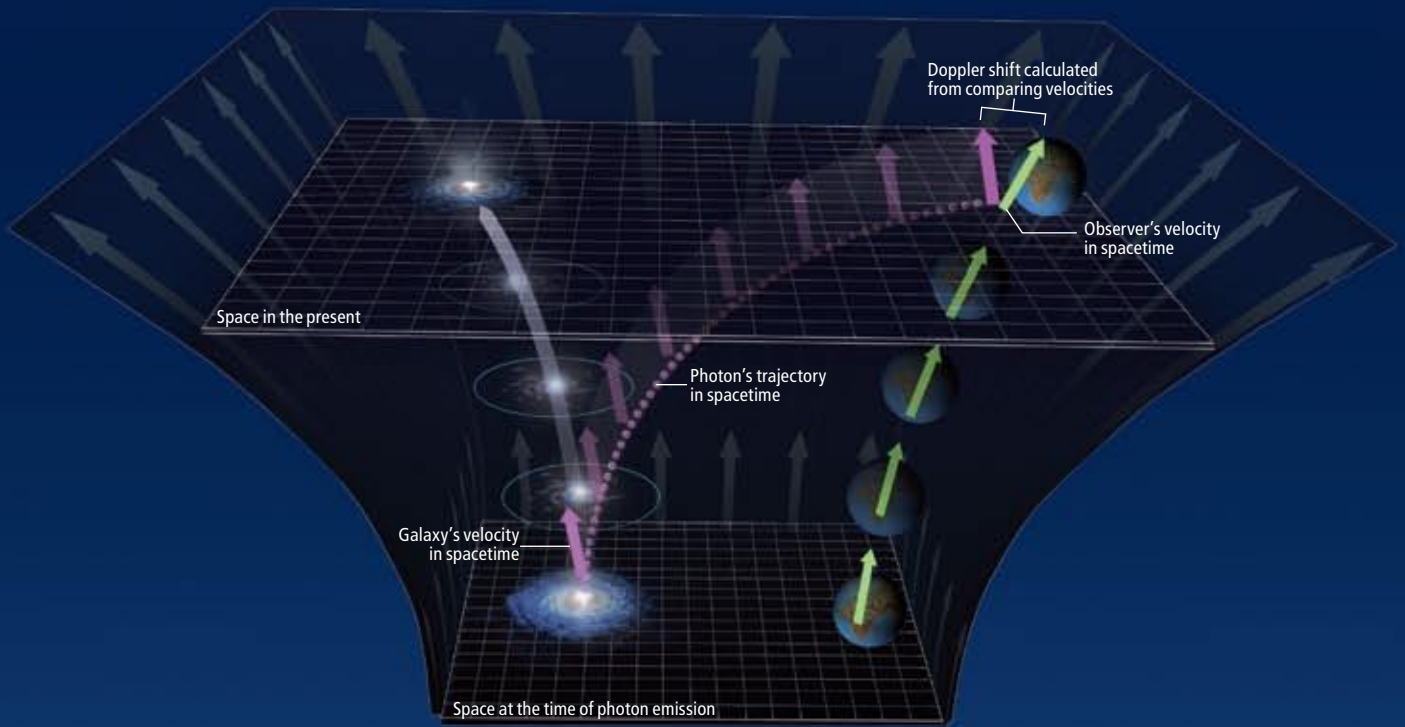
We have come to the limit of our cherished conservation principles: when time and space themselves are mutable, time symmetry is lost, and conservation of energy need no longer hold.

COSMIC SEMANTICS

EVEN IF CURVATURE does not change, however, trying to tally up the energy of the universe is a futile exercise: our accountants' godlike per-

spective does not pertain to any observer in the universe. In particular, they do not take into account the energy of comoving galaxies' motion with respect to one another, so to them, the galaxies appear to have no kinetic energy. Another issue is the gravitational energy associated with the galaxies' mutual attraction. A well-known problem with general relativity is that in the theory one cannot always unambiguously define gravitational energy in a way that applies to the universe as a whole.

Thus, the total energy of the universe is neither conserved nor lost—it is just undefinable. On the other hand, if we abandon the godlike point of view and instead focus on one particle at a time, we can find what many cosmologists believe is a more natural way of thinking of the journey of a photon from a distant galaxy. In this interpretation, the photon does not lose energy after all. The point is that our metaphor of the expanding rubber balloon, though useful to visualize the expansion, should be taken with a



GALAXY REDSHIFT AS A DOPPLER SHIFT

A galaxy's redshift is identical to the Doppler shift an observer would see when watching a police car recede at the same relative velocity as the galaxy—as long as “relative velocity” is interpreted in the appropriate way. First, one must trace the trajectories of the galaxy and of the observer not in space but in spacetime. (In the schematic view here, space is an evolving two-dimensional surface; spacetime trajectories cut through it.) Second, one must compare the velocity of the galaxy at the time when it

emitted the photon (*purple arrow*) with the velocity of the observer at the time when the photon was received (*green arrow*) and then—using the appropriate math derived from general relativity—calculate the relative velocity. The Doppler shift calculated from this relative velocity coincides with the galaxy's redshift, suggesting that the galaxy's redshift can be interpreted as the result of relative motion, rather than of the expansion of space. Therefore, no energy is lost.

grain of salt: empty space does not have a physical reality. As galaxies recede from one another, we are free to consider this relative motion as “expansion of space” or as “movement through space”; the difference is mostly semantics.

Cosmological redshift is usually described as a consequence of the expansion of space. But in Einstein's general relativity, space is relative, and what really matters is a galaxy's history—the trajectory it describes in *spacetime*. Thus, we should calculate the relative velocity of the distant galaxy with respect to us by comparing its trajectory in spacetime and ours. The amount of redshift seen in the galaxy turns out to be identical to the Doppler shift the observer would see in a car that is receding at the same relative velocity [*see box above*].

This happens because in small enough regions the universe makes a pretty good approximation of flat spacetime. But in flat spacetime there is no gravity and no stretching of waves, and any redshift must just be a Doppler effect.

So we can think of the light as making many tiny little Doppler shifts along its trajectory. And just as in the case of the police car—where it would not even occur to us to think that photons are gaining or losing energy—here, too, the relative motion of the emitter and observer means that they see photons from different perspectives and not that the photons have lost energy along the way.

In the end, therefore, there is no mystery to the energy loss of photons: the energies are being measured by galaxies that are receding from each other, and the drop in energy is just a matter of perspective and relative motion.

Still, when we tried to understand whether the universe as a whole conserves energy we faced a fundamental limitation, because there is no unique value we can ever attribute to something called the energy of the universe.

Thus, the universe does not violate the conservation of energy; rather it lies outside that law's jurisdiction. ■

MORE TO EXPLORE

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Misconceptions about the Big Bang. Charles H. Lineweaver and Tamara M. Davis in *Scientific American*, Vol. 292, No. 3, pages 36–45; March 2005.

The Kinematic Origin of the Cosmological Redshift. Emory F. Bunn and David W. Hogg in *American Journal of Physics*, Vol. 77, No. 8, pages 688–694; August 2009.