Questions students ask

Qu: What happens to the energy when a photon is redshifted as a result of the universe's expansion?

Ans: It is conserved: the photon loses energy; the universe increases is PE + KE.

Does the energy change?

more detail

Question:

Considering the Doppler increase (decrease) in frequency for an approaching (receding) light source, does not the energy (which is directly related via $E = h\nu$) also increase (decrease)? If so is this not a violation of energy conservation? What is the source (sink) of the additional (lesser) energy?

Don Sparks, *physics teacher of North Hollywood (CA) high school sent us this question for his student* Dean F 'us. *We are grateful to* George O. Abell *and* E. L. Wright *of the University of California, Los Angeles for the answer below. Dr. Abell is the author of several textbooks, the most recent being the fourth edition of* Exploration of The Universe. *Dr. Wright is a theoretical astrophysicist, and is a principal investigator in the Cosmic Background Explorer satellite, to be launched in the late 1980s.*

Answer:

The change in frequency of the radiation from an approaching or receding light source does indeed change the energy of the photons that make up that radiation. As the questioner points out, the energy of a photon is directly proportional to its frequency. Thus, for example, the light that we receive from a star that is moving away from us is less intense than it would be if the star were at rest with respect to us. In fact, the intensity is even further reduced because each successive photon emitted by the star has farther to travel to reach us, so that the photons entering our telescope are not only reduced in energy, but arrive at a d ased rate.

Nevertheless, there is no violation of the conservation of energy. Suppose the star is radiating with equal intensity in all directions (that is, *isotropically*). Now imagine a large sphere surrounding and centered on the star, and at rest with respect to it (that is, moving along with the star). All of the energy leaving the star eventually passes through that imaginary sphere, and since it is at rest with respect to the star there is no Doppler shift; clearly, the energy is all present and accounted for. But now suppose the sphere to be at rest with respect to us, so that the star is moving within it. An observer at the surface of the sphere

in our direction from the star will observe the same Doppler shift and decrease in energy of the starlight as we do. However, an observer at the surface of the sphere in the opposite direction would see the star approaching him, and its light Doppler shifted to higher frequencies; in other words he would see the starlight *increased* in energy by the same factor that we see it decreased. It is easy to see that if you sum up the starlight crossing the entire sphere all of the effects of the Doppler shifts will cancel, and, again, energy is conserved.

The situation is different if the star is *not* radiating isotropically. Suppose the star acts like a searchlight and collimates all of its radiation into a beam aimed at a distant receiver. Now, radiation has momentum; the momentum of a photon is equal to its energy divided by the speed of light. The momentum carried away from the star in the radiation beam must, by Newton's third law, be balanced by momentum imparted to the star in the opposite direction. The searchlight becomes a rocket engine accelerating the star away from the detector. As the star picks up speed, the detector will find the radiation Doppler shifted to lower and lower energy as time goes on. In realistic circumstances the effect would be small. Even if all of the sun's radiation could be directed in one direction the acceleration imparted to the sun would be less than a ten-billionth of a centimeter per second per second; it would take two days to move the sun its first centimeter, and nearly 50 million years to give the sun a speed of a full kilometer per second. Nevertheless, our hypothetical searchlight would accelerate the star, and in that case the total energy lost to the radiation being detected would be converted to the kinetic energy due to the star's motion.

The Hubble redshift, which results from the expanding universe, causes the total energy associated with the radiation in the universe to continually decrease with time. Energy is still conserved, however, because the energy lost to the radiation reappears in the total energy (potential plus kinetic) of the expanding universe. The effect is unimportant at the present time because the energy in radiation contributes negligibly to the total energy of the universe, but it was important indeed in the very early universe when radiation dominated the energy.