Doppler Shift and the Gravitational Red-Shift

We have seen how Doppler plays an important role in allowing relatively moving observers to determine their velocity with respect to a distant source or with respect to each other. In the chapters ahead, this phenomenon will play an even greater role in helping us discover some of the attributes of gravity and its influence on moving bodies. Implicit in our discussions on Doppler shift is the assumption that various observers have clocks measuring what we have referred to as absolute time. A measurement of frequency generally involves counting how many occurrences of a periodic event occur in a given unit of time, say, a second. Therefore, we can state that a measurement of frequency is basically a measurement of time, or vice-versa. Thus, if we cannot be sure of the rates of our clocks, then we can't be sure about the frequencies we are measuring. If we are unsure of our frequency observations, then we don't know if a particular Doppler shift is due to our relative motion with respect to the source or due to our clocks having the wrong rate and, thus, measuring the wrong frequency.

In special relativity, things become even more complicated. In special relativity, not only may our clocks be inaccurate, but also time itself changes depending on the relative motion of observers. In the Galilean transformation we have been using, time as measured in one reference frame is the same as time measured in another reference frame. The same is true of the lengths of rulers carried by observers in these reference frames. Under special relativity, the lengths of the rulers change, and the dimension of time changes. If you are in motion relative to me, time is running slow for you. Thus, if your clocks are properly calibrated, they will record less elapsed time for a given event than my clocks will.

We will study these important concepts of time and of clock rates in the next few chapters, but we must first develop a little more insight into the Doppler effect as it relates to light. We have already discussed the simplest case of Doppler seen by an observer moving radially toward or away from a source. We must now extend this idea to the case of an observer moving at various angles and directions with respect to a source. We begin with the case of light striking an observer at a direction that, to the observer, appears to be perpendicular to the direction of that observer's motion.

Apparently Perpendicular Incidence and the Doppler Shift

One interesting aspect of our studies is that light striking a moving observer at an angle perpendicular to the direction of motion experiences a Doppler shift due to this motion. Since there is no movement by the observer in the direction of travel of the light pulse, it seems that there should be no Doppler shift. That there is a Doppler shift is attributed in special relativity to the time dilation supposedly incurred by the moving observer. The reason this factor appears in RCM theory is not that time dilation exists, but rather that motion in the direction of the source effectively does occur. The only way to have perpendicular incidence on an observer with no relative motion along the line of travel is if a) the observer is strictly stationary with respect to the source, or b) light's travel time is instantaneous from the source to the observer. Since neither of these is the case, the observer's motion with respect to the source must be taken into account. Specifically, recall that in order for light to be observed it must strike the observer with a relative velocity of c in the observer's frame of reference. It is this requirement that results in the perpendicularly incident Doppler shift as described below.

Imagine that we wish to throw a snowball at a car that is some distance away from us and is moving perpendicularly past us. If we throw the snowball straight toward the car at the instant the car is directly in front of us, we will miss completely. The car will have moved on by the time the snowball reaches the road. If we wish to hit the car, we must "lead" the auto by aiming ahead to the position where the car will be when the snowball reaches the road. We see this pictorially in figure 4-1. If we release the snowball in a manner such as to "lead" the auto at the instant the car is directly in front of us, we can visualize what a passenger in the car will see. From the passenger's perspective, the ball has two velocity components, one in the direction the auto is moving with a speed equal to that of the auto, and another perpendicular to this line heading straight for the car. As the passenger looks out the window, there will be no awareness of any lateral motion to the snowball, since such motion matches the motion of the auto. The passenger will see a ball of ice heading straight toward the car, perpendicular to the motion of the car, at all times. The ball will strike the car with perpendicular incidence (not at any angle), just as if the car had been standing still the entire time.

What does the above have to do with the Doppler shift? The Doppler shift deals with velocity ratios, and the above discussion deals with hitting moving targets--the two seem unrelated. Actually, though, hitting a moving target also has to deal with velocity ratios as well. If we throw a ball at a stationary target at ten miles per hour, it

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will strike the target at that speed. However, if the target is moving as in the case of the car above, some of this velocity will go toward keeping up with the lateral motion of the target. If we look at figure 4-1, we can let each side of the triangle represent a velocity component of the ball. This is often referred to as a vector notation, where one velocity is made up of a combination of two perpendicularly opposed (orthogonal) velocity components. Clearly, the hypotenuse represents the total velocity of the ball, at ten miles per hour. As we stated above, this velocity can be broken into two components, represented by the two legs of the triangle. The leg running in the same direction of the car obviously represents the auto's speed. The remaining leg represents the speed at which the snowball would actually strike the car, in the car's frame of reference. These velocities are related by the Pythagorean theorem such that the sum of the squares of the two legs equals the square of the hypotenuse. Clearly, the speed with which the snowball strikes the car is less than the initial ten-mile-per-hour velocity of the snowball by a factor related to the square of the velocity of the car.

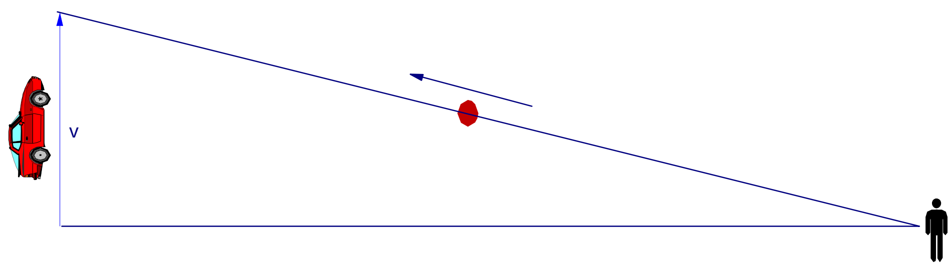
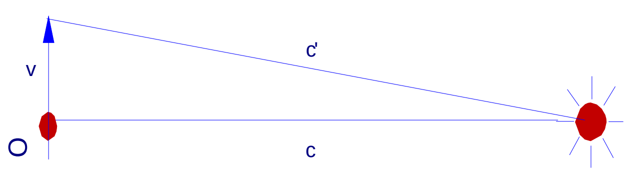


Figure 4-1. In order to hit a moving car with a snowball, you must "lead" the target such that the snowball is moving with the car as well as toward it.

In figure 4-2, we have a situation similar to the snowball fight above. An observer witnessing an explosion is some distance away from the source, traveling up the page at a fixed velocity. The observer is going to measure the frequency shift of that light that passes him at perpendicular incidence. Since the observer is in motion, the total velocity of the light component of interest measured with respect to the source is made up of two components. One of these components is c along the line joining the source and the observer, and the other matches the observer's velocity up the page. Clearly, from the Pythagorean theorem, the total velocity measured with respect to the source is equal to the square root of the sum of the squares of c and the observer's velocity. This light, traveling along the line c', will appear to the observer to be perpendicularly incident, even though it actually is not. Light that actually is perpendicularly incident will appear to strike the observer at an angle, an effect known as aberration, as discussed in a later section. The subtlety of this result, between *actual* perpendicular incidence and *apparent* perpendicular incidence, becomes very important when considering the effects of motion on clocks, as considered in chapter seven.

Figure 4-2 The initial velocity component of light approaching an observer with apparent perpendicular incidence



is greater than c proportional to the observer's velocity by the Pythagorean theorem relation.

Recall from chapter three that all components of light leaving a source have the same frequency, and that the wavelength changes with the velocity to accommodate this. Thus light leaving the source at the higher velocity of c' in figure 4-2 has a longer wavelength such that its frequency with respect to the source is constant. The section on Doppler shift and the determination of velocity demonstrated that the observed frequency is equal to the initial or source frequency times the ratio of the relative velocity of light which the observer sees, c, to the initial velocity of

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the light with respect to the source. This initial velocity, *c'*, is proportional to the square of the observer's velocity by the Pythogorean theorem. Thus the observed frequency is shifted to the red (lower frequencies) by an amount proportional to the square of the perpendicular velocity of the observer as well. The mathematical treatment of this effect results in equations identical to those used in relativity theory for observer velocities much less than *c*, and in solutions indistinguishable from relativity theory by current capabilities for velocities that are not small compared with *c*.

We can gain our first insight as to the effect of motion on clocks by considering again the situation depicted in figure 4-2. We will consider our frequency source to be a clock. Since frequency is defined as cycles per second, then we can simply count the number of cycles to determine how many seconds have gone by. If the frequency of the clock is 300,000 cycles per second, then each time we count that many cycles, one second will have passed according to that clock. By measuring the frequency of the light (or radio waves) received from this clock, we can determine if the clock slows down when in motion. Since the observed frequency is shifted to the red, we will see less than 300,000 cycles in one second, or, it will take longer than one second for that many cycles to pass. It would appear to us that the clock, which is moving with respect to our frame of reference, has slowed down by a factor proportional to the relative velocity between its frame and ours. Thus, from the observer's frame of reference, wherein the observer is stationary and the source, or clock, is moving, the time measured by the observer would be greater than the elapsed time on the frequency clock itself. According to the observer, the apparently moving clock will be running slow so that it takes more than one second to send out 300,000 cycles. Note that time itself has not slowed down in this example, nor has the clock actually slowed. Only the frequency received by the observer has changed, and it has been shifted to the red (lower frequencies) by the factor proposed by Lorentz and Einstein. This is not to say that clocks in motion *don't* actually slow down. That point is reserved for discussion in a later chapter. The point here is simply to distinguish between two distinct effects, 1) perpendicular incidence Doppler shift and 2) the slowing of clocks in motion.

Doppler Shift at an Arbitrary Angle of Incidence

We have seen that for parallel or perpendicular incidence, the value of the Doppler shift is given by the ratio of *c* to the initial velocity of the light component of interest as measured with respect to the source. In the case of parallel incidence (motion directly along the line from the observer toward the source), the initial velocity is simply *c* less the velocity of the observer toward the source. For perpendicular incidence the initial velocity is given by the Pythagorean theorem. We will now consider the more general case of an arbitrary angle of incidence. In figure 4-3, our observer is traveling to the left with a constant velocity. A burst of light is leaving the source, so that it will strike the observer at the angle indicated. It is interesting at this point to again break the motion of the observer into two orthogonal components, the first being along the line of sight to the source, the second being perpendicular to this line. We would expect that we would get two Doppler effects, one due to the parallel motion, the other due to the perpendicular motion. This is in fact what occurs. While one could calculate the effect due to one motion, and then shift the resulting frequency again to account for the other motion, it is easier in practice to simply determine the initial velocity required to ultimately strike the observer with a speed of *c* at the angle indicated. The figure illustrates the relations between *c'*, *c*, the velocity of the observer and the angle of incidence of the light. Once this velocity is determined, the Doppler shift is simply given by the ratio of *c* to the initial velocity as before. The dotted line in the figure represents the angle at which an observer would have to point his telescope in order to see the source. This angle is different from the angle of a line joining the source directly to the observer due to aberration. This effect, addressed initially in chapter three, is analyzed more fully in the next section.

When we compare the formula for the Doppler shift obtained by the above procedure to the formulas of relativity theory, we see that the results are the same for all speeds that are much less than *c*. This, of course, accounts for every experiment that has been performed to date, thus this model is consistent with all observed phenomenon. Even if we consider speeds that are a significant fraction of *c*, the difference between the predictions of special relativity and RCM theory are less than can be measured at the current time.

In the relativistic formula, the effect due to perpendicular motion represents the "time-delay" Doppler, while the effect due to parallel motion represents the standard "Newtonian" Doppler shift. For strictly perpendicular incidence, the "Newtonian" Doppler vanishes, and the only shift is the so called "time dilation" effect. As can be clearly seen, this Doppler effect is due, not to any physical impact on time, but rather to the perpendicular incidence effects already discussed. For motion only along the line from source to observer (as has been demonstrated in many

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of the examples in chapter four), the full Doppler shift is attributable to the "Newtonian" effect, as derived in the section on Doppler shift and the determination of velocity.

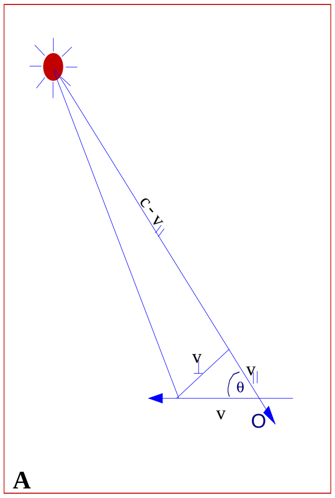

Figure 4-3 *An observer in motion with respect to a source at an arbitrary angle will experience Doppler effects due to motion along the line to the source and due to motion perpendicular to that line.*

In practical tests of these effects, it is important to note that the effects of even a small velocity in the parallel direction vastly outweigh the effects due to perpendicular motion. The reason for this is that the parallel Doppler is directly proportional to the ratio of the velocity to *c*. Since *c* is such a large value compared to the speed of any experimental apparatus, this effect itself can be quite small. However, the perpendicular Doppler is proportional to the square of the ratio of the velocity and *c*. Thus, instead of dividing by 300,000, in this case we are dividing by 90,000,000,000. For this reason, tests for the perpendicular effect are basically limited to observers moving in a circle around a source, or vice versa. In this set-up, the motion can be modeled as being only in the perpendicular direction, since the distance between the observer and the source never changes, and, therefore, there is no parallel component of velocity. As we shall see in a later section, such a test has been performed with results consistent with RCM theory.

Aberration

Aberration is a visual effect similar in nature to the Doppler shift due to apparently perpendicular incidence. We have all experienced this effect in a very real way when walking in a light drizzle. In such a situation, if we are walking slowly, the rain is basically falling straight down, perpendicular to our motion. While our hat or hair and shoulders may get wet, the rest of our body stays relatively dry. Even so, some of us are tempted to run, thus lessening the actual time we spend getting rained upon. However, as we begin to move faster, we also begin to get wetter. The rain which was previously falling straight down in a light drizzle is now heading at an angle toward us, and striking us with greater force. The faster we go, the steeper the angle of attack of the rain drops, and the greater the speed at which they strike our body. Ultimately we arrive at our door, soaked from head to toe on our front side. This change in the angle of incidence in the rain drops is the aberration effect, and the same situation arises with light.

Consider the case of actual perpendicular incidence of a light signal. Unlike the first section of this chapter, we are dealing with light that is raining straight down on our heads. However, due to our motion, the light will appear to

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be coming in from an angle, as in the example of the raindrops. We will imagine ourselves to be viewing a distant star as we sit on the earth, and take the star to be directly overhead while we are moving to the left, as in figure 4-4. We desire to point the long, narrow tube of our telescope along the effective line of sight to the star so that the light strikes our telescope's mirrors and not the walls of the tube. We know that the light that an observer ultimately detects has traveled along the line represented by the hypotenuse of a triangle. The question becomes which triangle? If we imagine the light from the star to be traveling perpendicularly towards us at a constant velocity of *c*, we would expect to point our telescope at the angle indicated in the left portion of figure 4-4. However, according to the RCM theory, the speed of the light ultimately striking the observer must be *c* in the observer's frame of reference. Since this speed is made up of a combination of the observer's velocity and the initial component velocity of the light, the initial speed of the light must be less than *c*. In this case, the angle would be defined by the triangle in the right portion of figure 4-4, where the hypotenuse of the triangle is represented by the velocity *c*. If RCM theory is correct, the result is that the actual angle at which we must point our telescope would be represented by this larger angle.

This effect is fairly easy to observe experimentally. If we are viewing a distant star in a direction perpendicular to the plane of the earth and the sun, then as the earth moves around the sun we will have to tilt the telescope to account for aberration, continually changing the angle with the earth's movement. In January we will point the telescope one way, while in July it will be pointed to the same angle but in the opposite direction. All the while, due to the extreme distance to the star, it is actually effectively straight overhead. It is only the aberration effect which changes the viewing angle, and the required angle is always in agreement with the larger angle of the RCM derivation, not the smaller angle portrayed in the left figure.

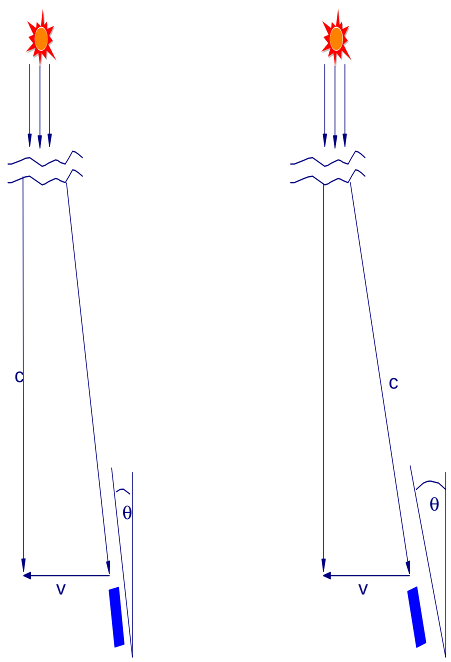

Figure 4-4 The aberration effect due to motion perpendicular to the source requires one to point a telescope at an angle to view a star which is directly overhead. The angle at which we must actually point the telescope and the angle predicted by RCM theory are the same.

The pictorial illustration of this effect given by figure 4-4 is a little misleading. Recall in the example of the snowball that all sides of the triangle represented *velocities*. The same is true in figure 4-4. While the picture seems to imply that we are comparing the distance to the star with the distance moved by the earth in the time it takes the light to arrive from the star, such is not the case. We are actually comparing the velocity of light with the velocity of the observer. Thus the distance to the star matters only to the extent that its distance is many times greater than the diameter of the earth's orbit, thus causing it to effectively be straight overhead at all times. Fortunately, for all stars except our own sun, this is indeed the case. The study of the angle of aberration from distant sources becomes very

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important in comparing some of the cosmological differences between RCM theory and special relativity, and we will return to this topic one more time in the chapter on cosmological considerations.

It is interesting to note that as we increase our velocity, the angle at which we view objects that are actually perpendicular to our line of motion continually increases. Thus objects which appear at slow speeds to be directly beside us will appear to be slightly ahead of us as our speed increases. At just under the speed of *c*, the aberration angle will have increased so dramatically that all objects will appear to be directly ahead of us. At the speed of *c*, we will see only the zero component velocity of light, thus we will be able to witness events only at the instant we cross their path, though we will still be able to see objects behind us. As we pass the speed of *c*, we will be unable to see any event in front of us, as we are traveling too fast to be sensitive to any component of light that may be approaching us. This would cause some very difficult navigation problems for a ship desiring to travel at speeds in excess of *c*, though they are practical problems, not theoretical limitations to possible velocities of physical spacecraft. In fact, the inability of light to reach us from a forward direct also means that no electromagnetic or gravitational effects could reach us either. Since this accounts for the only means by which material particles actually interact, then we shouldn't worry that we can't see what's in front of us when traveling at a speed greater than *c*. We would very likely simply pass through any object in our path as though it weren't even there.

We can derive the Doppler shift equation for light affected by aberration. In this case, the initial velocity of the light is less than *c*, though still related by the Pythagorean theorem to the square of the observer's velocity. Because of this, the shift in frequency is toward the blue or higher frequencies. For low velocities, such as that of the earth about the sun, this shift in frequency is very small, and, as we saw in a previous section, is dwarfed by other factors such as any component of motion directly along the line joining the source and the observer. The next section will clarify how insignificant the perpendicular and aberration Doppler effects are in almost all practical applications.

The Practical Differences Between RCM and Relativistic Doppler

The Doppler shift in light and radio frequencies is a valuable tool in tracking the velocities of objects ranging from cars to spacecraft to distant galaxies. Since the formula we have derived in the section on Doppler shift at an arbitrary angle of incidence differs slightly from the relativistic formula, we must determine what impact that has on velocity determination in general. We will find that, within the limits of experimental error, the predictions of RCM theory are in complete agreement with relativity theory and observation.

For speeds which are very low compared to *c*, such as an automobile or a plane, the perpendicular motion effects can be ignored completely. As we saw above, when trying to measure these effects at such slow speeds, even the random motions of the atoms within the material make the results immeasurable. In this case, then, the maximum Doppler effect would be experienced by a plane or automobile moving directly away from or towards us. We can perhaps measure the velocity of an automobile to any arbitrary degree of precision, since it is moving on the ground and its location can be very accurately determined. However, the speeds involved for an automobile are only an insignificant fraction of *c*. In this case, the relativistic "time-dilation" factor reduces to one--there is no such effect at these speeds, and the relativistic Doppler equations look exactly like the equations for sound. The same holds true for RCM theory, and the equations are identical. As we move on to the case of a plane, the speeds increase, but the means of measuring these speeds become less precise. In fact, the only way to accurately measure the velocity of a plane is to use the very Doppler effect which we are trying to validate. Even so, at such speeds, and at any angle we choose, the difference between RCM theory and relativity theory is so small as to be lost in the experimental determination of the velocity. The same unfortunately holds true for spacecraft and planetary orbits. While the velocity of and distance to the various planets is accurately known, the expected difference between the relativistic and RCM Doppler equations is still well below the limits of experimental precision. To see this more clearly, we will consider an actual example, in the case of the planet Mars.

Mars orbits the sun at a velocity of roughly sixty kilometers per second. If we ignore the effects produced by the sun, we could imagine that, on opposite sides of their orbits, the earth and mars have a velocity relative to one another of around one hundred kilometers per second. We can further imagine that these two planets have perfectly circular orbits, and therefore state that this motion is completely transverse. In this unlikely scenario, the only Doppler effect we need concern ourselves with would be that due to perpendicular incidence. We are interested in using the measured shift in frequency from a signal bounced of mars and returned to earth to measure the relative velocity of the two planets. Since the equations in the two formulas differ slightly, the speeds predicted from a given measured frequency shift would also differ. If the difference is great enough to be incompatible with other methods of calculating the velocity of these planets, then we could determine a preference for one method over the other.

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Since the frequency shift is a function of velocity and not of the source frequency, we can use any signal we like. The difference in calculated velocity will simply be related to the ratio of the two formulas for Doppler shift. When the calculation is carried out, for any particular frequency we choose, the difference in the calculated velocity between the two planets is about one part in twenty million. This means that for our assumed relative velocity of one-hundred kilometers per second, the discrepancy between the two formulas amounts to a difference of about five millimeters per second. Remember that we have also assumed that there is no velocity along the lines joining the planets, which of course there is, and the sun has no effect on these signals, which, as we will see, it does. Thus, even in the case of hypothetical, purely circular orbits for fast moving planets, the predicted velocities from each theory are so close as to be indistinguishable, and undetectable within the limits of experimental error.

There is one other area where we can view high speed objects, some of which even attain speeds which are a significant fraction of *c*. As we saw in chapter three, Edwin Hubble discovered that almost all distant galaxies are moving rapidly away from us. The further their distance, the greater their speed. As we move out an estimated five billion light years or so, the galaxies take on velocities that are a significant fraction of *c*. This is very fast indeed. Additionally, this velocity can be basically considered as being directly away from us along a line joining the galaxy to the earth. Here we can see a definite difference between the velocities predicted by relativity theory and those predicted by RCM theory. The "time-dilation" term of relativity theory still applies, and, due to the great velocities involved, is no longer dwarfed in its effect by the radial velocity. The RCM theory, on the other hand, only experiences such an effect when transverse motion is involved. In the case of distant galaxies, this motion can be ignored. Thus RCM theory reduces, basically, to the standard Newtonian Doppler equations, while relativity has a large time dilation effect. Thus, if, according to the relativistic model, a distant galaxy is traveling at one-tenth of *c*, or 30,000 km/sec, then, according to RCM theory, that galaxy has a velocity of about ninety-five percent of this, or 28,500 km/sec. If we could then obtain an independent measure of this velocity, we could confirm preference for one theory over the other. What is required for an independent determination of the velocity is an accurate estimate of the distance to the galaxy, as well as a very specific value for the Hubble constant--the rate of increase in velocity with distance. Unfortunately, the Hubble constant has not been determined to anywhere near the precision required to resolve such a difference in velocities. The Hubble constant, in fact, is known only to a precision on the order of plus or minus fifty percent of the accepted value. Further, the only means we have for determining the distance to such remote galaxies is by applying the Hubble relation in reverse to the red-shift obtained. Our measure of distance is based on the same equation we use to determine velocity. However, as we shall see in chapter ten, there are other cosmological tests of special relativity that can be used to refute or confirm that and many other theories.

The Gravitational Red Shift

If light originates on the surface of the sun at a certain frequency, then as that light moves away from the sun its frequency will decrease somewhat proportionally to its distance. The frequency decreases as the effect of the gravitational field drops off. At a certain distance, the effects of the gravitational field become negligible and the frequency stabilizes at a lower level. We could also begin with a photon (a unit of light) far away from the sun and heading toward it. As it moves deeper into the gravitational field of the sun, its frequency will increase. The effect is known as the gravitational red-shift whether the photon is moving away from the field or toward it, even though the frequency is actually blue-shifted as the photon heads deeper into a gravitational field. The question, of course, is what causes this effect. To answer this, we must first draw on the results of a later chapter and state that the frequency of a photon is equal to its energy divided by a very small number known as Planck's constant. This number is named after Max Planck, who discovered that light is emitted and absorbed by a material only with very specific energy levels, and then was able to derive the relation between these energy levels and the frequency of the light involved.

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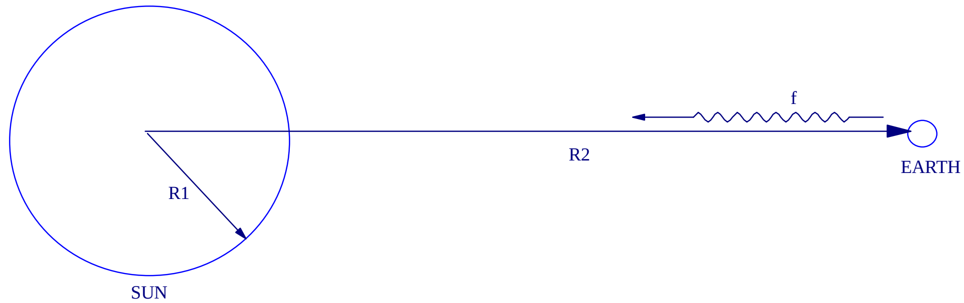

Figure 4-5 As a photon approaches the surface of the sun, its frequency is shifted to the blue or higher frequencies, due to the energy acquired in falling through the gravitational field.

Imagine a photon far removed from the sun, as in figure 4-5. The frequency of this photon is then simply its inherent energy divided by Planck's constant. As the photon approaches the sun, its energy with respect to its surroundings increases, in the same manner that a ball dropped from a tower gains energy as it heads toward the ground. Now, since a photon is pure energy, when it acquires additional relative energy in falling through a gravitational field, this increase in energy must effect a change in frequency. This is different from the case of a ponderable mass, such as the falling ball just described. In the case of a mass, the increased energy is in the form of kinetic energy, which is acquired and dissipated without an actual change in the mass of the object. As soon as the ball hits the ground and comes to a stop, all its acquired kinetic energy is lost in various forms such as heat, and the ending mass of the ball remains equal to its beginning mass. The only way for a photon to acquire excess energy is, by its very nature, to change its frequency. A mass in motion has energy equal to its inherent energy, given by mc^2, plus its kinetic energy, given by one-half its mass times its velocity squared. This kinetic energy term is flexible, requiring only a change in the velocity of the mass to change its total energy. A photon's energy, however, is expressed only by Planck's constant times its frequency, therefore, a change in energy must be accompanied by a change in frequency. For this reason, the frequency of the photon measured locally within the gravitational field will appear to have increased due to its fall through the field. The frequency is still equal to the energy divided by Planck's constant, but, since the relative energy has increased, the locally measured frequency must increase as well. Thus the frequency of the light is shifted to the blue. For a photon leaving the sun, the relative energy of the photon decreases, and therefore the observed frequency of the light is shifted to the red. The results of this analysis and the equations thus obtained in RCM theory are consistent with the results obtained in relativity theory.

We are immediately left with a relativistic type question. When we say the photon’s energy increases in falling through a gravitational field, we must ask: Increases with respect to what? We know the photon’s energy can’t increase with respect to itself, as this is a meaningless statement. Thus, the photon’s energy must increase as compared to its overall surroundings. As we will see in chapter seven, due to the principle of equivalence, the frequency, or energy, of a photon in free-fall is conserved and must remain constant in its own frame of reference. However, due to reasons similar to those just discussed, clocks in a gravitational field will run slow. Thus, the frequency as measured with these slower running clocks will indeed appear to have increased, and by the amounted anticipated by the above discussions.

Note that the gravitational red-shift effect is due only to conservation of energy principles. Even in relativity theory, the red-shift is due only to energy considerations, and not to the Einstein's second postulate, the Lorentz transformations, or any other property of relativity theory. We will see in chapter seven how the principle of equivalence combines with these energy considerations to accommodate the slowing of clocks in a gravitational field. As we saw in chapter two, the principle of equivalence can be attributed to Galileo, who saw such a principle as almost intuitively obvious. The reason this is important is that the search for the gravitational red-shift is considered to be one of three fundamental tests of general relativity theory; the other two being the deflection of light in a gravitational field and the anomalous advance in the perihelion of mercury's orbit. Each of these will be dealt with later. The critical point here is that one of the three classical tests of the general theory is not even attributable to the effects of relativity at all.

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The gravitational red-shift will appear several times throughout the rest of this book. An interesting aspect of this frequency shift is that it can be countered by a motion induced Doppler shift. Thus, even though the effect was shown to be derivable from energy considerations alone, the effect is the same as if we had somehow changed the component velocities of the light wave, or in some manner made the velocity appear to have changed. Thus we should be able to exactly offset a gravitational red-shift by moving the observer toward the source at a velocity that would cause a blue-shift of the same magnitude. This intimacy between actual and measured or apparent velocities and gravitational effects will be developed more fully in discussions on clocks in a gravitational field, the effects of gravity on a moving observer, and the effect of gravity on the speed of a light signal passing near the sun. But first, we will review an experiment that confirmed the relation between the gravitational red-shift and motion induced Doppler performed at Harvard University in the sixties.

The Pound-Rebka-Snyder Experiment

Measurements of the gravitational red-shift of light leaving the surface of the sun and other stars have been inconclusive due to the effects of a large number of other factors. It is generally accepted that there is indeed a red-shift, but determining its exact value experimentally has proved difficult, leaving a wide margin for error.

In 1960 at Harvard University, Robert Pound and Glen Rebka devised and carried out an experiment to test for the effects of the gravitational red-shift near the surface of the earth. As with the rotor Doppler experiments, they required an extremely stable transmitter and receiver, and therefore exploited the Mossbauer effect. The results of the experiment we are about to investigate were cited as one of the contributing factors to the award of the 1961 Nobel prize in physics to Rudolph Mossbauer in 1961.

The way the experiment was performed was to place the transmitter at the bottom of the Jefferson Physical Laboratory. The receiver was then placed further up the tower at a distance of 22.5 meters. Over such a short distance, the gravitational field, which varies as the distance from the center of the earth, can be considered as constant. As the transmitted signal climbs through this constant gravitational field, it will be shifted toward the red, or lower frequencies, as a result of the gravitational red-shift. The Mossbauer emitter releases gamma rays of a very specific frequency. Since the receiver expects to see the same frequency as was emitted, it will, in theory, be unable to detect a shifted frequency. In actuality, as accurate as this frequency source is, there is still a very slight spread in the transmitted and absorbed frequencies. Thus, instead of no reception, the receiver will obtain a weak signal due to the shift in the bulk of the transmitted frequencies.

Rather than try to measure this shift directly, we can devise an experiment whereby the detector is placed in motion toward the source at a velocity such that the blue shift (increase in frequency) induced by that motion exactly cancels the gravitational red shift (decrease in frequency). If we adjust the velocity of the detector to the right value, the received signal will strengthen. By setting the velocity such that the maximum signal intensity is obtained, we can be sure that the motion induced blue-shift exactly matches the gravitationally induced red-shift. In order to calculate the velocity required by the receiver, we need to know the acceleration due to gravity at the surface of the earth, the height of the tower, and the speed of the light component along its entire path. Fortunately, over such a short distance in the gravitational field of the earth, the velocity of the component of light of interest does not change appreciably from c. In fact, the initial component is slightly greater than c, and slows to c during its climb, but the effect on this changing velocity on trip time is so small as to be well below the limits of experimental error, and, therefore, plays no role in the analysis of this experiment. Fortunately, as small as the change in velocity is, the shift in frequency thus obtained is very noticeable to the gamma-ray detector, and we do need to place the receiver in motion to offset this effect.

It turns out that the speed required by the receiver is the same speed that would be obtained by any object climbing the height of the tower at a velocity of c. This speed is equal to the acceleration due to gravity times the height of the tower divided by c, and works out to roughly 7.3×10^{-7} meters per second, or seven ten-thousandths of a millimeter per second. Obtaining this low of a velocity with accurate control is an engineering marvel in itself, but it was done quite effectively by the Harvard team. When the receiver was placed in motion at this speed, the received signal strength did indeed reach a maximum, and the gravitational red-shift was confirmed. This experiment was repeated several times, sometimes with the receiver at the top of the tower, and sometimes with the emitter so placed. The successful results of this experiment were published in the April first issue of *Physical Review Letters* in that same year.

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While the experiment was touted as a confirmation of one of the three classical tests of general relativity, it is clear from the previous section that this was simply a confirmation of the principle of conservation of energy as it relates to a photon in free-fall in a gravitational field. This principle, of course, carries as much weight in RCM theory as it does in relativity theory, but the results to be obtained from a test of this principle alone are identical in both theories. Nevertheless, the experiment ranks among the best in its use of state of the art technology and experimental design and execution. Sixteen years after the Pound-Rebka experiment, another test of the gravitational red-shift was performed using atomic clocks and a Scout D rocket. This experiment tested not only the gravitational red-shift, but also the so-called relativistic time-dilation of the special theory. We will study this experiment in chapter seven when we explore the effects of motion on clocks. But first we must return to the test that started it all--the search for the motion of the earth through the aether using interferometers performed by Michelson and Morley at the close of the nineteenth century.

Note that the Pound-Rebka effect must be due only to the differing clock rates, and not at all due to an actual change in photon energy, or the effects would compound and be double what is actually observed.