Cosmic Chemistry: Cosmogony

The Doppler Effect – Are you coming or going?

Student Text

The Doppler effect, discovered by the Austrian scientist Christian Doppler in the 19th century, is a phenomenon of fundamental importance to astronomers, although it finds applications in more mundane areas as well. It applies to wave motion: sound waves, light waves, or even waves on water. You have experienced the consequences of the Doppler effect if you have ever listened carefully to the sound of a siren or high-pitched racecar engine as it approaches and then recedes from you. You will have noted that the pitch (frequency) of the sound increases as the source of the sound approaches you and then decreases as source moves away.

The physics behind this is easy to understand. Sound consists of a series of traveling compressions and rarefactions of air pressure, which the physicists call longitudinal or compressional waves. When the compressions (wave crests) impact on your eardrums, they are perceived by your auditory nerves and a message is sent to your brain that you interpret as sound. The more closely spaced the wave crests, the higher the sound frequency and Christian Doppler vice-versa. Carefully distinguish between pitch and loudness. Pitch has to do with the frequency with which the wave crests hit your eardrums, and loudness is a physiological response that has to do with how hard the wave crests bang into your eardrums.

As a sound source approaches, the waves ahead of the source get shoved together, giving rise to an apparent increase infrequency or a higher pitch as the intervals between wave crests diminish. As the sound source moves away, the waves are farther apart and the sound drops in pitch. These are called Doppler shifts.

Note that the same phenomenon would apply if a stationary source was emitting a sound and you were moving quickly toward the source. Because of your motion, the frequency with which your eardrums encounter a wave crest would increase, and the apparent pitch of the sound would increase. If you were moving away from the source, the frequency would decrease.

The ideas above may be expressed mathematically and exact calculations of apparent pitch can be calculated.

The mathematical relationships describing the Doppler shifts for sound are as follows:

For a moving source:

F2=F1V/(V±vs) (F2 equals F1 times the absolute value of V divided by V plus or minus vs) where F2 is the apparent or observed frequency, F1 is the true frequency of the sound source, V is the speed of sound, and vs is the speed of the source. Use the negative sign if the source is moving toward the observer and a positive sign if the source is moving away.

For a moving observer: F2=F1[(V±vo)/V], (F2 equals F1 times the quantity V plus or minus vo divided by V) where F2, F1, and V have the same meaning as above, vo is the speed of the observer and the negative sign applies if the observer is receding from the source.

Scientists have learned that electromagnetic radiation emitted by a moving object also exhibits a Doppler effect highly comparable to that observed for sound. After all, electromagnetic radiation is just another wave phenomenon. Electromagnetic waves moving toward an observer are squeezed together, their frequency appears to increase, and is therefore said to be “blue shifted.” Similarly, if an object is moving away from an observer, light emitted by the object is stretched, the frequency decreases, and is said to be “red shifted.” Doppler shifts of radiation emitted by stars and other celestial objects are invaluable in determining the movement of the objects with respect to our location in space. Historically, most astronomical research involved visible light, but today, virtually all parts of the electromagnetic spectrum are used to investigate Doppler effects. Because of the inverse relationship between frequency and wavelength of light (remember f=ν/λ, where f, ν, and λ represent frequency, the velocity of light, and wavelength, respectively), we can describe the Doppler shift for light in terms of wavelength instead of frequency. Radiation is blue shifted when its wavelength decreases, and red shifted when its wavelength increases. That is to say, if an object is receding, the wavelength is shifted to a higher value, a red shift. If an object is approaching, the wavelength shifts to a lower value, a blue shift. In astronomy, scientists refer to longer-wavelength radiation as “redder” and shorter-wavelength radiation as “bluer,” than the original spectral line. The terms “red shift” and “blue shift” do not relate to actual colors except for the very narrow visible part of the spectrum.

Astronomers can use red shifts and blue shifts to calculate exactly how fast stars and other objects move toward and away from Earth. An oft-quoted example involves the spectral lines (i.e. light) emitted by hydrogen gas in distant galaxies [see Cosmic Chemistry, Sun and Solar Wind]. An important spectral emission line for hydrogen is found in labs here on Earth at a wavelength of 21 cm. The 21 cm line is the spectral position of the line, or a measure of the energy the photons have. If a cosmic source of hydrogen emits this spectral line and it is subsequently observed at 21.1 cm on Earth, we would call this a red shift of 0.1 cm. This shift would indicate that the source is moving away from us at more than 1,400 kilometers per second.

The mathematical relationship that applies is:

Vo = (Δλ/λ)c, (Vo equals the quantity delta lambda divided by lambda times c) where Vo is the velocity of the light source, λ is the wavelength if the source were standing still (i.e. the wavelength at the source), Δλ is the change in wavelength arising from the motion of the source, and c is the velocity of light.

This equation assumes that the velocity of the source is much less than the velocity of light. Also, note that, unlike the Doppler shift for sound, it does not matter whether the observer or the source is in motion. One needs to know only their relative velocities. It should be mentioned here that shifts in wavelength can arise not only from relative motion. Two other phenomena can come into play, both arising from Einstein’s general theory of relativity. The first is the Gravitational Redshift that is associated with strong gravitational fields. The other is the Cosmological Redshift, which arises from the stretching of space subsequent to the Big Bang. Most stellar objects are red shifted, implying that the universe is expanding.

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Student Reporting Data Sheet

1. Slinky Redshift Demo

Hold one end of the slinky and have another person hold the other end and stretch it between you. This represents a light wave. Have a third person use their hand to push part of the wave toward you. What happens to the wavelength as it moves toward you? Feel the change in the slinky as it moves toward you.

Now have them push the wave away from you. What happens to the wavelength as it moves away from you? Feel the change in the wavelength as it moves away from you.

How does this translate to light waves? How does it affect what we see?

Questions

a). Refer to the student handout, Figure 1. Spectrum A represents a possible spectrum of a star not moving toward or away from Earth. Spectra B and C show what would happen if the same star were moving with respect to the Earth. Compare the three spectra and answer the following questions:

i. Which spectrum is that of a star moving toward Earth? \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

ii. Which spectrum is that of a star moving away from Earth? \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

iii. Explain your answers using the terms blue shift and red shift.

b) Refer to the student handout, Figure 2. This is the spectrum of quasar 3C 273 showing four visible spectral lines of hydrogen. The arrows show how the lines are shifted by the motion of the quasar relative to Earth. Is the quasar moving toward or away from Earth? Explain your answer in terms of red or blue shifts.

c) Refer to the Spectral Data Sheet, Figure 3. This series of emission lines have been observed in galaxies having varying distances from Earth. The spectra have been redrawn from actual spectra of hydrogen measured in a laboratory to enhance their clarity. What conclusions about the motion of distant galaxies might be drawn from these observed astronomical spectra?

d) Assume that there is a distant galaxy speeding away from Earth at a speed of 3500 km/sec. If a hydrogen atom in this galaxy emits electromagnetic radiation having a wavelength of 21 cm, what wavelength will the radiation have when it is received on Earth? Question: Would the radiation be blue or red shifted? Calculate the wavelength.

e) Assume that in a distant galaxy an atom emits green light having a wavelength of 500 nm (nanometer abbreviated – 109 meter) and assume that this galaxy is moving relative to Earth. Determine the minimum velocity with which the galaxy would have to be moving for the green light to be shifted out of the range of human vision. The human eye can detect light/radiation with a wavelength of 400-800 nm. Question: In which case would the velocity have to be greater for the light to be shifted out of the range of human vision: if the galaxy is moving toward Earth or away from Earth? Calculate the velocity.

f) Refer again to Figure 2 on the Spectral Data sheet and estimate the speed of quasar 3C 273 relative to Earth.

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Student Handout

Spectral Data Sheet

Figure 1

This figure shows three absorption spectra. Spectra A has three absorption lines in the yellow part of the spectrum. Spectra B has the same three lines but they are in the orange part of the spectrum. Spectra C has the same three absorption lines but they are in the blue part of the spectrum.

Figure 2

This figure is a spectral graph of an emission spectra. The y axis is intensity and the x axis is wavelength in 10 to the minus 5 cm units. Four hydrogen emission lines are marked, as well as how much they have shifted. This is done by showing where the H line would be at rest as well as where it is for this object. The four H emission lines are described below. The units are wavelength, 10^-6 cm.

The Ha at rest line is at 6.6 and the Ha emission line is at 7.6

The Hb at rest line is at 4.9 and the Hb emission line is at 5.6

The Hg at rest line is at 4.4 and the Hg emission line is at 5.1

The Hd at rest line is at 4.1 and the Hd emission line is at 4.8

Figure 3

This figure shows five galaxies absorption spectra. Their distances and redshift are given.

Virgo galaxy: 78,000,000 light years, 0.0040 redshift

Ursa Major galaxy: 1,000,000,000 light years, 0.050 redshift

Corona Borealis galaxy: 1,400,000,000 light years, 0.073 redshift

Bootes galaxy: 2,500,000,000 light years, 0.13 redshift

Hydra galaxy: 3.960,000,000 light years, 0.20 redshift