IB Physics Topic C5 The Doppler Effect; SL & HL

By timthedev07, M25 Cohort

Table of Contents

1 The Doppler Effect for Sound

The Doppler effect is a change in observed the frequency and wavelength of a wave that arises from relative motion between the source and the observer. In the following parts we will look at how one can compute the shifted frequencies; it must be noted, however, that these only hold for low speeds, below $0.2c$. Otherwise, one must use the relativistic Doppler effect, which is not covered.

1.1 Case I: Stationary Observer, Moving Source

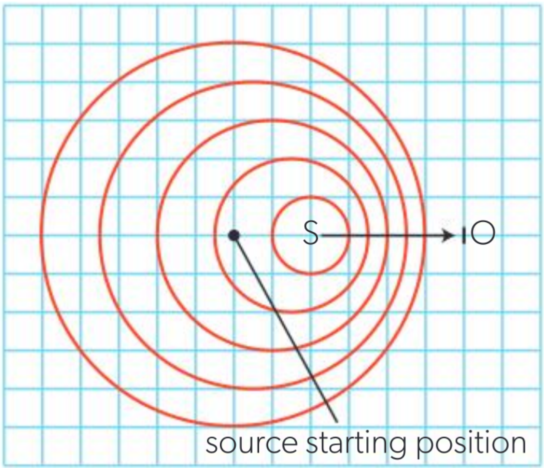

Figure 1: Moving towards the observer

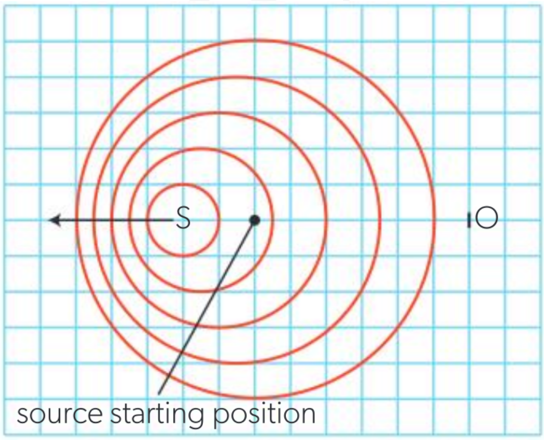

Figure 2: Moving away from the observer

- In the first sub-case, where the source is moving towards the observer at speed u_s, the the observed frequency is higher, as the wavefronts are compressed. The formula for the shifted frequency is given by the following, **where v is the wave speed**

$$f' = f\left(\frac{v}{v - |u_s|}\right) > f \tag{1}$$

- In the second sub-case, where the source is moving away from the observer, the observed frequency is lower, as the wavefronts are stretched.

$$f' = f\left(\frac{v}{v + |u_s|}\right) < f \tag{2}$$

1.2 Case II: Moving Observer, Stationary Source

When the source is stationary and the observer is moving, there are also shifts in the observed frequency.

- If the observer is moving towards the source, the observed frequency is higher, as it will cross more wavefronts in a given time than if it were stationary.

$$f' = f\left(\frac{v + |u_o|}{v}\right) > f \tag{3}$$

- Inversely, if the observer is moving away from the source, the observed frequency is lower, as it will cross fewer wavefronts in a given time.

$$f' = f\left(\frac{v - |u_o|}{v}\right) < f \tag{4}$$

1.3 The Combined Effect

The complete equation that encapsulates both cases is given by

$$f' = f\left(\frac{v \pm |u_O|}{v \pm |u_S|}\right) \tag{5}$$

where

- f is the frequency of the source
- f' is the observed frequency
- v is the wave speed
- u_O is the velocity of the observer
- u_S is the velocity of the source

The ones discussed before are just special cases of this general relation.

2 The Doppler Effect for Light

The previous analysis does not apply to light for the following reasons:

- E.M. waves do not require a medium
- Light travels at the same speed in all frames of reference, but this is not the case with sound.
- In special relativity, there is no such concept as a source and an observer, as all motion is relative. Thus, only the relative velocity between the source and the observer matters.

When Δu, **the relative velocity between the two is much less than the speed of light**, we may use a relation that is modified by

- substituting the speed of light for the wavespeed
- using the relative velocity between the source and the observer, denote it as Δu

Eventually we arrive with the relation

$$f' = f\left(1 - \frac{\Delta u}{c}\right) \tag{6}$$

If we denote the change in frequency as $\Delta f = f - f'$, we can rewrite the equation as

$$\Delta f = f\frac{\Delta u}{c} \iff \frac{\Delta\lambda}{\lambda} = \frac{\Delta f}{f} = \frac{\Delta u}{c} \tag{7}$$

2.1 Stellar and Galatic Motion

The Doppler effect is used to determine the motion of stars and galaxies.

Observe the light spectra of light emitted by a star at two distinct timestamps.

- If the most recent one's spectra lines are shifted toward the blue terminal of the spectrum, which represents a blue shift (increase in frequency and hence decrease in wavelength), the star is moving towards the observer.

- If the most recent one's spectra lines are shifted toward the red terminal of the spectrum, which represents a red shift (decrease in frequency and hence increase in wavelength), the star is moving away from the observer.

3 Applications of the Doppler Effect

3.1 Blood Flow Measurement

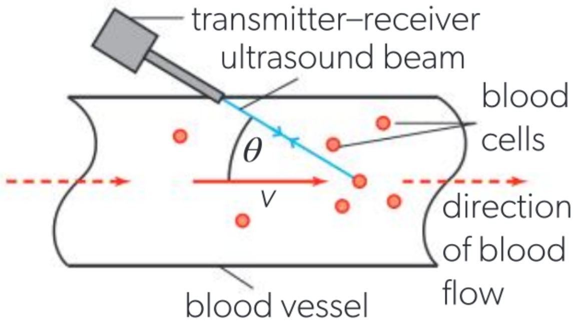

Figure 3: Blood flow measurement

$$\frac{\Delta f}{f} = \frac{2u\cos\theta}{v} \tag{8}$$

where

- u is the speed of the blood (wrong in the diagram)
- θ is the angle between the direction of the blood flow and the direction of the sound wave
- v is the speed of sound in the blood

3.2 RADAR

This includes the following applications:

- flow measurements, e.g. medical, rain cloud speed measurements, weather forecasting
- vehicle speed determinations (police speed traps)
- remote sensing of ocean currents
- measurement of turbulence in river and ocean flow