

THEME C · WAVE BEHAVIOUR

SL & HL ≈ 25 min read

IB Physics C.5 Doppler Effect — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). SL and HL students both need the wavefront picture, the light equation $\Delta f/f = \Delta\lambda/\lambda \approx v/c$ and red-shift/blue-shift. C.5 also has **additional HL content**: the exact Doppler equations for sound and other mechanical waves, shown in the purple HL box.

 SL C.5 questions HL C.5 questions Flashcards Doppler effect simulation

What this page covers

- ✓ What the Doppler effect is, for sound waves and for electromagnetic waves
- ✓ Wavefront diagrams for a moving source and for a moving observer
- ✓ The fractional change in frequency or wavelength of light, $\Delta f/f = \Delta\lambda/\lambda \approx v/c$, when the relative speed is much less than c
- ✓ How red-shifted and blue-shifted spectral lines tell us how stars and galaxies move
- ✓ (HL) The observed frequency of sound and other mechanical waves for a moving source, $f' = f \frac{v}{v \pm u_s}$
- ✓ (HL) The observed frequency for a moving observer, $f' = f \frac{v \pm u_o}{v}$, and finding the speed of the source or observer
- ✓ Uses of the Doppler effect: radar speed measurement and Doppler ultrasound in medicine

In one minute

- The Doppler effect is the change in observed frequency when a wave source and an observer move relative to each other. The source itself keeps emitting the same frequency.
- Approaching → higher observed frequency. Receding → lower observed frequency. A moving source (and any relative motion, for light) also changes the wavelength: shorter when approaching, longer when receding.
- A **moving source** bunches the wavefronts up ahead of it and spreads them out behind: the wavelength in the medium changes. A **moving observer** meets the unchanged wavefronts more or less often.
- For light with $v \ll c$: $\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$. A red-shift (λ increases) means the body is moving away; a blue-shift means it is approaching.
- HL: for sound, $f' = f \frac{v}{v \pm u_s}$ (moving source) and $f' = f \frac{v \pm u_o}{v}$ (moving observer). Choose the sign that makes f' larger when they approach.

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What is the Doppler effect?

The Doppler effect is the change in the observed frequency of a wave when there is relative motion between the source of the wave and the observer.

- When the source and observer **approach** each other, the observed frequency is **higher** than when they are at rest.
- When they **move apart**, the observed frequency is **lower**.
- The observed wavelength also changes (shorter when approaching, longer when moving apart) when the source moves, and for light whichever body moves. For sound with only the observer moving, the wavelength in the air is unchanged (see below).
- The frequency that the source *emits* does not change. What changes is the number of wavefronts that reach the observer each second.
- The everyday example: the pitch of a siren or a car engine is higher as it comes towards you and drops as it passes and moves away.
- Only the component of velocity along the line joining source and observer matters. Motion at right angles to that line produces no Doppler shift.

Sound waves and electromagnetic waves

The Doppler effect happens for every kind of wave, but there is an important difference between mechanical waves such as sound and electromagnetic waves such as light.

	Sound (mechanical waves)	Light and other EM waves
Medium	needs a medium (air, water, tissue); the wave speed v is fixed relative to the medium	no medium needed; speed c is the same for every observer (A.5, HL)
What matters	whether the source or the observer moves relative to the medium — the two cases give different results	only the relative velocity of source and observer
Equation in this course	HL only: $f' = f \frac{v}{v \pm u_s}$ or $f' = f \frac{v \pm u_o}{v}$	SL and HL: $\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$ for $v \ll c$
Typical examples	sirens, passing trains, Doppler ultrasound of blood flow	red-shift of galaxies, rotating stars, radar speed guns

TRY IT YOURSELF

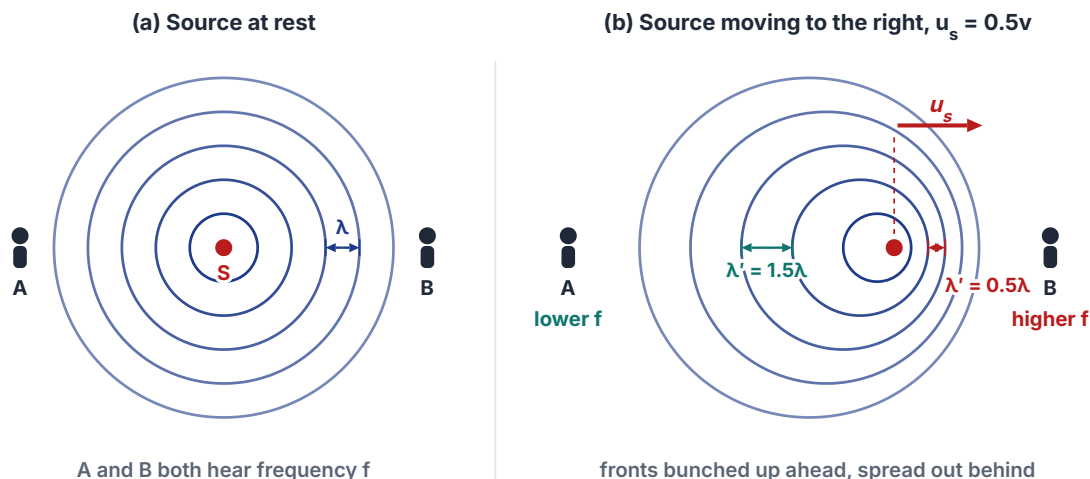
C.5 Doppler Effect simulation: move the source or the observer, change the speed and watch the wavefronts bunch up ahead and spread out behind.

How do wavefront diagrams explain the Doppler effect?

A wavefront diagram shows successive crests as lines, one wavelength apart. For a point source at rest they are concentric circles, and every observer receives the same frequency f and wavelength λ .

Moving source

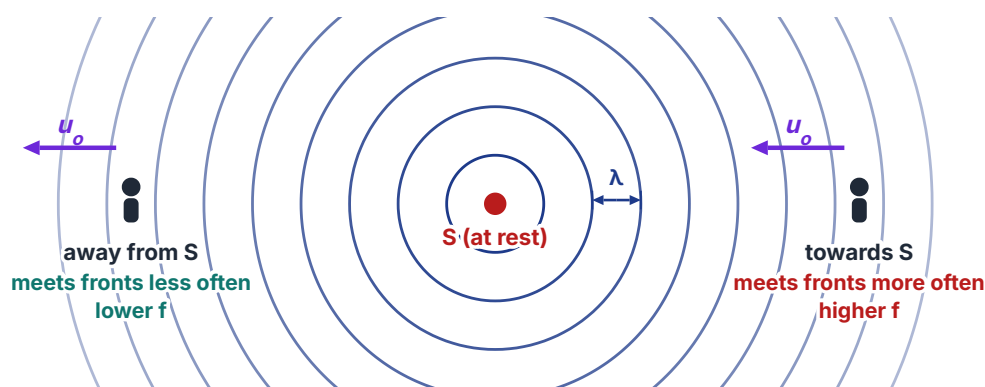
- Each wavefront spreads out at the wave speed v from the point where the source was **when it emitted that front**.
- Between emitting one front and the next (one period T), the source moves forward a distance $u_s T$. So the circles are no longer concentric: their centres move along with the source.
- **Ahead** of the source the fronts are closer together: the wavelength is shorter, $\lambda' = \lambda - u_s T$. The waves still travel at v , so more fronts arrive each second: the observed frequency is higher.
- **Behind** the source the fronts are further apart: $\lambda' = \lambda + u_s T$, and the observed frequency is lower.



Wavefronts drawn to scale, five periods after the source started emitting. (a) Source at rest: concentric circles, wavelength λ in every direction. (b) Source moving at half the wave speed: the wavelength is 0.5λ ahead of the source and 1.5λ behind it.

Moving observer

- When the source is at rest, the wavefronts are concentric circles and the wavelength in the medium is unchanged.
- An observer moving **towards** the source runs into the fronts: the speed of the waves relative to the observer is $v + u_o$, so more fronts are met each second and the observed frequency is higher.
- An observer moving **away** meets them less often (relative speed $v - u_o$), so the frequency is lower.
- The key contrast: a moving source changes the **wavelength**; a moving observer changes the **relative speed** of the waves. Both change the observed frequency.



λ is the same everywhere: the observer's motion changes only the rate at which wavefronts are met — speed of the waves relative to the observer is $v \pm u_o$

A stationary source S. The wavefronts are unchanged by the observers' motion. The observer moving towards S crosses wavefronts more often than once per period; the observer moving away crosses them less often.

EXAM TIP — EXPLAINING WITH WAVEFRONTS

A full “explain” answer for a moving source has three steps: (1) the source moves between emitting successive wavefronts, (2) so the wavefronts are closer together ahead of it — the wavelength is shorter, (3) the wave speed is unchanged, so by $v = f\lambda$ the observed frequency is higher. Saying only “the waves are squashed” rarely earns full marks.

How is the Doppler effect for light calculated?

For light (or any electromagnetic wave), when the relative speed v between source and observer is much smaller than the speed of light c , the fractional change in frequency and in wavelength are equal in size and approximately v/c .

$$\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$$

- Δf = change in frequency (Hz), f = emitted frequency (Hz), $\Delta \lambda = \lambda_{\text{observed}} - \lambda_{\text{emitted}}$ (m or nm), λ = emitted wavelength.

- v = relative speed of source and observer along the line joining them (m s^{-1}); $c = 3.00 \times 10^8 \text{ m s}^{-1}$. In the data booklet.
- The equation gives magnitudes. Decide the direction yourself: **λ increases (red-shift) $\rightarrow$ moving apart; λ decreases (blue-shift) $\rightarrow$ approaching.** Frequency changes the opposite way to wavelength.
- Here v is *not* the wave speed — it is the relative speed of the bodies. Do not confuse it with the v in the HL sound equations.
- The approximation is valid only if $v \ll c$. Galaxies and stars in IB questions usually move at well under 10 % of c .
- Because $\Delta\lambda = \lambda \frac{v}{c}$, every line in a spectrum shifts by the same *fraction* of its wavelength: longer-wavelength lines shift by more nanometres.

WORKED EXAMPLE 1 Easy · State / Calculate

A hydrogen absorption line has a wavelength of 656.3 nm when measured in the laboratory. In the spectrum of a distant galaxy the same line is observed at 667.1 nm.

(a) State whether the galaxy is moving towards or away from the Earth. (b) Calculate the speed of the galaxy relative to the Earth.

(a) The observed wavelength is longer than the emitted one (red-shift), so the galaxy is **moving away from the Earth**.

(b) $\Delta\lambda = 667.1 - 656.3 = 10.8 \text{ nm}$

$$v = c \frac{\Delta\lambda}{\lambda} = 3.00 \times 10^8 \times \frac{10.8}{656.3} = 4.9 \times 10^6 \text{ m s}^{-1} \quad (4.94 \times 10^6 \text{ m s}^{-1})$$

Check: $v/c = 0.016$, so $v \ll c$ and the approximation is justified. The wavelengths can stay in nm because only their ratio is used.

WORKED EXAMPLE 2 Medium · Show that / Calculate

Radio telescopes detect an emission line of hydrogen with a laboratory frequency of 1420.41 MHz. From a cloud of gas in our galaxy, the line is received at 1420.12 MHz.

(a) Show that the speed of the cloud along the line of sight is about 60 km s^{-1} , and state its direction. (b) Calculate the change in wavelength of the line.

(a) $\Delta f = 1420.12 - 1420.41 = -0.29 \text{ MHz}$

$$v = c \frac{|\Delta f|}{f} = 3.00 \times 10^8 \times \frac{0.29}{1420.41} = 6.12 \times 10^4 \text{ m s}^{-1} = \mathbf{61.2 \text{ km s}^{-1}}$$

$\approx 60 \text{ km s}^{-1}$

The received frequency is lower, so the cloud is **moving away** from us.

(b) $\lambda = \frac{c}{f} = \frac{3.00 \times 10^8}{1420.41 \times 10^6} = 0.2112 \text{ m}$

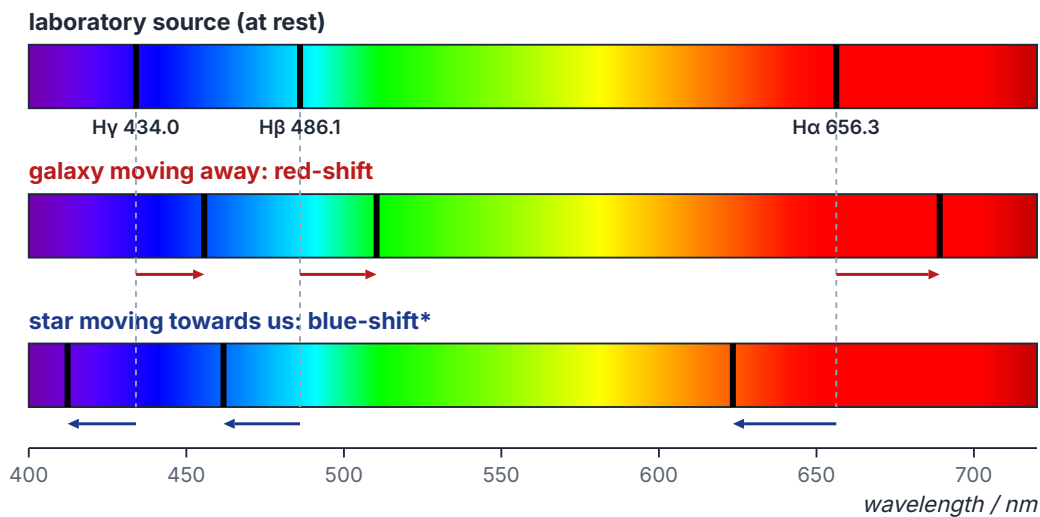
$$\Delta \lambda = \lambda \frac{v}{c} = 0.2112 \times \frac{6.12 \times 10^4}{3.00 \times 10^8} = \mathbf{4.3 \times 10^{-5} \text{ m}} \text{ (an increase)}$$

Notice that $|\Delta f|/f = |\Delta \lambda|/\lambda = 2.0 \times 10^{-4}$: the same fraction, with frequency falling and wavelength rising.

How do shifts in spectral lines reveal the motion of stars and galaxies?

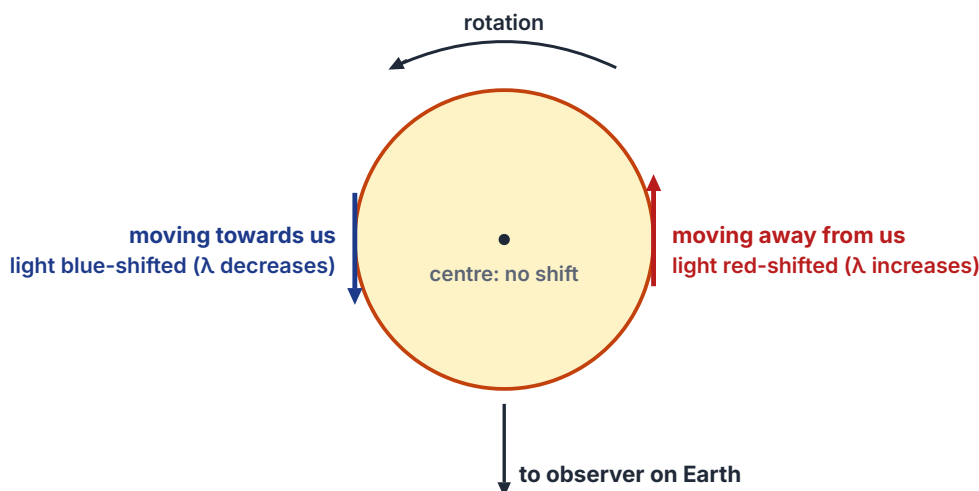
Each element absorbs and emits light at its own set of wavelengths (its line spectrum, E.1). The **pattern** of lines identifies the element even when every line has been shifted, so astronomers can compare observed wavelengths with laboratory values.

Red-shift is an increase in the observed wavelength of spectral lines, caused by the source moving away from the observer; blue-shift is a decrease, caused by the source moving towards the observer.



Three hydrogen lines (H α , H β , H γ). The galaxy spectrum is drawn to scale for $\Delta\lambda/\lambda = 0.05$, so every line moves by 5 % of its own wavelength (H α by 33 nm, H γ by 22 nm). *The blue-shift for the star is exaggerated to the same 5 % for clarity; real stars in our galaxy give shifts of order 10^{-4} of the wavelength.

- **Galaxies:** light from almost all distant galaxies is red-shifted, showing that they are moving away from us. Measuring $\Delta\lambda$ for a known line gives the speed of recession.
- **Stars:** stars in our galaxy show small red- or blue-shifts that give their speed towards or away from us (only the component along the line of sight).
- **Orbiting stars:** in a binary system each star's lines shift alternately towards blue and red as it moves towards and away from us in its orbit. The period of the oscillation gives the orbital period; the maximum shift gives the component of the orbital speed along the line of sight (the full orbital speed if the orbit is seen edge-on).
- **Rotation:** light from one edge (limb) of a rotating star or galaxy is blue-shifted and from the other edge red-shifted. The difference gives the rotational speed.



A rotating star or galaxy seen from above its axis of rotation; the observer on Earth is far away towards the bottom, in the plane of rotation. One limb approaches the observer and the other recedes, so a single spectral line is spread out (broadened) or split; the shift of each limb gives the speed of rotation.

HL: How do you calculate the Doppler shift for sound?

HL Doppler equations for sound and other mechanical waves

HL students must use the exact equations for sound and other mechanical waves (waves on water, ultrasound in tissue, ...). The wave speed v is measured relative to the medium, which is assumed to be still. Both equations are in the data booklet.

$$\text{moving source: } f' = f \frac{v}{v \pm u_s} \qquad \text{moving observer: } f' = f \frac{v \pm u_o}{v}$$

- f' = observed frequency (Hz), f = frequency emitted by the source (Hz),
 v = speed of the wave in the medium (m s^{-1}).
- u_s = speed of the source relative to the medium; u_o = speed of the observer relative to the medium (m s^{-1}).
- **Signs:** moving source — use $v - u_s$ when it approaches (smaller denominator, higher f') and $v + u_s$ when it recedes. Moving observer — use $v + u_o$ when approaching and $v - u_o$ when receding. Check: approaching must give $f' > f$.

- Problems never have both source and observer moving. The source speed is always less than the wave speed.

Where the equations come from

Moving source. In one period $T = 1/f$ the front travels vT while the source follows it by $u_s T$. The wavelength ahead is $\lambda' = (v - u_s)T = \frac{v - u_s}{f}$. The wave still travels at v , so $f' = \frac{v}{\lambda'} = f \frac{v}{v - u_s}$.

Moving observer. The wavelength is unchanged, $\lambda = v/f$, but the waves pass the observer at $v + u_o$. So $f' = \frac{v + u_o}{\lambda} = f \frac{v + u_o}{v}$.

WORKED EXAMPLE 3 Medium · HL · Calculate / Explain

An ambulance siren emits sound of frequency 950 Hz. The ambulance travels at a constant 25 m s^{-1} along a straight road towards a pedestrian standing beside the road, passes her and drives away. The speed of sound in air is 340 m s^{-1} .

(a) Calculate the frequency heard by the pedestrian as the ambulance approaches and as it moves away. (b) Calculate the wavelength of the sound in front of the ambulance. (c) Explain why the frequency she hears does not increase as the ambulance gets closer.

(a) Approaching: $f' = 950 \times \frac{340}{340 - 25} = \mathbf{1030 \text{ Hz}}$ (1025 Hz)

Receding: $f' = 950 \times \frac{340}{340 + 25} = \mathbf{885 \text{ Hz}}$

The pitch drops by about 140 Hz as the ambulance passes.

(b) $\lambda' = \frac{v - u_s}{f} = \frac{340 - 25}{950} = \mathbf{0.332 \text{ m}}$ (compared with $340/950 = 0.358 \text{ m}$ from a stationary siren).

(c) The observed frequency depends on the source's **velocity**, not on its distance. The ambulance approaches at a constant speed, so while it is still far from her compared with her distance from the road (its velocity is then effectively along the line to her), the wavelength

reaching her and therefore the frequency are constant. Only the *loudness* increases as it gets closer.

WORKED EXAMPLE 4 Medium · HL · Determine

A loudspeaker at rest emits a steady note of 1200 Hz. A cyclist rides at constant speed directly towards the loudspeaker and hears a frequency of 1250 Hz. The speed of sound is 340 m s^{-1} .

(a) Determine the speed of the cyclist. (b) Determine the frequency she hears after she has passed the loudspeaker and rides directly away from it at the same speed. (c) State the wavelength of the sound she receives.

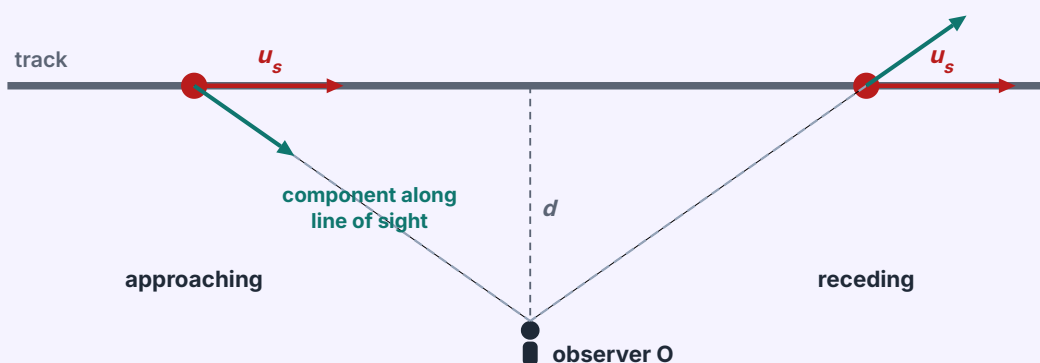
(a) Observer approaching: $f' = f \frac{v + u_o}{v} \Rightarrow u_o = v \left(\frac{f'}{f} - 1 \right) = 340 \left(\frac{1250}{1200} - 1 \right) = \mathbf{14 \text{ m s}^{-1}}$ (14.2 m s^{-1})

(b) Observer receding: $f' = 1200 \times \frac{340 - 14.2}{340} = \mathbf{1150 \text{ Hz}}$

(c) The source is at rest, so the wavelength in the air is unchanged: $\lambda = \frac{340}{1200} = \mathbf{0.283 \text{ m}}$. Her motion changes the rate at which she meets the wavefronts, not their spacing.

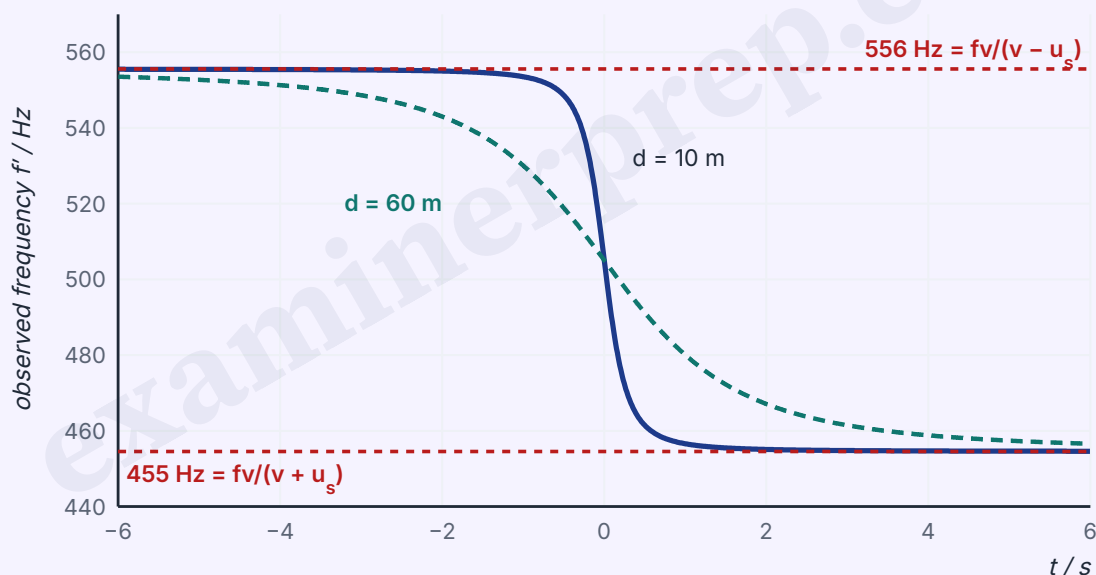
A source passing at a distance

In exam problems the source moves straight towards or away from the observer. In real life a train or car passes at some distance d from you. Only the component of its velocity along the line of sight counts, and this component falls smoothly from u_s to zero and then reverses as the source passes. The observed frequency therefore drops smoothly rather than suddenly.



Only the velocity component along the line to the observer changes the frequency; it shrinks to zero as the source passes the nearest point.

A source moving along a straight track passes an observer at perpendicular distance d . Far away, the velocity is almost along the line of sight; near the closest point, the component along the line of sight is small.



Computed frequency heard by a stationary observer as a train sounding its horn passes at constant speed ($v = 340 \text{ m s}^{-1}$), for perpendicular distances of 10 m and 60 m. $t = 0$ is when the source is at its closest point (the sound arrives slightly later). Far from the observer both curves approach 556 Hz before and 455 Hz after; the closer the observer is to the track, the sharper the drop.

WORKED EXAMPLE 5 Hard · HL · Determine (graph) / Explain

The graph above shows the frequency heard by an observer standing 10 m from a straight railway line as a train sounding its horn passes at constant speed. Long before and long after the train passes, the frequencies heard are steady.

(a) State the two steady frequencies shown on the graph. (b) Determine the speed of the train and the frequency emitted by the horn. (c) Explain why the curve for an observer 60 m from the track falls more gradually.

(a) Approaching: $f_1 = 556 \text{ Hz}$; receding: $f_2 = 455 \text{ Hz}$.

(b) $f_1 = f \frac{v}{v - u_s}$ and $f_2 = f \frac{v}{v + u_s}$. Dividing: $\frac{f_1}{f_2} = \frac{v + u_s}{v - u_s} \Rightarrow$

$$u_s = v \frac{f_1 - f_2}{f_1 + f_2}.$$

$$u_s = 340 \times \frac{556 - 455}{556 + 455} = \mathbf{34 \text{ m s}^{-1}} \text{ (34.0 m s}^{-1}\text{)}$$

$$f = f_1 \frac{v - u_s}{v} = 556 \times \frac{340 - 34.0}{340} = \mathbf{500 \text{ Hz}}$$

Check: at the closest point the train's velocity is at right angles to the line of sight, so there is no shift there. Both curves do pass through 500 Hz in the middle of the drop.

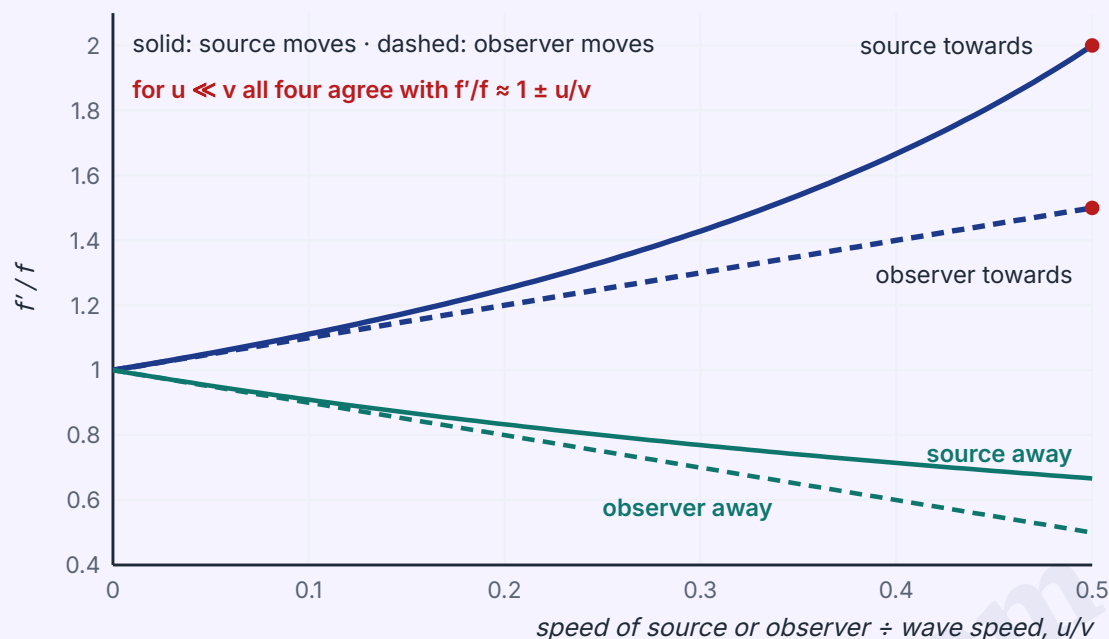
(c) Only the component of the train's velocity along the line to the observer causes the shift. For a distant observer the angle between the track and the line of sight changes slowly, so this component — and the frequency — changes over a longer time. For an observer close to the track it reverses almost instantly as the train passes.

Why do a moving source and a moving observer give different results?

For sound, the medium provides a preferred frame. A source moving at u changes the wavelength in the air; an observer moving at u does not. So

$f \frac{v}{v - u} \neq f \frac{v + u}{v}$: a source approaching at half the speed of sound

doubles the frequency, while an observer approaching at the same speed raises it by only 50 %.



Ratio f'/f against u/v , computed from the two HL equations. The curves separate at large speeds, but for $u \ll v$ all four collapse onto $f'/f \approx 1 \pm u/v$ — the same form as the light equation $\Delta f/f \approx v/c$.

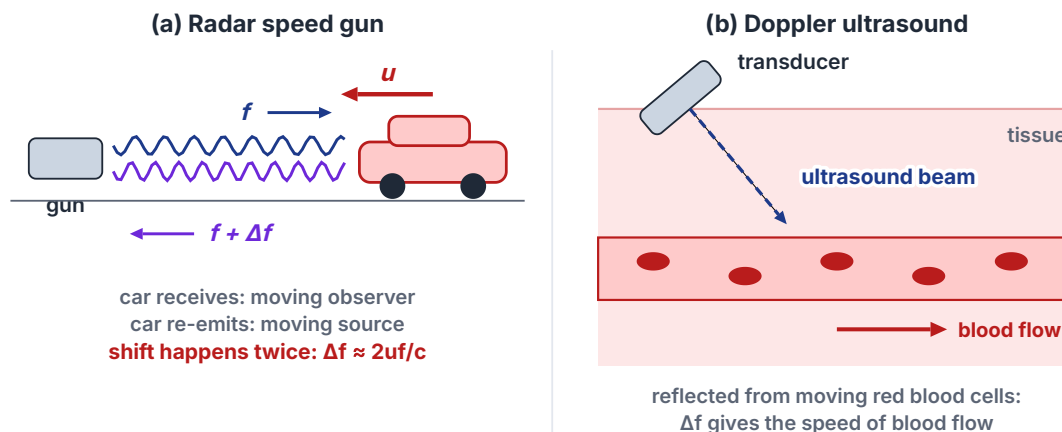
Light has no medium, so only the relative velocity of source and observer can matter. When $u \ll v$, $\frac{v}{v-u} \approx 1 + \frac{u}{v}$, which is why the simple approximation $\Delta f/f \approx u/v$ works for sound at low speeds too, and why the SL light equation has the same form.

How is the Doppler effect used in radar and medicine?

In both applications a wave is sent towards a moving target and the **reflected** wave is detected. The frequency is shifted twice: first the moving target receives the wave as a *moving observer*, then it re-emits (reflects) it as a *moving source*. For speeds much less than the wave speed, each step gives a fractional shift of about u/v , so

$$\Delta f \approx \frac{2uf}{c} \quad (\text{radar}) \qquad \Delta f \approx \frac{2uf}{v} \quad (\text{ultrasound, } v = \text{speed of sound in medium})$$

These are not data-booklet equations. Derive the factor 2 from the two-step argument whenever you use it.



(a) A radar speed gun compares the frequency of the reflected microwaves with the emitted frequency. (b) Doppler ultrasound: the frequency shift of ultrasound reflected from moving red blood cells gives the speed of blood flow; only the component of the blood velocity along the beam counts.

- **Radar (police speed guns, air-traffic control, weather radar):** microwaves reflect from a vehicle or from raindrops. The shift is tiny (parts in 10^7), so the gun measures the difference between the emitted and reflected frequencies electronically. Approaching targets give a higher reflected frequency.
- **Doppler ultrasound (medical physics):** ultrasound of a few MHz is reflected by red blood cells. For a 4.0 MHz beam, blood moving at 0.25 m s^{-1} along the beam and $v = 1540 \text{ m s}^{-1}$ in tissue, $\Delta f \approx \frac{2 \times 0.25 \times 4.0 \times 10^6}{1540} = 1.3 \text{ kHz}$. This is used to detect narrowed arteries, check heart valves and monitor a fetal heartbeat.

WORKED EXAMPLE 6 Hard · Explain / Determine

A police radar gun emits microwaves of frequency 24.0 GHz. A car drives directly towards the gun at 31 m s^{-1} .

(a) Explain why the microwaves reflected from the car have a higher frequency than those emitted, and why the shift is approximately $2uf/c$. (b) Determine the frequency difference measured by the gun. (c) For a second car the measured difference is 3.2 kHz. Determine its speed.

(a) The car moves towards the gun, so it meets the wavefronts more often than they are emitted: it *receives* a frequency raised by a fraction $\approx u/c$. It

then reflects them as a source moving towards the gun, so the wavefronts it sends back are bunched up and the frequency rises by a further fraction $\approx u/c$. Since $u \ll c$, the total fractional shift is $\approx 2u/c$.

$$\text{(b)} \Delta f \approx \frac{2uf}{c} = \frac{2 \times 31 \times 24.0 \times 10^9}{3.00 \times 10^8} = \mathbf{5.0 \text{ kHz}} \text{ (4.96 kHz)}$$

$$\text{(c)} u = \frac{c \Delta f}{2f} = \frac{3.00 \times 10^8 \times 3.2 \times 10^3}{2 \times 24.0 \times 10^9} = \mathbf{20 \text{ m s}^{-1}}$$

The most common error is forgetting the factor 2, which doubles the calculated speed.

Exam tips for C.5

EXAM TIP 1 — THE SOURCE DOES NOT CHANGE ITS FREQUENCY

Write “the **observed** (received) frequency increases”. Answers that say “the frequency of the siren increases” or “the source emits a higher frequency” are physically wrong and lose the mark.

EXAM TIP 2 — SOURCE OR OBSERVER?

For a moving source, say that the **wavelength** changes. For a moving observer, say that the wavelength is **unchanged** and the observer meets more (or fewer) wavefronts per second because the speed of the waves relative to the observer is $v \pm u_o$. Mixing these up is the most common error in wavefront questions.

EXAM TIP 3 — CHECK THE SIGN WITH COMMON SENSE (HL)

After substituting, ask: are they approaching? Then f' must be larger than f . If not, you picked the wrong sign. When you are asked to find the speed, rearrange first, then substitute — and keep at least three significant figures in intermediate values, because Doppler shifts are often small differences of large numbers.

EXAM TIP 4 — TWO DIFFERENT V'S

In $\Delta f/f \approx v/c$, v is the **relative speed of the bodies**. In the HL sound equations v is the **speed of the wave**. State which you mean. For light, always calculate $\Delta\lambda = \lambda_{\text{obs}} - \lambda_{\text{emit}}$ first and use the sign to decide red-shift (receding) or blue-shift (approaching).

EXAM TIP 5 — SKETCHING F' AGAINST TIME

For a source moving straight past you at constant speed, the sketch is a constant high value, a drop as it passes, then a constant low value. The high value is further above f than the low value is below it (556 Hz and 455 Hz around 500 Hz in worked example 5), because of the $v - u_s$ in the denominator. A graph that rises steadily while the source approaches is wrong.

Common misconceptions

Misconception	Why it is wrong	Correct idea
The pitch rises steadily as an approaching source gets closer.	The shift depends on velocity, not distance. At constant speed along the line of sight the observed frequency is constant.	The loudness increases as it approaches; the pitch is constant, then drops as it passes.
A moving source emits a different frequency.	The source vibrates at the same rate whatever its motion.	Only the observed frequency changes, because of the spacing or rate of arrival of wavefronts.
A moving observer changes the wavelength.	The wavefronts in the medium are set by the source; the observer does not alter them.	A moving observer changes the relative speed of the waves, so it changes the frequency but not the wavelength.
Red-shift means the light becomes red.	Every line shifts by the same fraction; a blue line that is red-shifted may still be blue.	Red-shift means an increase in wavelength (towards the red end), caused by recession.
For sound, a source moving at u and an observer moving at u give the same shift.	Sound has a medium; the source's motion changes the wavelength, the observer's does not.	The results differ (HL equations); they agree only when $u \ll v$.
Any motion of a star produces a Doppler shift.	Motion across the line of sight does not change the distance between source and observer.	Only the velocity component along the line of sight produces a shift.

How this topic connects

Light and sound compared: shared wave behaviour, different natures

Both are waves that carry energy, obey $v = f\lambda$, and show reflection, refraction, diffraction, interference and the Doppler effect (C.2, C.3). Sound is a longitudinal mechanical wave that needs a medium and travels at a few hundred m s^{-1} in air; light is a transverse electromagnetic wave that travels through a vacuum at c . For the Doppler effect, this means sound has different equations for a moving source and a moving observer (motion relative to the medium matters), while for light only the relative velocity of source and observer matters.

Measuring how fast stars and galaxies spin from Doppler-shifted spectral lines

Light from the limb of a rotating star, planet or galaxy that is turning towards us is blue-shifted, and light from the opposite limb is red-shifted. Measuring the wavelength of the same spectral line at the two limbs gives $\Delta\lambda$ for each; then $v = c\Delta\lambda/\lambda$ is the speed of each limb along the line of sight, i.e. the rotational speed at the edge. Combined with the radius, this gives the rotation period ($T = 2\pi r/v$, A.2). For a distant unresolved star the two shifts merge into a broadened line, and the width of the line indicates the rotational speed.

Beyond $v \ll c$: when the simple Doppler formula for light breaks down

Then $\Delta\lambda/\lambda \approx v/c$ is no longer accurate, because it is only the low-speed approximation of the exact result, which must include the time dilation of special relativity (A.5). The approximation can even give impossible answers: a measured $\Delta\lambda/\lambda$ of 1 would imply $v = c$. The full relativistic Doppler equation is not required in this course; you only need to recognise that the simple equation requires $v \ll c$.

Tools & inquiry — measuring a Doppler shift (NOS: inferring speed from light)

- **In the lab:** attach a small buzzer to a trolley or swing it on a string, and record it with a frequency-analyser app or a microphone and data logger. Compare the frequency when the buzzer is at rest with that when it moves towards and away from the microphone, and calculate its speed (HL). Repeat to estimate the uncertainty in the frequency readings.

- **Small differences:** the shift is often a small difference between two large numbers, so its percentage uncertainty is large. Measure frequencies to as many significant figures as the equipment allows.
- **NOS — speed from light:** astronomers cannot measure the speed of a galaxy directly. They assume that atoms in distant galaxies emit the same spectral lines as atoms in a laboratory (the laws of physics are the same everywhere), identify a line by its pattern, and then calculate the speed from $\Delta\lambda/\lambda$. The conclusion depends on that assumption and on the model being valid ($v \ll c$).

Key equations

Equation	Use	In data booklet?
$\frac{\Delta f}{f} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$	Doppler effect for light, relative speed $v \ll c$ (SL & HL)	yes
$f' = f \frac{v}{v \pm u_s}$	moving source, sound/mechanical waves (HL); – when approaching	yes (HL section)
$f' = f \frac{v \pm u_o}{v}$	moving observer, sound/mechanical waves (HL); + when approaching	yes (HL section)
$v = f\lambda$	link between wave speed, frequency and wavelength (C.2)	yes
$\Delta f \approx \frac{2uf}{c}$	reflection from a moving target (radar); use v for ultrasound	no — derive from the two-step argument

Check your understanding

1. A source of sound is at rest and an observer moves towards it. State and explain what happens to the wavelength and the frequency that the

observer measures.

The wavelength is **unchanged**: the source is at rest, so the spacing of the wavefronts in the air is unaffected. The frequency **increases**: the waves pass the observer at a relative speed $v + u_o$, so more wavefronts are met each second.

2. A spectral line with a laboratory wavelength of 500.0 nm is observed at 499.8 nm in the light from a star. Determine the velocity of the star relative to the Earth.

$$\Delta\lambda = -0.2 \text{ nm (blue-shift), so the star is approaching. } v = c \frac{|\Delta\lambda|}{\lambda} = 3.00 \times 10^8 \times \frac{0.2}{500.0} = 1.2 \times 10^5 \text{ m s}^{-1} \text{ (120 km s}^{-1}\text{) towards the Earth.}$$

3. (HL) A source of sound of frequency 800 Hz moves directly away from a stationary observer at 15 m s^{-1} . The speed of sound is 340 m s^{-1} . Calculate the frequency heard.

$$\text{Receding source: } f' = 800 \times \frac{340}{340 + 15} = 766 \text{ Hz (770 Hz to 2 s.f.).}$$

4. (HL) An observer moves directly away from a stationary 600 Hz source at 20 m s^{-1} . The speed of sound is 340 m s^{-1} . Calculate the frequency heard.

$$\text{Receding observer: } f' = 600 \times \frac{340 - 20}{340} = 565 \text{ Hz (564.7 Hz).}$$

5. A star is viewed with its axis of rotation at right angles to the line of sight. A spectral line of laboratory wavelength 600.0 nm appears at two wavelengths, one from each limb, separated by 0.040 nm. Determine the speed of the limbs due to rotation.

One limb is blue-shifted and the other red-shifted by the same amount, so each is shifted by $\Delta\lambda = 0.020 \text{ nm}$. $v = c \frac{\Delta\lambda}{\lambda} = 3.00 \times 10^8 \times \frac{0.020}{600.0} = 1.0 \times 10^4 \text{ m s}^{-1} \text{ (10 km s}^{-1}\text{)}.$

Practise C.5 with exam-style questions

Original Paper 1A, 1B and 2 questions on the Doppler effect for sound and light, with full mark schemes. Tick the questions you want and print them as your own test.

SL C.5 questions

HL C.5 questions

Revise and explore

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- [C.5 Doppler Effect simulation](#)
- [Full IB Physics question bank](#) (all sub-topics, SL & HL)

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