IB DP PHYSICS

Theme C: Wave Behaviour

C.5 Doppler Effect

Revision Notes · Standard and Higher Level

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Original notes prepared for the IB Diploma Programme Physics course (first assessment 2025)

What the syllabus requires

By the end of C.5 you should be able to work confidently with each of the following. Use this list as a final checklist before the exam.

Understanding	You should be able to...
The Doppler phenomenon (SL)	Describe qualitatively, with wavefront diagrams, how relative motion between a source and an observer changes the observed frequency and wavelength.
Doppler shifts for light (SL)	Use $\Delta f / f = \Delta\lambda / \lambda \approx v / c$ for electromagnetic waves when the relative speed is much less than c; interpret redshift and blueshift.
Applications (SL)	Explain how Doppler shifts are used in radar speed measurement, medical ultrasound and astronomy (receding galaxies, rotating bodies).
Moving source (HL)	Apply $f' = f v / (v \pm u_s)$ and the corresponding wavelength change for a source moving through a medium.
Moving observer (HL)	Apply $f' = f (v \pm u_o) / v$ for an observer moving through the medium, and explain why this case is physically different.
Sign conventions (HL)	Select signs systematically for any combination of source and observer motion, and check answers against the expected direction of the shift.

> **SL / HL split:** The wavefront picture, the light equation and all the applications are core (SL and HL). The two equations for sound - moving source and moving observer - are HL only. HL sections below are flagged (HL).

1. The phenomenon: what the Doppler effect is

The **Doppler effect** is the change in the observed frequency (and wavelength) of a wave when there is relative motion between the source and the observer. Nothing about the source itself changes - it still oscillates at its own frequency f - but the observer receives wavefronts at a different rate, and so measures a different frequency f'.

You hear it every time an ambulance passes: the siren sounds higher-pitched than normal while the ambulance approaches, then drops noticeably as it passes and recedes. A race car does the same - the famous “eeeee-yowwww” as it flashes past a trackside microphone is a falling Doppler shift. Note carefully what does *not* happen: the pitch is not “rising as it gets closer”. While the car approaches at constant speed the pitch is steady but *high*; while it recedes the pitch is steady but *low*. The sudden drop happens as it passes.

Wavefront picture for a moving source

Imagine a source emitting circular wavefronts once every period T. Each wavefront, once emitted, spreads out at the wave speed v centred on the point where it was emitted. If the source moves, each successive wavefront is emitted from a point slightly further along the direction of motion. The result:

- **Ahead** of the source the wavefronts are **bunched together**: the wavelength is shortened, so a stationary observer in front receives crests more often and hears a **higher** frequency.
- **Behind** the source the wavefronts are **stretched apart**: the wavelength is lengthened, so an observer behind hears a **lower** frequency.

- To the **side**, the shift is between these extremes; exactly side-on (at closest approach) the observed frequency passes through the true frequency *f*.

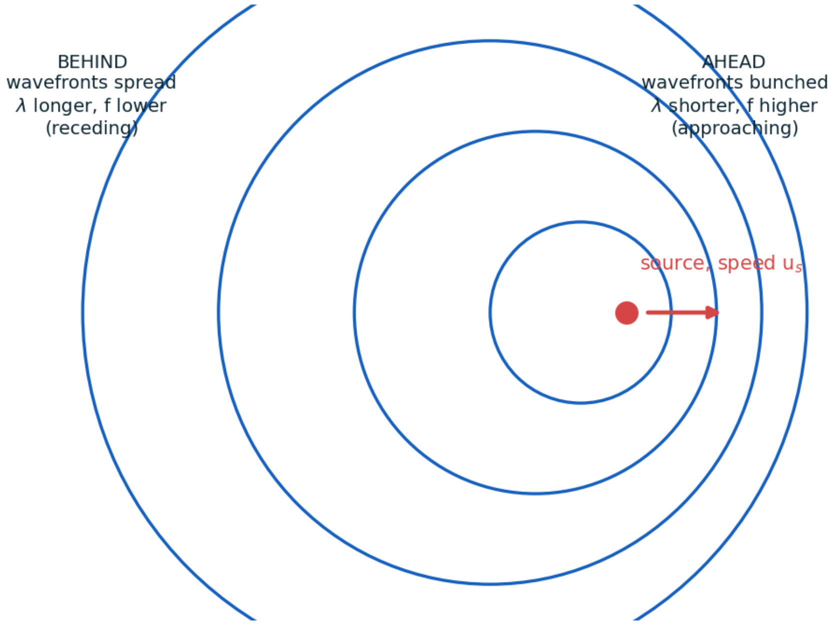

Figure 1. Wavefronts from a source moving to the right (Mach 0.5). Ahead of the source the circles bunch up - the wavelength is shortened, so a stationary observer in front receives a higher frequency (approaching). Behind, the wavefronts spread out - a longer wavelength and lower frequency (receding). Here $\lambda_{behind} / \lambda_{ahead} = (v + u_s) / (v - u_s) = 3$.

Wavefront picture for a moving observer

Now keep the source at rest, so the wavefronts form evenly spaced concentric circles - the wavelength in the medium is completely unchanged. An observer who runs **towards** the source sweeps through these wavefronts at an increased rate: relative to the observer the crests arrive faster, so the observed frequency rises. An observer running **away** crosses wavefronts less often, so the frequency falls; run at the wave speed and you would keep pace with one crest and hear nothing new at all.

> **Describe it, don't just name it:** "The frequency changes because of the Doppler effect" earns nothing. Say *why*: approaching source means wavefronts emitted from successively closer points, so the wavelength ahead is compressed and the observed frequency is higher.

2. Why the two cases are physically different (for sound)

For a mechanical wave such as sound, the wave travels through a **medium** (the air), and the wave speed *v* is fixed by the medium, not by the motion of the source. This is why "source moving" and "observer moving" are genuinely different physical situations, even at the same relative speed:

	Moving source, stationary observer	Moving observer, stationary source
What changes	The **wavelength** in the medium: wavefronts are emitted from moving positions, so they are compressed ahead and stretched behind.	Nothing in the medium changes. The observer crosses wavefronts at a different rate: the wave speed **relative to the observer** becomes $v \pm u_o$.

	Moving source, stationary observer	Moving observer, stationary source
What stays the same	Wave speed in the medium is still v (set by the air).	Wavelength in the medium is still $\lambda = v / f$.
Observed frequency	$f' = v / \lambda'$, with the new wavelength λ'.	f' = (relative speed) / $\lambda = (v \pm u_o) / \lambda$.

Because the mechanisms differ, the formulas differ, and a source moving at speed u does **not** give exactly the same shift as an observer moving at the same speed u (though the two agree closely when u is small compared with v). For light there is no medium, so only the relative velocity can matter - see Section 6.

> **Frame of reference:** All speeds in the sound formulas (v, u_s, u_o) are measured relative to the **medium** (the still air), not relative to each other.

3. (HL) Moving source: the equation

Let the source emit frequency f, let the wave speed in the medium be v, and let the source move at speed u_s directly along the line to the observer. In one period $T = 1/f$ a wavefront travels a distance vT, but the source has chased it a distance u_sT. The gap between successive wavefronts ahead of the source is therefore $\lambda' = (v - u_s)/f$, and behind it $\lambda' = (v + u_s)/f$. The stationary observer receives these wavefronts at speed v, so $f' = v / \lambda'$:

$$\boldsymbol{f' = f \times v / (v \pm u_s)} \quad \textbf{(- for approach, + for recession)}$$

The sign logic in words: an **approaching** source squeezes the wavelength, which means a **smaller denominator**, which makes f' **larger** - a higher pitch, as your ears expect. A receding source stretches the wavelength: larger denominator, lower frequency. If you ever forget which sign to use, decide first whether the pitch should rise or fall, then pick the sign that does it.

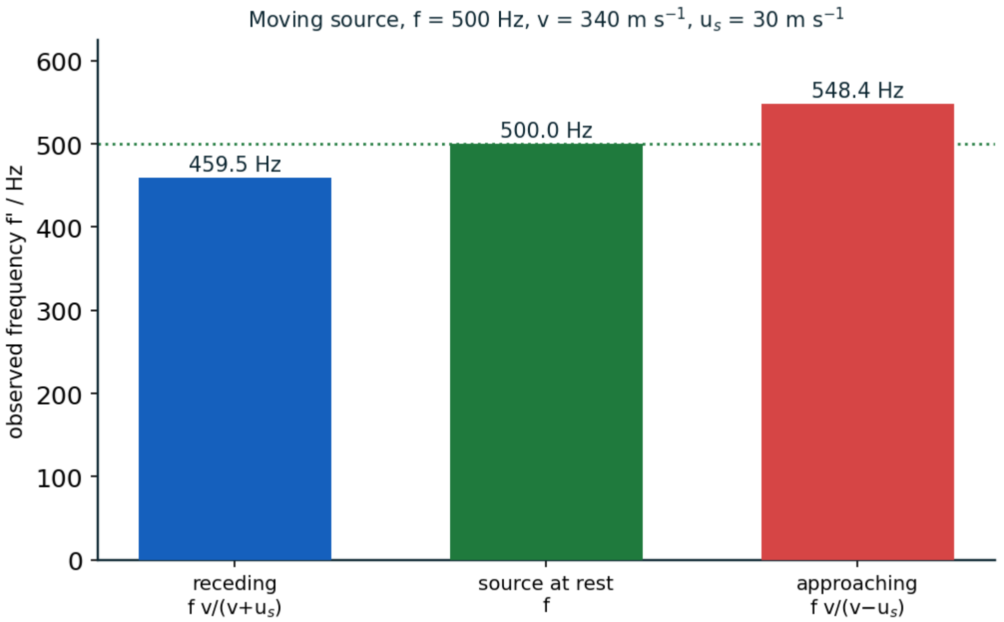

Figure 2. Observed frequency for a moving source, $f' = f \cdot v/(v \pm u_s)$. For f = 500 Hz, v = 340 m s^{-1} and u_s = 30 m s^{-1}: approaching gives f' = 500·340/310 ≈ 548.4 Hz, receding gives f' = 500·340/370 ≈ 459.5 Hz.

Worked example 1 (HL) - ambulance siren

An ambulance siren emits a 700 Hz tone. The ambulance drives at 25 m s^{-1} along a straight road past a stationary pedestrian. Speed of sound = 340 m s^{-1}. Find the frequency heard (a) as it approaches, (b) as it recedes.

(a) Approach - smaller denominator: f' = 700 × 340 / (340 - 25) = 700 × 340 / 315 = **756 Hz** (higher, as expected).

(b) Recession: f' = 700 × 340 / (340 + 25) = 700 × 340 / 365 = **652 Hz** (lower).

The pedestrian hears the pitch drop by about 104 Hz - roughly a whole tone - as the ambulance passes.

Worked example 2 (HL) - wavelengths around a moving source

A train whistle emits 400 Hz while the train travels at 30 m s^{-1} (speed of sound 340 m s^{-1}). Find the wavelength of the sound (a) ahead of the train, (b) behind the train, and (c) the frequency heard by a person standing on the track far ahead.

Stationary wavelength would be λ = 340 / 400 = 0.850 m.

(a) Ahead: $\lambda' = (v - u_s) / f$ = (340 - 30) / 400 = **0.775 m** (compressed).

(b) Behind: λ' = (340 + 30) / 400 = **0.925 m** (stretched).

(c) $f' = v / \lambda'$ = 340 / 0.775 = **439 Hz** - identical to using f' = 400 × 340 / 310 directly.

Check the physics, not just the algebra: After every Doppler calculation ask: should this shift be up or down? Approach must give $f' > f$; recession must give $f' < f$. A sign slip is instantly visible.

4. (HL) Moving observer: the equation

Now the source is at rest in the medium, so the wavelength everywhere is $\lambda = v / f$. An observer moving at speed u_o towards the source meets the wavefronts at a relative speed $v + u_o$, so crests arrive at the rate

$$f' = f \times (v \pm u_o) / v \quad \text{(+ for approach, - for recession)}$$

Sign logic in words: moving **towards** the source increases the rate at which you cross wavefronts - a **larger numerator**, so a higher frequency. Moving away decreases it. Notice the pleasing symmetry of the two formulas: the source speed lives in the **denominator** (it changes the wavelength), while the observer speed lives in the **numerator** (it changes the effective wave speed).

Worked example 3 (HL) - cyclist and a fire-station siren

A fire-station siren emits a steady 512 Hz. A cyclist rides directly towards the station at 15 m s^{-1}, passes it, and rides away at the same speed. Speed of sound = 340 m s^{-1}. Find the two frequencies heard.

Approaching: $f' = 512 \times (340 + 15) / 340 = 512 \times 355 / 340 =$ **535 Hz**.

Receding: $f' = 512 \times (340 - 15) / 340 = 512 \times 325 / 340 =$ **489 Hz**.

Both shifts are about 4.4% of f, matching the ratio $u_o / v = 15/340 \approx 4.4\%$.

Combined motion

If both the source and the observer move along the line joining them, apply both corrections at once:

$$f' = f \times (v \pm u_o) / (v \pm u_s)$$

Choose each sign *independently* using the same physical logic: observer moving towards the source → numerator +; source moving towards the observer → denominator -. IB questions rarely combine both motions, but the logic is exactly the same and it is an excellent test of whether you understand the signs rather than memorise them.

Worked example 4 (HL) - both moving towards each other

A car sounding its 600 Hz horn drives at 20 m s^{-1} towards a cyclist, who is riding at 10 m s^{-1} towards the car. Speed of sound = 340 m s^{-1}. What frequency does the cyclist hear?

Observer approaching → numerator (340 + 10); source approaching → denominator (340 - 20).

$f' = 600 \times (340 + 10) / (340 - 20) = 600 \times 350 / 320 =$ **656 Hz**.

Sense check: both motions raise the pitch, so f' must exceed both 600 Hz and either single-motion answer - it does.

5. (HL) A systematic sign strategy - the four cases

Use this three-step routine every time:

- **Step 1:** Decide physically whether the gap is closing (pitch up) or opening (pitch down).
- **Step 2:** Put the source speed in the denominator, the observer speed in the numerator.
- **Step 3:** Choose each sign so that the fraction moves f' in the direction Step 1 demands, then check the final number really is on the correct side of f.

Case	Equation	Shift	Quick check (f = 1000 Hz, u = 34 m s^{-1}, v = 340 m s^{-1})
Source → observer (approach)	$f' = f v / (v - u_s)$	Up	1000 × 340/306 = 1111 Hz
Source ← observer (recede)	$f' = f v / (v + u_s)$	Down	1000 × 340/374 = 909 Hz

Case	Equation	Shift	Quick check (f = 1000 Hz, u = 34 m s^{-1}, v = 340 m s^{-1})
Observer → source (approach)	$f' = f(v + u_o) / v$	Up	1000 × 374/340 = 1100 Hz
Observer ← source (recede)	$f' = f(v - u_o) / v$	Down	1000 × 306/340 = 900 Hz

The quick-check column makes an important point: at the *same* speed of 34 m s^{-1} (10% of v), the moving-source shift (+111 Hz) is slightly bigger than the moving-observer shift (+100 Hz) on approach. The two cases only become equivalent in the limit $u \ll v$, where both reduce to $\Delta f / f \approx u / v$.

Worked example 5 (HL) - a train passes: find f and u from the two pitches

A stationary observer beside a track hears a train horn at 470 Hz while the train approaches and 410 Hz after it passes. Speed of sound = 340 m s^{-1}. Find the emitted frequency and the train's speed.

Approach: $470 = f \times 340 / (340 - u_s)$; recession: $410 = f \times 340 / (340 + u_s)$.

Divide the equations: $470 / 410 = (340 + u_s) / (340 - u_s)$, so $470(340 - u_s) = 410(340 + u_s)$.

$159\,800 - 470u_s = 139\,400 + 410u_s \rightarrow 20\,400 = 880u_s \rightarrow u_s =$ **23 m s^{-1}**.

Then $f = 470 \times (340 - 23.2) / 340 = 470 \times 316.8 / 340 =$ **438 Hz**. Check: 438 × 340 / 363.2 = 410 Hz. Consistent.

What you actually hear as a source passes: the f-t graph

A very common exam sketch: plot the observed frequency against time as a source drives past at constant speed. While the source is still far away and approaching, almost all of its velocity is along the line of sight, so f' sits on a nearly constant **high plateau** at $f v / (v - u_s)$. As it passes, the radial component of the velocity falls to zero and then reverses, so f' falls **smoothly** (not in a step), passing through the true value f exactly at closest approach, and settles on a **low plateau** at $f v / (v + u_s)$. The closer the observer stands to the line of motion, the steeper the drop. Loudness, by contrast, peaks at closest approach - never confuse the two curves.

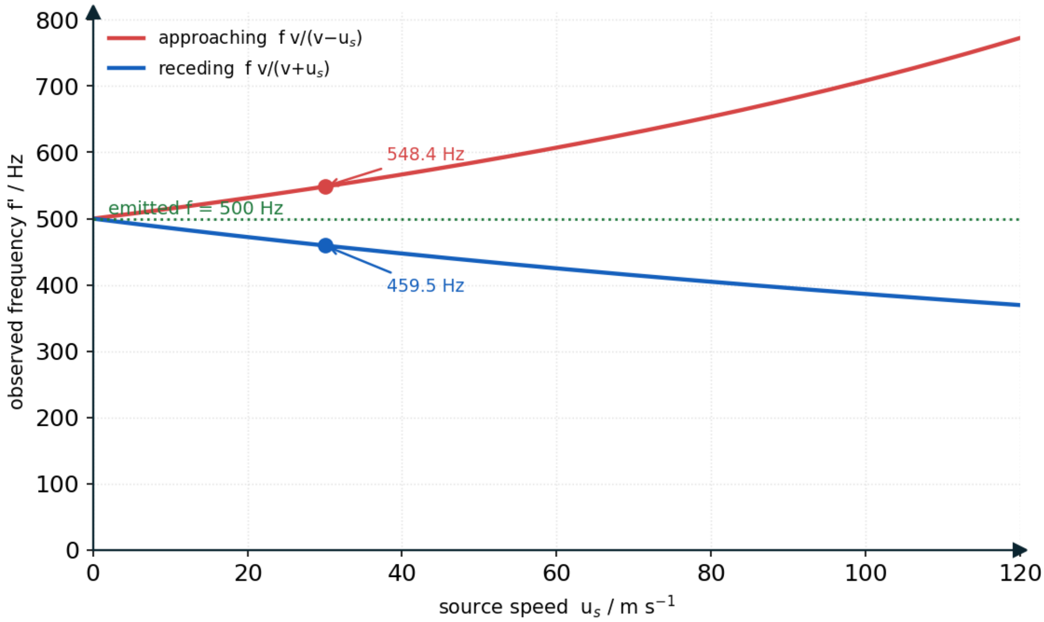

Figure 3. Observed frequency versus source speed for f = 500 Hz and v = 340 m s^{-1}. The approaching branch $f \cdot v/(v - u_s)$ rises steeply (diverging as $u_s \to v$), while the receding branch $f \cdot v/(v + u_s)$ falls gently. At u_s = 30 m s^{-1} the two branches read 548.4 Hz and 459.5 Hz.

Worked example 6 (HL) - echo from a wall (double shift with sound)

A car drives at 5.0 m s^{-1} directly towards a large wall, sounding its 400 Hz horn. Speed of sound = 340 m s^{-1}. (a) What frequency does the wall receive? (b) What echo frequency does the driver hear? (c) What beat frequency is heard between the horn and its echo?

(a) The wall is a stationary observer of a moving source: f_1 = 400 × 340 / (340 - 5.0) = 400 × 340 / 335 = **406 Hz**.

(b) The wall re-emits 406 Hz as a stationary source; the driver is an observer approaching it: f_2 = 406.0 × (340 + 5.0) / 340 = **412 Hz**. (One line: f_2 = 400 × 345 / 335 = 411.9 Hz.)

(c) Beat frequency = 411.9 - 400 = **12 Hz**. This is the sound analogue of the radar gun's double shift in Section 7.

6. Light and electromagnetic waves

Light needs no medium, so the sound formulas - which are built on speeds measured relative to the air - **cannot be applied to light**. There is no “frame of the medium”; special relativity (A.5) tells us that only the *relative* velocity of source and observer can matter, and that every observer measures the same wave speed *c*. The exact relativistic formula is not required. For the IB you use the approximation, valid whenever the relative speed *v* is much less than *c*:

$$\Delta f / f = \Delta\lambda / \lambda \approx v / c \text{ (for } v \ll c)$$

Here Δf and $\Delta\lambda$ are the magnitudes of the shifts in frequency and wavelength, f and λ are the emitted (rest) values, and v is the relative speed along the line of sight (the **radial** component). Direction of the shift:

- **Recession** → wavelength increases → visible light moves towards the red end: **redshift**.

- **Approach** → wavelength decreases → **blueshift**.
- Motion **across** the line of sight produces no shift at this level of approximation - only the radial component counts.

Worked example 7 - speed of a receding galaxy

A hydrogen spectral line has laboratory wavelength 656.3 nm. In the spectrum of a distant galaxy the same line is observed at 662.9 nm. Find the galaxy's radial velocity.

$\Delta\lambda$ = 662.9 - 656.3 = 6.6 nm. The wavelength has *increased*, so the galaxy is receding (redshift).

$v = c \times \Delta\lambda / \lambda = 3.00 \times 10^8 \times 6.6 / 656.3 = \mathbf{3.0 \times 10^6\ m\ s^{-1}}$, about 1% of the speed of light - comfortably within the small-speed approximation.

Why no ± fuss for light: The light formula is quoted with magnitudes. You decide approach or recession from whether the observed wavelength is shorter or longer than the laboratory value, then state redshift (receding) or blueshift (approaching) explicitly in your answer.

Worked example 7b - blueshift of an approaching galaxy

The Andromeda galaxy approaches the Milky Way at about 110 km s^{-1}. By how much is the 656.3 nm hydrogen line shifted in its spectrum, and in which direction?

$\Delta\lambda = \lambda\, v / c = 656.3 \times 1.10 \times 10^5 / (3.00 \times 10^8) = \mathbf{0.24\ nm}$.

The galaxy approaches, so the observed wavelength is *shorter*: the line appears at about 656.1 nm - a **blueshift**. Note how tiny the fractional shift is (≈ 0.04%): precise spectroscopy is needed, which is why spectral *lines*, with sharply defined laboratory wavelengths, are used rather than the broad continuous spectrum.

7. Applications

7.1 Radar speed measurement

A radar gun fires microwaves at a moving car. Two shifts happen in succession: the car acts first as a **moving observer** (it receives an already-shifted frequency) and then as a **moving source** (it re-emits, i.e. reflects, that shifted frequency while moving). The received echo is therefore shifted **twice**, and for $v \ll c$ the total beat frequency between the outgoing and returning waves is

$$\Delta f \approx 2f\, v / c$$

The gun mixes the transmitted and reflected signals electronically and measures this small beat frequency directly - far easier than measuring a tiny change in an enormous frequency.

Worked example 8 - radar gun

A police radar operates at 24.0 GHz. A car approaches and the reflected signal beats with the transmitted one at 4.8 kHz. Find the car's speed.

$v = \Delta f \times c / (2f) = 4800 \times 3.00 \times 10^8 / (2 \times 24.0 \times 10^9) =$ **30 m s^{-1}** (108 km h^{-1}).

Note the factor 2 for the double shift (receive, then re-emit), and note that the radar measures only the component of velocity *along the beam*.

7.2 Medical ultrasound (blood flow)

In Doppler ultrasound, a probe sends high-frequency sound (typically 2-10 MHz) into the body. Moving red blood cells reflect it, and exactly as with radar the echo is Doppler-shifted twice, so $\Delta f \approx 2f\,u / v$, where u is the blood speed along the beam and $v \approx 1540$ m s^{-1} is the speed of sound in soft tissue. Flow towards the probe raises the echo frequency; flow away lowers it. Machines colour-code this (conventionally red towards, blue away) and can detect narrowed arteries, where the same volume of blood must flow faster, as regions of unusually large shift.

Worked example 9 - blood flow

A 5.0 MHz ultrasound beam is directed along an artery. The echo returns shifted by 2.6 kHz. Taking the speed of sound in tissue as 1540 m s^{-1}, estimate the blood speed.

$u = \Delta f \times v / (2f) = 2600 \times 1540 / (2 \times 5.0 \times 10^6) =$ **0.40 m s^{-1}**.

This is a typical peak speed in a healthy large artery; a stenosed (narrowed) artery can double or triple it.

7.3 Astronomy

- **Receding galaxies:** absorption lines in the spectra of almost all galaxies are redshifted, and the shift grows with distance. Interpreting $\Delta\lambda/\lambda$ as a recession speed leads to Hubble's law and the expanding-universe model (Theme E context).
- **Binary stars and exoplanets:** a star orbiting a companion moves alternately towards and away from us, so its spectral lines swing periodically between blueshift and redshift. The period and size of the swing reveal the orbit.
- **Rotating bodies broaden spectral lines:** when a star (or galaxy, or Saturn's rings) rotates, one edge approaches us while the opposite edge recedes. Light from the approaching limb is blueshifted, from the receding limb redshifted, and from the centre unshifted. A single sharp emitted line is therefore received smeared over a range of wavelengths - **Doppler broadening**. The width of the line measures the rotation speed.

> **Qualitative marks:** Rotation questions are almost always explain-style. The three ideas examiners look for: opposite edges have opposite radial velocities; each produces an opposite shift; the superposition of all shifts broadens (not displaces) the line.

7.4 Other uses worth recognising

- **Weather radar:** raindrops reflect microwaves; the double Doppler shift maps wind speeds inside storms and gives early warning of rotation in severe weather.
- **Bats and sonar:** a bat closing on an insect receives its returning ultrasound chirp shifted upward; some species even lower their emitted pitch to keep the echo in the sweet spot of their hearing.
- **Satellite tracking:** the smooth rise and fall of a satellite's radio frequency as it passes overhead locates it precisely - the principle behind the earliest satellite navigation systems.

Choosing the right relationship

Situation in the question	Use
Sound; source moves through the air (HL)	$f' = f v / (v \pm u_s)$
Sound; observer moves through the air (HL)	$f' = f (v \pm u_o) / v$
Sound; both move along the line joining them (HL)	$f' = f (v \pm u_o) / (v \pm u_s)$
Light or any EM wave, v << c (SL)	$\Delta f / f = \Delta\lambda / \lambda \approx v / c$
Reflection off a moving target (radar, ultrasound, echo)	double shift: $\Delta f \approx 2 f u$ / (wave speed)

8. Common pitfalls

- **Sign errors:** choosing + or - by memory instead of physics. Always predict "pitch up or down?" first, then make the equation agree.
- Using the sound (medium-based) formulas for light. Light has no medium: use $\Delta f/f \approx v/c$.
- Putting the observer speed in the denominator or the source speed in the numerator. Source changes the wavelength (denominator); observer changes the effective wave speed (numerator).
- Saying the pitch of an approaching siren "increases as it gets closer". At constant speed the observed frequency is constant (and high) during approach; it is loudness that grows. The frequency drops as the source passes.
- Forgetting the factor 2 in reflection (radar, ultrasound) problems - or inserting it when the source itself moves and no reflection occurs.
- Using the full speed when only the radial (line-of-sight) component causes a shift.
- Claiming the source's own frequency changes. It never does - only the observed frequency differs.

9. Quick reference

Result	Statement
Moving source (HL)	$f' = f v / (v \pm u_s)$ - approach: minus sign (smaller denominator, higher f')
Wavelength near a moving source (HL)	$\lambda' = (v \pm u_s) / f$ - compressed ahead, stretched behind
Moving observer (HL)	$f' = f (v \pm u_o) / v$ - approach: plus sign (larger numerator, higher f')
Light, v << c (SL)	$\Delta f / f = \Delta\lambda / \lambda \approx v / c$ - redshift = receding, blueshift = approaching
Reflection (radar / ultrasound)	$\Delta f \approx 2 f u$ / (wave speed) - double shift: target receives, then re-emits

Result	Statement
Rotating body	opposite limbs shift oppositely → spectral line is broadened, not displaced

10. Test yourself

Attempt these without notes; full answers below. Take the speed of sound in air as 340 m s^{-1} and c = 3.00 × 10^8 m s^{-1} throughout.

1. (SL) Using a wavefront diagram, explain why an observer standing behind a receding siren hears a lower pitch.

2. (SL) State two physical differences between the Doppler effect for sound and for light.

3. (HL) A car horn emits 800 Hz. The car approaches a stationary listener at 30 m s^{-1}. Find the observed frequency.

4. (HL) A loudspeaker fixed on a pole emits 680 Hz. A jogger runs directly away from it at 25 m s^{-1}. Find the frequency heard.

5. (HL) How fast must an observer move towards a stationary 500 Hz source to hear 550 Hz?

6. (HL) A source emitting 1.2 kHz recedes from a stationary observer at 20 m s^{-1}. Find the observed frequency and the wavelength behind the source.

7. (SL) A spectral line of laboratory wavelength 486.1 nm appears at 500.7 nm in a quasar spectrum. Find the radial speed and state the direction of motion.

8. (SL/HL) A radar gun transmitting at 10.5 GHz measures a beat frequency of 2.1 kHz from an approaching motorbike. Find its speed.

9. (SL/HL) A 4.0 MHz Doppler ultrasound probe records an echo shift of 1.8 kHz from blood in a vein (sound speed in tissue 1540 m s^{-1}). Estimate the blood speed along the beam.

10. (SL) The hydrogen line from the east limb of the rotating Sun is measured at a very slightly shorter wavelength than from the west limb. Explain what this shows and how the difference could give the Sun's rotation speed.

Answers

1. Each wavefront is emitted from a point further from the observer than the previous one, so successive wavefronts behind the source are spaced further apart: the wavelength is increased. The wave still travels at v in the medium, so the observer receives fewer wavefronts per second - a lower frequency.

2. Sound travels in a medium, so source motion and observer motion relative to that medium are physically different cases with different formulas; light has no medium, so only the relative velocity matters. Also, sound shifts can be large fractions of f, while the light formula used is an approximation valid only for $v \ll c$.

3. f' = 800 × 340 / (340 - 30) = 800 × 340 / 310 = **877 Hz**.

4. f' = 680 × (340 - 25) / 340 = 680 × 315 / 340 = **630 Hz**.

5. 550 = 500 (340 + u_o) / 340 → 340 + u_o = 374 → u_o = **34 m s^{-1}**.

6. f' = 1200 × 340 / (340 + 20) = 1200 × 340 / 360 = **1133 Hz** (≈ 1.13 kHz). Wavelength behind: λ' = 360 / 1200 = **0.300 m** (check: 340 / 0.300 = 1133 Hz).

7. $\Delta\lambda$ = 14.6 nm, so $v = c\,\Delta\lambda / \lambda = 3.00 \times 10^8 \times 14.6 / 486.1 =$ **9.0×10^6 m s^{-1}**. Wavelength increased → redshift → the quasar is **receding**.

8. $v = \Delta f\, c / (2f) = 2100 \times 3.00 \times 10^8 / (2 \times 1.05 \times 10^{10}) =$ **30 m s^{-1}**.

9. $u = \Delta f\, v / (2f) = 1800 \times 1540 / (2 \times 4.0 \times 10^6) =$ **0.35 m s^{-1}**.

10. The east limb's light is blueshifted, so that limb is rotating towards us while the west limb recedes: the Sun rotates. The wavelength difference between the limbs corresponds to $2v$ (one limb approaching, one receding), so $v = c\,\Delta\lambda / (2\lambda)$ gives the equatorial rotation speed.