INTERNATIONAL BACCALAUREATE · IB DIPLOMA · PHYSICS · HL • EXERCISE SHEET

15.3 Doppler effect (full C.5, HL)

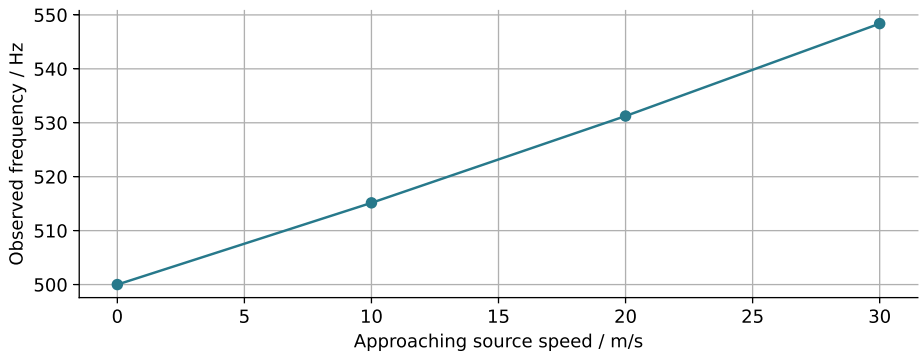
Name: _____ Class: _____ Date: _____ **Total: 29 marks**

KEY WORDS Doppler effect • redshift • blueshift • rest wavelength

Objective

Practise the full guide C.5 toolkit including AHL: the Doppler effect for sound and electromagnetic waves, wavefront diagrams for a moving source or observer, the low-speed light shift $\Delta f/f = \Delta\lambda/\lambda \approx v/c$, spectral-line shifts as evidence of stellar and galactic motion, the radar and medical applications; at higher level also the sound Doppler equations $f' = f\,v/(v \mp u_s)$ for a moving source and $f' = f\,(v \pm u_o)/v$ for a moving observer. Original practice; not an official IB paper.

1 Key knowledge and worked examples



■ **The C.5 rule set (HL)**

$$\frac{\Delta f}{f} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c} \quad (v \ll c) \qquad f' = f\,\frac{v}{v \mp u_s} \qquad f' = f\,\frac{v \pm u_o}{v}$$

Wavefronts bunch ahead of a moving source (observed frequency rises) and stretch behind it (frequency falls). For light: blueshift on approach, redshift on recession; the shift of a known spectral line from its rest wavelength gives the radial speed of a star or galaxy.

■ **Worked example: reading a galaxy spectrum**

A hydrogen line with rest wavelength 656 nm appears at 659 nm. $\Delta\lambda = 3$ nm, so $\Delta\lambda/\lambda = 3/656 = 4.6 \times 10^{-3}$ and $v = 0.0046c = 1.4 \times 10^6$ m/s – redshift, so the galaxy recedes. Two habits: always compare with the rest wavelength of a known line, and check the direction of the shift before naming the motion.

2 Practice

2.1 Describe, in terms of wavefronts, why the pitch of a siren rises as it approaches a stationary listener. [2]

2.2 State what is meant by a redshift, and what it indicates about the motion of the source. [2]

2.3 State the condition under which the relation $\Delta\lambda/\lambda \approx v/c$ may be used for light. [1]

2.4 Name two applications of the Doppler effect, one in medicine and one outside it. [2]

2.5 A fire engine's 500 Hz siren travels at 34 m/s toward a stationary listener; the speed of sound is 340 m/s. Calculate the observed frequency approaching, and receding at the same speed. [3]

3 Exam-style questions

3.1 A distant star's hydrogen line, rest wavelength 486 nm, is observed at 484 nm. Calculate the fractional shift and the radial velocity, and state the direction of motion. [3]

3.2 Explain how comparing several spectral lines from a galaxy with laboratory rest wavelengths gives both the direction and the speed of its motion. [4]

3.3 A radar speed gun emits radio waves that reflect from a moving car and return with a shifted frequency. Explain why the reflected wave is shifted, and why the car's speed can be found from the size of the shift. [3]

3.4 A police siren passes a stationary observer. Describe how the observed pitch changes as the siren approaches, passes and recedes, explaining the change at each stage in terms of wavefronts. [4]

3.5 A 400 Hz source and a listener can each move at 20 m/s (v = 340 m/s), one at a time. Calculate the observed frequency when the source moves toward the stationary listener, and when instead the listener moves toward the stationary source, and explain why the two answers differ. [5]

Solutions

Original-task marking: M1 method, A1 accuracy, B1 reasoning.

2.1 The moving source chases the wavefronts it emits ahead of itself, so the fronts are bunched together ahead – more fronts reach the listener per second and the observed frequency (pitch) rises.

2.2 A shift of spectral lines to longer wavelengths than the rest values; the source is moving away from the observer.

2.3 The relative speed v must be much smaller than the speed of light.

2.4 Medical: Doppler ultrasound measuring blood-flow speed; any other: radar speed guns, weather radar, astronomy redshifts.

2.5 Approaching: $f' = fv/(v - u_s) = 500 \times 340/306 = 556$ Hz; receding: $f' = 500 \times 340/374 = 455$ Hz.

3.1 $\Delta\lambda/\lambda = (484 - 486)/486 = -4.1 \times 10^{-3}$; $v = 4.1 \times 10^{-3} \times 3.0 \times 10^{8} = 1.2 \times 10^{6}$ m/s; the negative shift is a blueshift – the star approaches.

3.2 Each element emits at known rest wavelengths, so matching the observed pattern identifies the lines and the shift is measured line by line; all lines shifting together by the same fraction confirms real motion rather than an instrumental effect; shift to longer wavelengths = recession, shorter = approach; the fractional shift times c gives the radial speed.

3.3 The reflection from the moving car acts like a re-emitting moving source, so the returned wave's frequency differs from the emitted one; the shift grows with the car's speed – $\Delta f/f \approx v/c$; comparing returned and emitted frequencies therefore yields the speed.

3.4 Approaching: fronts bunch at the listener – pitch high; at the moment of passing: relative radial speed passes through zero – the pitch slides down through its true value; receding: fronts stretch behind the siren – pitch low; the source frequency never changes; only the observed frequency does.

3.5 Moving source: $f' = 400 \times 340/320 = 425$ Hz; moving observer: $f' = 400 \times 360/340 = 424$ Hz; the moving source changes the wavelength in the medium – fronts are physically crowded – while the moving observer only crosses the unchanged wavefronts faster, so the two shifts are not identical.