BAAO
British Astronomy and Astrophysics Olympiad

British Astronomy and Astrophysics Olympiad 2024-25

Astro Challenge Paper

September to December 2024

Instructions

Time: 1 hour (30 marks).

Questions: Answer all questions in Sections A and B, but only **one** question in Section C.

Marks: Marks allocated for each question are shown in brackets on the right. Working must be shown in order to get full credit, and it is helpful to write down numerical values of any intermediate steps.

Solutions: Answers and calculations are to be written on loose paper or in examination booklets. Students should ensure their name and school is clearly written on all answer sheets and pages are numbered. A standard formula booklet with standard physical constants should be supplied.

Eligibility: All sixth form students (or younger) are eligible to sit any BAAO paper.

Further Information about the British Astronomy and Astrophysics Olympiad

To progress to the next stage of the BAAO, you must take the BPhO Round 1 (which is a general physics problem paper) in November 2024 and / or the BAAO Round 1 in January 2025. Those achieving a Top Gold in either paper will be invited to take the BAAO Round 2 on **Tuesday 25th February 2025**. *A Distinction in this paper, whilst highly commendable, no longer grants access to BAAO Round 2.*

To be eligible for a grade in this paper, it should be sat under exam conditions and all papers should have their results recorded using the online form by **Friday 13th December 2024**.

For Sections B and C, you **must** *show your working. This paper is challenging to complete in time - do as many questions as you can and later try those did you not complete or skipped.*

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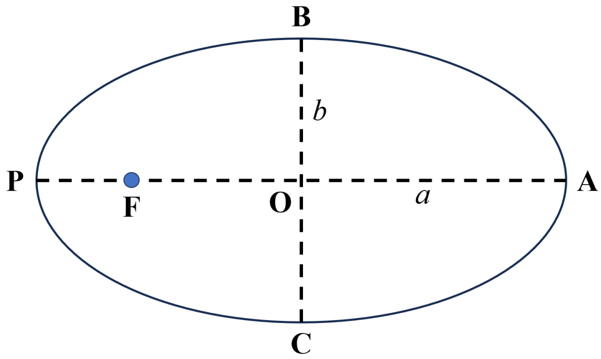
Important Constants

Constant	Symbol	Value
Speed of light	c	$3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$
Earth's rotation period	1 day	24 hours
Earth's orbital period	1 year	365.25 days
parsec	pc	$3.09 \times 10^{16}\,\mathrm{m}$
Astronomical Unit	au	$1.50 \times 10^{11}\,\mathrm{m}$
Radius of the Sun	$R_{\odot}$	$6.96 \times 10^{8}\,\mathrm{m}$
Radius of the Earth	$R_{\oplus}$	$6.37 \times 10^{6}\,\mathrm{m}$
Mass of the Sun	$M_{\odot}$	$1.99 \times 10^{30}\,\mathrm{kg}$
Mass of the Earth	$M_{\oplus}$	$5.97 \times 10^{24}\,\mathrm{kg}$
Luminosity of the Sun	$L_{\odot}$	$3.83 \times 10^{26}\,\mathrm{W}$
Absolute magnitude of the Sun	$\mathcal{M}_{\odot}$	4.74
Hubble constant	H_0	70 km s^{-1} Mpc^{-1}
Gravitational constant	G	6.67×10^{-11} m^3 kg^{-1} s^{-2}
Boltzmann constant	k_{B}	1.38×10^{-23} J K^{-1}
Permittivity of free space	ε_0	8.85×10^{-12} F m^{-1}
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ H m^{-1}
Planck's constant	h	6.63×10^{-34} J s
Elementary charge	e	1.60×10^{-19} C
Proton rest mass	m_{p}	1.67×10^{-27} kg
Electron rest mass	m_{e}	9.11×10^{-31} kg
Avagadro's constant	N_A	6.02×10^{23} mol^{-1}

Important Formulae

You might find the diagram of an elliptical orbit below useful in solving some of the questions:



Elements of an elliptic orbit:

$a = \mathbf{OA}\ (= \mathbf{OP})$	semi-major axis
$b = \mathbf{OB}\ (= \mathbf{OC})$	semi-minor axis
$e = \sqrt{1 - \frac{b^2}{a^2}}$	eccentricity
$\mathbf{F}$	focus
$\mathbf{PF} = a(1-e)$	periapsis distance (shortest distance from $\mathbf{F}$)
$\mathbf{AF} = a(1+e)$	apoapsis distance (longest distance from $\mathbf{F}$)
πab	area of the ellipse

Kepler's Third Law:

$$T^2 = \frac{4\pi^2}{GM}a^3$$

Brightness (Intensity):

$$b = \frac{L}{4\pi d^2}$$

Magnitudes:

$$\frac{b_1}{b_0} = 10^{-0.4(m_1 - m_0)}$$

$$m - \mathcal{M} = 5\log\left(\frac{d}{10}\right)$$

Distance-Parallax Relation:

$$d = \frac{1}{p}$$

Redshift:

$$z = \frac{\Delta\lambda}{\lambda_{\text{emit}}} \approx \frac{v}{c}$$

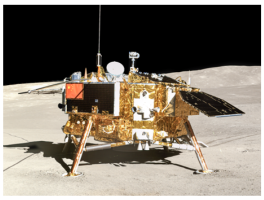
Hubble's Law:

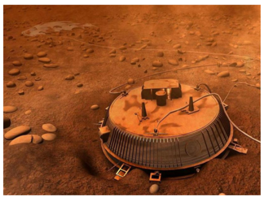
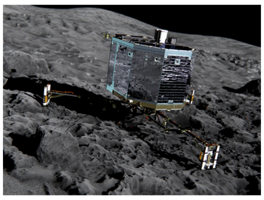
$$v = H_0 d$$

Section A: Multiple Choice

Write the correct answer to each question. Each question is worth 1 mark. There is only one correct answer to each question. **Total: 10 marks**.

1. The year 2024 marks the 10^{th} anniversary of the landing by which of the following spacecraft?

A.

B.

C.

D.


   A. Chang'e 4 (landed on the Moon)
   B. Curiosity (landed on Mars)
   C. Huygens (landed on Titan)
   D. Philae (landed on comet 67P/Churyumov-Gerasimenko)

2. If the Moon appears to be exactly half illuminated by the Sun, what is the Sun-Earth-Moon angle, assuming the Earth and Moon travel in circular orbits? The (centre-to-centre) average distance between the Earth and the Moon is $384\,400$ km.

   A. $87°$
   B. $89.85°$
   C. $90.00°$
   D. $90.15°$

3. Using Hubble's law for recessional velocities of distant objects, find a possible expression to estimate the recessional acceleration, a, of an object as a function of distance, d, and the Hubble constant, H_0.

   A. $a = H_0^2 d$
   B. $a = H_0 d^2$
   C. $a = (H_0 d)^2$
   D. $a = H_0 d$

4. T Coronae Borealis (T CrB), nicknamed the Blaze Star, is a binary star system about 920 pc away in the constellation Corona Borealis. It is famous for being a 'recurrent nova' - that is, an object whose brightness suddenly increases and then dims again periodically. The last eruption was in 1946, and there are signs the next one will happen either at the end of 2024 or the beginning of 2025. When it does, its apparent magnitude will increase from 10.8 to around 2.5. By approximately what factor will its brightness change?

   A. 4
   B. 50
   C. 2×10^3
   D. 2×10^8

5. The Euclid space mission, launched in 2023, will image 36% of the sky in extremely high resolution to investigate the nature of dark energy and dark matter by looking at the shapes of huge numbers of distant galaxies. The visible instrument (VIS) consists of a 6×6 matrix of 4096×4132 pixel CCDs. If the scale of the image on the CCD is $0.101''$ pixel^{-1} in each axis, estimate the minimum number of photos the instrument needs to take to get the planned coverage (ignoring any gaps between the CCDs)?

   A. $31\,000$
   B. $49\,000$
   C. $86\,000$
   D. $135\,000$

6. An observer is lost at sea and sees that Polaris is $33°$ above the horizon. What is their latitude?

   A. $57°$ N
   B. $33°$ N
   C. $33°$ S
   D. $57°$ S

7. Which of the following constellations is south of the celestial equator?

   A. Andromeda
   B. Canis Major
   C. Gemini
   D. Perseus

8. Which of the following Messier objects is a nebula that can be found in the same constellation as the star Aldebaran?

   A. M1
   B. M31
   C. M42
   D. M45

9. Which of these stars will culminate at the highest altitude, as seen by an observer in Rio de Janeiro ($22.91°$ S, $43.17°$ W)?

   A. Castor (RA: $07^{\mathrm{h}}35^{\mathrm{m}}$, Dec: $+31.89°$)
   B. Rigel (RA: $05^{\mathrm{h}}15^{\mathrm{m}}$, Dec: $-8.20°$)
   C. Nunki (RA: $18^{\mathrm{h}}55^{\mathrm{m}}$, Dec: $-26.30°$)
   D. Hadar (RA: $14^{\mathrm{h}}04^{\mathrm{m}}$, Dec: $-60.37°$)

10. Between September 2024 and January 2025, Mars, Saturn, Uranus, and Neptune will all be in opposition: Mars in Gemini, Saturn in Aquarius, Uranus in Taurus, and Neptune in Pisces. In what order will their oppositions occur?

    A. Mars, Uranus, Neptune, Saturn
    B. Neptune, Uranus, Mars, Saturn
    C. Saturn, Neptune, Uranus, Mars
    D. Saturn, Uranus, Neptune, Mars

Section B: Short Answer

Each short question is worth 5 marks. **Total: 10 marks**.

Light Pollution

11. A study by Kyba et al. (2023) found that between 2011-2022 the night sky has brightened by a global average of 9.60% per year, brightening the limiting apparent magnitude and hence greatly reducing the number of stars that people can see (with much of this change attributed to a vast uptake in LED lighting over that period). Figure 1 shows the effect of changing the naked eye limiting magnitude from 5.50 to 2.50 looking in the direction of the constellation of Orion.

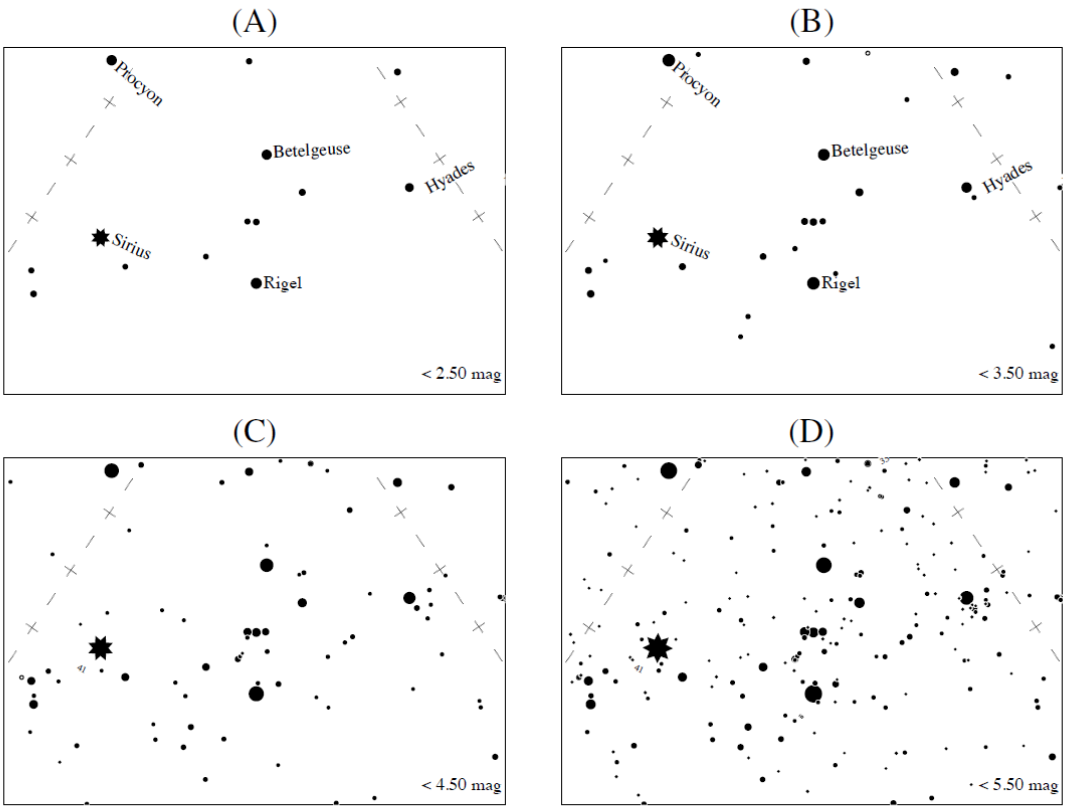


Figure 1: Four panels showing how the night sky near Orion looks for four different values of naked eye limiting magnitude, going from magnitude 2.50 (top left, very few stars) to magnitude 5.50 (bottom right, many stars). The change in limiting magnitude makes a vast difference to the number of stars visible at a site, and the increase in light pollution means this is happening well within human lifetimes. Credit: Kyba et al. (2023).

(a) Assuming you were in a place with a limiting apparent magnitude of $m = 5.0$ in 2011 and an increasing sky brightness equal to the global average, what would it now be in 2024? [2]

(b) If the trend continues, in what year will even the brightest star in the sky, Sirius ($m = -1.46$), no longer be visible at your location? [3]

Bright Comet

12. On 12 October 2024, comet C/2023 A3 (Tsuchinshan-ATLAS) is expected to have its closest approach with the Earth. When it does, the angular distance between it and the sun will be around $14.3°$ and it has the possibility to be one of the brightest comets for over a decade, easily visible to the naked eye even in towns and cities just before sunrise in the constellation of Virgo (see Figure 2).

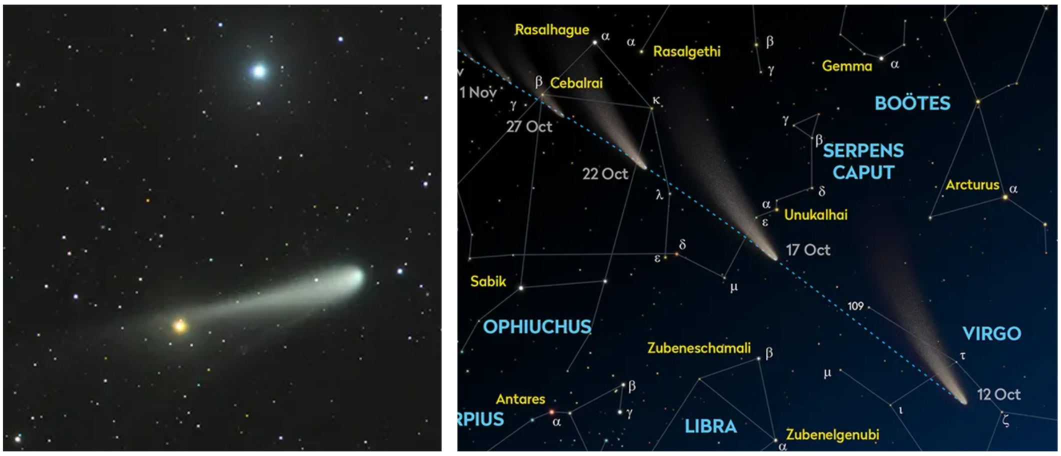


Figure 2: *Left:* C/2023 A3 (Tsuchinshan-ATLAS) from the Southern Hemisphere, captured 1 August 2024. Credit: José J. Chambó. (www.cometografia.es)
Right: Chart showing the location of Comet C/2023 A3 (Tsuchinshan-ATLAS) in October 2024. It will be best observed just before dawn. Credit: Pete Lawrence / BBC Sky at Night Magazine.

Because the luminosity of a comet is affected by its distance from the sun, an extra factor is added to the conversion between cometary apparent and absolute magnitudes as shown in the formula below:

$$m = \mathcal{M} + \frac{5}{2} K \log_{10}\left(\frac{d_{\text{Comet-Sun}}}{1\ \text{au}}\right) + 5\log_{10}\left(\frac{d_{\text{Comet-Earth}}}{1\ \text{au}}\right) .$$

K is a parameter relating to the activity of the comet and in this case can be taken to be 4.0 for the remainder of the question. The absolute magnitude of C/2023 A3 is 4.3.

Astronomers have also predicted that the comet may be ejected from the solar system after its perihelion. This is due to the very high eccentricity of its orbit, which means that interactions with the planets may significantly affect its orbit. The acceleration experienced by the comet due to the Earth's gravity, however, will not exceed 8.0×10^{-8} m s^{-2}.

(a) What will be the apparent magnitude of the comet at closest approach to Earth?

[3]

(b) The comet was first reported by the Purple Mountain Observatory, and then later reported by the Asteroid Terrestrial-impact Last Alert System (ATLAS), with an apparent magnitude of 18.1. Given that at the time of its discovery the comet was a long distance from the Sun, estimate $d_{\text{Comet-Sun}}$ when it was first announced. Give your answer in au.

[2]

Section C: Long Answer

Each long question is worth 10 marks. Answer **either** *Qu 13* **or** *Qu 14.* **Total: 10 marks**.

SpaceX Starship

13. In June 2024, the upper stage of SpaceX's experimental Starship rocket successfully performed a controlled re-entry into the earth's atmosphere for the first time during a test flight. This is a significant milestone, as Starship is intended to be the world's first fully reusable rocket, and successfully recovering the upper stage is an essential part of this. At a mass of 85 tonnes, the Starship upper stage is one of the largest and heaviest man-made objects ever to re-enter the atmosphere.

    Due to the extremely high speeds involved, the vehicle experiences extreme heating effects during its re-entry, which must be appropriately managed to prevent destruction of the vehicle. For this reason, the forwards-facing side of Starship is covered in a thermal protection system comprised of thousands of hexagonal silica tiles.

Figure 3: *Left:* Plasma build-up on Starship during re-entry, as captured by an onboard camera. The black silica tiles for the thermal protection system are visible on the bottom right of the spacecraft. Credit: SpaceX
Right: A computer rendering of starship entering the atmosphere. The direction of travel is down and to the right. Credit: SpaceX.

(a) Before entering the atmosphere, Starship is on a sub-orbital trajectory which reaches a maximum altitude above the Earth's surface of 213 km. Since the test is designed to simulate re-entering from orbit, at this point Starship is travelling at 94% of the circular orbit velocity for that height - just slow enough to re-enter the atmosphere instead of orbiting the Earth. Determine the the total energy of Starship at this point.

[4]

(b) Starship is decelerated by atmospheric drag forces until it reaches negligible speed and altitude. Determine the work done by the atmosphere during re-entry.

[2]

Starship is 50 m tall, has a diameter of 9 m, and the nose cone takes up the top 14 m. Its outer skin is made of 4 mm thick stainless steel, which has a specific heat capacity of 500 J kg^{-1} K^{-1}, a density of 8000 kg m^{-3} and a maximum operational temperature of 900 °C. To maximise the amount it is slowed down by atmospheric forces, Starship travels through the atmosphere pointing perpendicular to its direction of travel, as shown in Figure 3.

(c) Given that it initially has a temperature of approximately $0\ ^\circ$C, calculate the maximum thermal energy which can be safely transferred to the steel during re-entry. Assume all heating occurs uniformly on the forwards facing side of the spacecraft body, and that conduction to the rest of the spacecraft is negligible.

[3]

(d) Show that this means the thermal protection system has to be good enough that $< 1\%$ of the thermal energy generated by the deceleration of the Starship by the atmosphere is transferred to the steel body of the spacecraft. [1]

Speed of Sound on Mars

14. The atmosphere of Mars is carbon dioxide rich, very low pressure and rather cold – this makes it an interesting place to consider the acoustics should any future humans live on Mars as sound waves behave rather differently than what we are used to on Earth.

    The conditions of the Martian atmosphere mean that it is well modelled as an ideal gas, and so the speed of sound is given as

    $$c = \sqrt{\frac{\gamma R T}{M}}$$

    where γ is the adiabatic index (derived from thermodynamics), $R = 8.314$ J K^{-1} mol^{-1} is known as the molar gas constant, T is the absolute temperature, and M is the molar mass in kg mol^{-1}.

    For a stiff molecule like CO_2, the value of γ changes with frequency, as at low frequencies any vibrational excitation (alongside rotational excitation) can relax again before the next wave hits, whilst at high frequencies only the rotational excitation is able to relax, and so there are fewer degrees of freedom. The relaxation frequency when this transition occurs is called f_R. This means that for sound waves travelling through CO_2, there are two regimes with separate speeds:

    $$\begin{aligned} f < f_R \qquad &\text{then} \qquad \gamma = \frac{9}{7} \\ f > f_R \qquad &\text{then} \qquad \gamma = \frac{7}{5} \end{aligned}$$

    For CO_2 on Earth, $f_R \approx 40$ kHz so is outside the range of human hearing, but in the low-pressure environment on Mars that is no longer true, and humans would experience the effect of high and low frequencies travelling at different speeds when listening to everyday sounds.

    (a) Given that f_R is directly proportional to atmospheric pressure and Mars has a surface atmospheric pressure of about 0.6 kPa, show that f_R is within the human hearing range. [1]

    (b) Taking a typical temperature on the surface of Mars to be 230 K and the molar mass of the Martian atmosphere to be 43.34 g mol^{-1}, show that high frequencies travel about 10 m s^{-1} quicker than low frequencies. [2]

    As well as having a much lower pressure than on Earth, the Martian atmosphere is also much less dense, with a density of only $\rho = 0.02$ kg m^{-3} and so has a much smaller acoustic impedance, given by the formula $Z = \rho c$. The consequence of this is that a given source of sound will be much quieter on Mars than on Earth, with the difference measured in decibels as

    $$10 \log_{10} \left(\frac{Z_{Earth}}{Z_{Mars}} \right).$$

    (c) Given the density of Earth's atmosphere (at sea level) is 1.217 kg m^{-3} with a typical sound speed of 340 m s^{-1} (at room temperature) whilst in the $f < f_R$ regime, calculate how much quieter a sound on Mars will be to human ears compared to Earth, giving your answer in decibels. [2]

The speed of sound on Mars has long been derived from temperature measurements. However, the Perseverance rover, which landed on Mars in 2021, had a microphone on board that was able to make in-situ recordings and test some of these models.

One experiment involved laser-induced sparks (with $3 < f < 15$ kHz and so $f > f_R$) used as the sound source, but perhaps the most creative was to use the small helicopter the probe had brought with it (called Ingenuity) as a low frequency source (and so $f < f_R$) where they could use the Doppler effect on the recorded frequency of the noise made by its blades (with emitted sound frequency of 84.44 Hz) as it flew past Perseverance in order to calculate the speed of sound directly.

Data from the fourth flight of Ingenuity is shown in Figure 4, where it takes off 76 m from Perseverance, and travels in a straight line coming as close as 69 m and ending its flight 123 m from the microphone before stopping and coming back the way it came. Data for the first 60 s was not reliable due to interference from wind and gusts, but from 60 s onwards the recording was clean and allowed a good determination of the speed of sound in this regime.

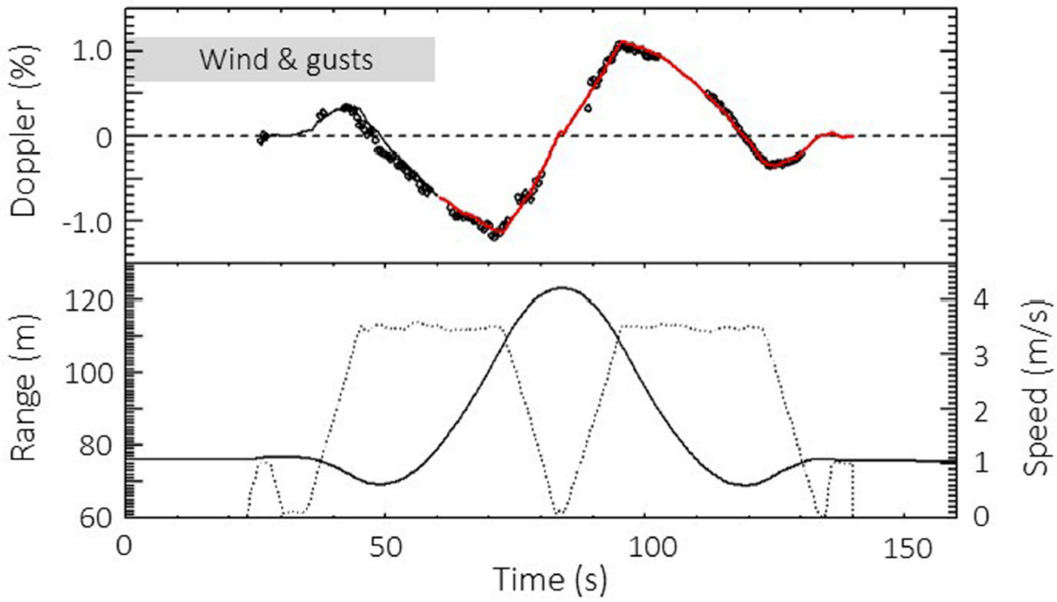


Figure 4: *Top:* Variations of the received frequency along the trajectory of the flight (diamond symbol) along with the best fitting model (solid line). During the first 60 s, the recording is perturbed by high winds so the data is less reliable. Credit: Maurice et al. (2022)
Bottom: Range between the rover and Ingenuity (solid line, left y-axis) and the speed of Ingenuity at the time (dotted line, right y-axis). Credit: Maurice et al. (2022)

(d) Take measurements from Figure 4 to determine the speed of sound on Mars. Compare your value to the low frequency sound speed calculated in part (b) and comment on your answer. [5]

END OF PAPER

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