British Astronomy & Astrophysics Olympiad (BAAO) Syllabus

(Updated Oct 2023)

The BAAO offers several competitions at different levels of difficulty, and with different formats. This document hopes to clarify and summarise the syllabus examined in each one after the major update in summer 2023.

How does the major update affect use of past papers pre-2023?

The academic year 2022-23 was the last year of the original format of papers and competitions. After listening to lots of feedback from teachers at schools that take part regularly some changes have been made – in general, the papers have been pushed back later into the year to allow more students to have covered the relevant material in their A Level courses to be able to successfully engage with a greater selection of questions. The major headlines are:

- Astro Challenge will no longer be a route to Astro Round 2 and will be simplified to increase the number of distinctions. Observational astronomy will be a larger part of the multiple-choice section. It will still be released at the beginning of September, but the distinction certificate eligibility deadline will be moved to the end of the autumn term and there will no longer be a need for a scan
    - Past papers are therefore harder than the 2023 onwards papers, so your students should find the new ones more accessible – please encourage them to have a go
    - The number of distinctions, merits and commendations will be recorded in an online form
- A new competition, Astro Round 1, will be launched in late Jan 2024. It will follow a similar format to the Physics Round 1, with short questions and long questions, and will have paid entry (although some schools will get free entry for some students, like for Physics Round 1)
    - A sample paper is available on the BPhO website to give examples of the sorts of questions faced in Section 1 (short questions) and Section 2 (optional long questions, including an example of the new observational astronomy questions)
- The BAAO Competition paper will be rebranded as the Astro Round 2 and will be available to those that get a Top Gold in either the Physics OR Astro Round 1 - no paid entry, and no entry via distinction in the Astro Challenge. It will be sat in mid-late February, with students notified if they have made the Easter selection camp at the beginning of March
    - There are no major changes to Astro Round 2 and so all past papers are good preparation for the level of demand required

Additional Resources

All of the papers will pose some challenge to even the brightest students, so if there are questions they find hard or cannot do, that should not put them off from applying their problem solving skills.

Many of the topics in the syllabus are covered at A Level, but no one specification covers them all and in some cases the material will be in an optional module. However, do not let that put your students off as we have the following accommodations:

- **Many of the formulae will be given in the paper**. Those not given are generally in an A Level equations sheet, which they are also free to use when solving the paper
- Much of the new material is relatively easy to pick up oneself. To help with this, **self-study guides are available on the BPhO website** to help with independent study on any unfamiliar material through several worked examples showing how to apply these formulae / concepts

Syllabus at a Glance

<table>
<tr><th></th><th colspan="5">TOPIC AREA</th></tr>
<tr><th>COMPETITION</th><th>Celestial Mechanics</th><th>Stars, Blackbodies, and Magnitudes</th><th>Optics</th><th>Galactic Physics and Cosmology</th><th>Observational Astronomy</th></tr>
<tr><td>Junior Astro Challenge (JAC)</td><td colspan="5">This covers general astronomical knowledge consistent with Key Stage 3, most GCSEs, and an interest in Astronomy from general wider reading. It is meant as a quiz rather than an exam, so a syllabus will not be included here.</td></tr>
<tr><td>Astro Challenge (AC)</td><td>Gravitational fields
Escape velocity (parabolic orbits)
Circular motion
Elliptical orbits
Kepler’s 3rd Law</td><td>Brightness (intensity) and luminosity (power)
Apparent magnitude
Absolute magnitude</td><td>Photon energy
Arcminutes and arcseconds
Parallax</td><td>Spectral absorption / emission lines
Doppler Effect
Redshift
Hubble’s Law</td><td>Only examined in the multiple-choice section (see Appendix A for details)</td></tr>
<tr><td>Astro Round 1 (R1)</td><td>Same as AC plus:

Cartesian and parametric forms of an ellipse
Vis-viva equation
Binary star systems
Eclipses, occultations & transits</td><td>Same as AC plus:

Blackbody equations
Thermal physics
Nuclear physics
Stellar evolution
Schwarzschild radius</td><td>Same as AC plus:

Aperture size and focal length
Rayleigh criterion
Thin lens equation
Refracting telescope
Reflecting telescope</td><td>[No extra assumed knowledge]</td><td>Only examined as an optional question in Section 2 (see Appendix B for details)</td></tr>
<tr><td>Astro Round 2 (R2)</td><td>Same as R1 plus:

Hyperbolic orbits
Kepler’s 2nd law</td><td colspan="4">R2 will also require advanced mathematical skills:

Calculus (some basic calculus also in R1), numerical methods, vectors, statistical methods

Observational astronomy will not be examined in this paper</td></tr>
</table>

This list is NOT exhaustive, and questions may include core AS and A Level material in a space-based context (e.g. a circuits question in the context of the electronics inside a space probe). They may also not stick rigidly to these rows, although if they do (or if they are on material outside this syllabus e.g. angular momentum), relevant formulae and information will be given in the question.

Detailed Syllabus

Key:

Non-bold text	Material in Astro Challenge
Bold text	Material only in Round 1
<u>Bold italic underlined text</u>	Material only in Round 2
Blue text	Potentially unfamiliar from A Level and so covered in self-study guide
$Formula *$	Formula given in the exam paper (note: others may be given in the question)

Note: This list is NOT exhaustive, and other parts of core AS and A Level material can be examined

<u>0. General</u>: Subscript notation ⊙ for 'solar' and ⊕ for 'Earth' e.g. $M_\odot, R_\oplus$ for solar mass, Earth radius

<u>1. Celestial Mechanics</u>

a. Standard gravitational fields material from A Level
   i. Newton's law of gravitational attraction giving the magnitude of the gravitational force between masses m_1 and m_2 separated by a distance r from the centre of mass of each object
$$F_G = \frac{Gm_1m_2}{r^2}$$
   ii. Gravitational field strength (magnitude) in radial fields; M is the total mass enclosed within radius r
$$g = \frac{GM}{r^2}$$
Field inside solid spheres and spherical shells. Neutral points (*g* = 0) and field lines.
Graphical relationship between *g* and F_G
   iii. Gravitational potential energy of an object of mass m in the radial field of an object of mass M at a distance from the centre of mass r
$$E_P = -\frac{GMm}{r}$$
Applying energy conservation in a binary system (total energy = [sum of KE of both objects] + GPE of one in the other's field)
   iv. Gravitational potential a distance r from the centre of mass of an object M
$$V_G = -\frac{GM}{r}$$
Potential inside solid spheres and spherical shells. Equipotentials.
Graphical relationship between E_P and V_G

b. Escape velocity is achieved when the total energy (KE + GPE) is zero; this is a parabolic path
$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

c. Standard circular motion material from A Level
   i. Angular frequency
$$\omega = 2\pi f = 2\pi/T$$
   ii. Centripetal acceleration
$$a = v\omega = \frac{v^2}{r} = r\omega^2$$
   iii. Centripetal force
$$F = ma = mv\omega = \frac{mv^2}{r} = mr\omega^2$$
   iv. Speed in a circular orbit (in a gravitational field)
$$v = \frac{2\pi r}{T} = r\omega \left(= \sqrt{\frac{GM}{r}} \right)$$

d. Properties of elliptical orbits
   i. Orbit of the object is around one of the foci of the ellipse
   ii. Semi-major (a) axis and semi-minor (b) axis of an ellipse
   iii. Eccentricity of an ellipse defined as

$$e = \sqrt{1 - \frac{b^2}{a^2}} \qquad *$$

   For a circle, e = 0. For a parabola, e = 1. ***For a hyperbola e > 1***
   iv. Closest distance to the orbiting focus is the periapsis

$$r_p = a(1 - e) \qquad *$$

   v. Furthest distance from the orbiting focus is the apoapsis

$$r_a = a(1 + e) \qquad *$$

   vi. Area of an ellipse

$$A = \pi ab \qquad *$$

   vii. An ellipse can also be given in cartesian form and parametric form

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad (x, y) = (a\cos t, b\sin t) \quad \text{for } 0 \le t \le 2\pi$$

   viii. Total energy (KE + GPE) in an elliptical orbit is negative. **Total energy in a parabolic (escape) orbit is zero.** ***Total energy in hyperbolic orbit is positive***
   ix. The speed of an object a distance r from the focus is given with the vis viva equation

$$v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right) \qquad *$$

e. Kepler's 1st law: the orbit of a planet is an ellipse with a star at one of the two foci

f. ***Kepler's 2nd law: a line segment between an orbiting body and the focus of the ellipse sweeps out equal areas in equal times [this comes from conservation of angular momentum]***

$$\frac{dA}{dt} = \frac{1}{2}r^2\frac{d\theta}{dt} = \frac{\pi ab}{T}$$

g. Kepler's 3rd law applied to both circular and elliptical orbits
   i. For an elliptical orbit

$$T^2 = \frac{4\pi^2}{GM_{tot}}a^3 \qquad *$$

   Using the Earth's orbit as a reference, if T is in years and a is in astronomical units (au) and M_{tot} is in solar masses then $T^2 = a^3/M_{tot}$
   ii. The M_{tot} is the mass of the whole system. For a planet of mass m and star of mass M then $M_{tot} \approx M$ (since m << M)
   iii. For a circular orbit of radius r then a = r

h. Modifications for binary systems
   i. Kepler 1: Each object moves in its own elliptical orbit with the centre of mass of the system coincident with one focus in each ellipse
   ii. Kepler 3: For objects for which one mass is not negligible compared to the other, M_{tot} must be used, and $a = a_1 + a_2$ where a_1 and a_2 are the semi major axes of each object's own elliptical orbit

i. Eclipses, occultations and transits
   i. Eclipse: one astronomical object is temporarily obscured by another (e.g. the moon eclipses the Sun during a solar eclipse)
   ii. Occultation: an eclipse where the background object is completely obscured (e.g. a star might be occulted by a planet)
   iii. Transit: an eclipse where there is only partial obscuration of the background object (e.g. a transit of Venus across the Sun means we see its silhouette move across the solar disc). The effect on the light curve of a star of a transit by an exoplanet is one of the methods of detection used to find them

2. Stars, Blackbodies and Magnitudes

a. Brightness (intensity) from a point source of luminosity (power) L a distance d away from it is

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

b. Apparent magnitude
   i. This scale has large positive numbers corresponding to faint objects and large negative numbers corresponding to bright objects
   ii. The human eye can (in a dark sky) see down to an apparent magnitude of +6
   iii. A change in apparent magnitude of 5 magnitudes corresponds to a change in brightness of a factor of 100
   iv. The relationship between the apparent magnitudes of two objects and their brightness is

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

c. Absolute magnitude
   i. The absolute magnitude is the apparent magnitude of an object when observed from a distance of 10 parsecs (pc)
   ii. The relationship between apparent and absolute magnitude is

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

   where d is the distance in parsecs

d. Blackbody equations
   i. The wavelength corresponding to the maximum in a blackbody spectrum is related to its absolute temperature (in kelvin) via Wien's displacement law

$$\lambda_{max} T = \text{constant} \qquad *$$

   where the constant is 2.90×10^{-3} m K (metres kelvin)
   ii. The total luminosity of a blackbody is related to its temperature and its emitting surface area via the Stephan-Boltzmann law

$$L = A\sigma T^4$$

   where σ is the Stephan-Boltzmann constant. Often the object is spherical and so $A = 4\pi R^2$ where R is the radius of the sphere, and so

$$L = 4\pi R^2 \sigma T^4 \qquad *$$

   iii. Thermal equilibrium achieved from radiative balance (where the input power equals the emitted power)

e. Standard thermal physics material from A Level
   i. Specific heat capacity

$$Q = mc\Delta\theta$$

   ii. Specific latent heat

$$Q = mL$$

   iii. Idea of conduction in solids and convection in fluids
   iv. Applications of ideal gas equations in astrophysical situations

$$pV = Nk_BT = nRT = \frac{1}{3}Nmc_{rms}^2$$

$$p = \frac{1}{3}\rho c_{rms}^2$$

$$KE_{av} = \frac{1}{2}mc_{rms}^2 = \frac{3}{2}k_BT$$

f. Standard nuclear physics material from A Level
   i. Energy-mass equivalence

$$E = mc^2$$

   ii. Binding energy and mass defect
   iii. Balancing nuclear equations using conserved quantities

g. **Stellar evolution**
   i. **Basic understanding of the lifecycle of low and high mass stars (GCSE is sufficient)**
   ii. **Schwarzschild radius of a black hole (derived classically from setting the escape velocity of an object equal to the speed of light)**

$$r_S = \frac{2GM}{c^2}$$

<u>3. Optics</u>

a. Energy of a photon

$$E = hf = \frac{hc}{\lambda}$$

b. Small measures of angle (useful to astronomers)
   i. Arcminute (’) = 1/60th of a degree (°)
   ii. Arcsecond (”) = 1/60th of an arcminute = 1/3600th of a degree (so 1° = 60’ = 3600”)

c. Parallax
   i. A way of measuring the distance to an object by looking for an angular shift relative to the “fixed” background stars
   ii. A distance of 1 astronomical unit (au) subtends a parallax angle of 1 arcsecond when it is a distance of 1 parsec (pc) away (from the definition of a parsec), leading to the distance-parallax equation

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

   where d is the distance in parsecs and p is the parallax angle in arcseconds

d. **Telescope aperture and focal length**
   i. **The aperture size of a telescope is typically taken to be the diameter of the objective element (whether a lens or a mirror), often the same as the diameter of the opening of the telescope tube**
   ii. **Since the rate of received photons from a source is proportional to the area of the aperture, the larger the aperture the fainter objects can be seen**
   iii. **The focal length is the distance from the objective element to the focal point (principal focus) for incoming parallel rays (typical of a very distant object)**
   iv. **The f-number is the ratio of the aperture size and the focal length of the telescope**

e. **For a circular aperture, the Rayleigh criterion is**

$$\theta = \frac{1.22\lambda}{D} \qquad *$$

where θ is the smallest angular distance that can be resolved (or the closest two objects can be on the sky before they look like a single object), λ is the wavelength being used for observations and D is the aperture size

f. **Behaviour of thin lenses**
   i. **Draw and use ray diagrams for the action of converging and diverging lenses to find the location of real and virtual images**
   ii. **Use the thin lens formula (presented here using the Cartesian sign convention, but any other convention would be acceptable)**

$$\frac{1}{u} + \frac{1}{f} = \frac{1}{v}$$

   where u is the object distance, f is the focal length, and v is the image distance
   iii. **Magnification of a single lens**

$$M = \frac{v}{u}$$

g. Refracting and reflecting telescopes

  i. Refracting telescopes use a lens as the objective element, whilst reflecting telescopes use a mirror. In both cases, the objects element has focal length f_o

  ii. The eyepiece contains a lens, with focal length f_e

  iii. When in normal adjustment, the eyepiece creates a virtual image at infinity, meaning the magnification of the two-element system is

$$M = \frac{f_o}{f_e}$$

  and the total distance from the objective lens to the eyepiece lens (for a refracting telescope) is $f_o + f_e$

4. Galactic Physics and Cosmology

a. Spectral (atomic) absorption and emission lines
  i. Caused by electrons moving between atomic energy levels
  ii. The energy of the photons emitted / absorbed corresponds to the energy difference between the levels

b. The Doppler effect is a shift in the observed wavelength / frequency of a spectral line due to relative motion between the observer and emitter

$$\lambda_{obs} = \lambda_{emit}\left(1 \pm \frac{v}{c}\right)$$

c. Redshift is an effect on spectral lines that appears as a Doppler effect due to high recessional velocities (although is due to the expansion of space between the observer and emitter rather than rapid movement through space)

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

This is the formula for non-relativistic recessional velocities (i.e. $v \lesssim 0.1\,c$) – if the relativistic formula is required, it will also be given

d. Hubble's Law links the recessional velocity derived from redshifts with the distance to the emitter

$$v = H_0 d \qquad *$$

Mathematical Skills for Round 1 and Round 2

a. Basic calculus
  i. Differentiation and integration of elementary functions and their sums
    I. Exponentials
    II. Polynomials
    III. Integral of 1/x
    IV. Trigonometric functions
  ii. Geometric interpretation of derivatives and integrals
  iii. Finding constants of integration using initial conditions
  iv. Use of the chain rule, product rule, quotient rule, and integration by parts
  v. Solving differential equations (first and second order ODEs only)

b. Numerical methods
  i. Linearisation of equations and expressions
  ii. Iterative solving of functions
  iii. Estimating area under a curve by graphical method and/or by numerical approximations
  iv. Taylor series approximations of common functions

c. Vectors
  i. Basic properties of vector sums
  ii. Dot and cross products
  iii. Geometrical interpretation of a time derivative of a vector quantity

- ***d. Statistical methods***
  - ***i. Mean, median, mode, percentiles, box plots***
  - ***ii. Standard deviation***
  - ***iii. Basic probabilities***
  - ***iv. Uncertainty estimation and propagation***
    - ***I. Accept linear addition of percentage uncertainties (standard A Level method) or adding in quadrature***

Appendix A – Observational Astronomy needed for the Astro Challenge (multiple-choice section only)

a. For each of the following eight constellations, know
   - i. their shape
   - ii. where they are located relative to each other
   - iii. which are above / below the celestial equator
   - iv. which are above / below the ecliptic

   1. Andromeda
   2. Canis Major
   3. Cassiopeia
   4. Gemini
   5. Orion
   6. Pegasus
   7. Perseus
   8. Taurus

b. Be able to recognise the following three asterisms, and know whether the stars they contain are from only one constellation or from several different constellations
   1. Big Dipper
   2. Great Square of Pegasus
   3. Winter Hexagon

c. Know which constellation each of the following eight stars can be found in
   1. Aldebaran (Taurus)
   2. Alpheratz (Andromeda)
   3. Betelgeuse (Orion)
   4. Castor (Gemini)
   5. Polaris (Ursa Minor)
   6. Pollux (Gemini)
   7. Rigel (Orion)
   8. Sirius (Canis Major)

d. Know what is meant by the latitude and longitude of a location

e. Remember that the declination of a star is the angle between the plane of the equator and the direction to that star

f. For each of the following four Messier objects
   - i. know the constellation where each object is located
   - ii. know their object types
   - iii. be able to recognise each object from a black and white photo
   - iv. know their Messier catalogue numbers

   1. Crab Nebula (M1, nebula in Taurus)
   2. Andromeda Galaxy (M31, galaxy in Andromeda)
   3. Orion Nebula (M42, nebula in Orion)
   4. Pleiades (M45, open cluster in Taurus)

g. Understand how the 23.5° axial inclination of the Earth leads to the lengthening and shortening of days in the northern hemisphere and remember the approximate dates on which the summer solstice, winter solstice, spring equinox and autumnal equinox occur

h. Understand how the declination of the Sun changes over the course of a year

i. Understand the meaning of the following terms:
   1. Zenith
   2. Culmination
   3. Altitude
   4. Celestial equator
   5. Ecliptic

j. If told which zodiac constellation the Sun appears to be in, be able to state the month of the year it is
    1. Aries: April
    2. Taurus: May
    3. Gemini: June
    4. Cancer: July
    5. Leo: August
    6. Virgo: September
    7. Libra: October
    8. Scorpius: November
    9. Sagittarius: December
    10. Capricornus: January
    11. Aquarius: February
    12. Pisces: March
k. If told which zodiac constellation a new, first quarter, full or third quarter moon is seen, be able to work out which zodiac constellation the Sun is in
l. Understand that if a planet is in opposition, the Sun is directly opposite that planet in the sky. Hence, be able to work out what zodiac constellation the Sun is in, if told what zodiac constellation a planet in opposition is in
m. If told when an astronomical event occurs in one location, be able to calculate when that event will occur in another location on the same day, given the longitudes of both locations
n. If told what the angle between the horizon and Polaris is for a particular observer, recognise that this is the same as the latitude of the observer

Appendix B – Observational Astronomy needed for Astro Round 1 (Section 2 optional question only)

a. Be able to locate the following 27 constellations on a star map:

i. The 13 found on the ecliptic (essentially the zodiac)

1. **Aquarius**
2. **Aries**
3. **Cancer**
4. **Capricornus**
5. **Gemini**
6. **Leo**
7. **Libra**
8. **Ophiuchus**
9. **Pisces**
10. **Sagittarius**
11. **Scorpius**
12. **Taurus**
13. **Virgo**

ii. A further 14 familiar to those in the northern hemisphere

1. **Andromeda**
2. **Aquila**
3. **Auriga**
4. **Boötes**
5. **Canis Major**
6. **Canis Minor**
7. **Cassiopeia**
8. **Cygnus**
9. **Lyra**
10. **Orion**
11. **Pegasus**
12. **Perseus**
13. **Ursa Major**
14. **Ursa Minor**

b. Be able to locate the following 17 stars on a star map:

1. **Aldebaran (Taurus)**
2. **Alpheratz (Andromeda)**
3. **Altair (Aquila)**
4. **Arcturus (Boötes)**
5. **Bellatrix (Orion)**
6. **Betelgeuse (Orion)**
7. **Capella (Auriga)**
8. **Castor (Gemini)**
9. **Deneb (Cygnus)**
10. **Polaris (Ursa Minor)**
11. **Pollux (Gemini)**
12. **Procyon (Canis Minor)**
13. **Regulus (Leo)**
14. **Rigel (Orion)**
15. **Sirius (Canis Major)**
16. **Spica (Virgo)**
17. **Vega (Lyra)**

c. Be able to locate the following 5 asterisms on a star map:

1. **Big Dipper**
2. **Great Square of Pegasus**
3. **Summer Triangle**
4. **Winter Hexagon**
5. **Winter Triangle**

d. For each of the following great circles, understand what they are and know which of the required constellations the line passes through, and which are above or below each line

1. **Celestial equator**
2. **Ecliptic**
3. **Galactic equator**

e. For each of the following 6 Messier objects

- **i. Know their location on a star map**
- **ii. Know their object types**
- **iii. Know their Messier catalogue numbers**

1. **Crab Nebula (M1): nebula (supernova remnant) in Taurus**
2. **Andromeda Galaxy (M31): galaxy in Andromeda**
3. **Orion Nebula (M42): nebula in Orion**
4. **Pleiades (M45): open cluster in Taurus**
5. **Ring Nebula (M57): (planetary) nebula in Lyra**
6. **Little Dumbbell Nebula (M76): nebula in Perseus**

f. Know how to identify planets on a star map.

g. Understand that if a planet is "in opposition", it is directly opposite the Sun in the sky

h. Understand how the stars appear to move due to the rotation of the Earth, and know which direction they would appear to move on a star map (note that cardinal points will be labelled on any maps given)

i. Know that if a star / object / etc is culminating, then it is on the meridian, which is the line directly from north to south across the sky (detailed understanding is not essential)

j. Know what is meant by solar time

k. Know how to estimate the time of day (solar time) using

- **i. the Sun visible in the sky**
- **ii. a full moon or a planet in opposition visible in the sky**

l. Understand what is meant by the latitude and longitude of a location

m. Know how to estimate the altitude of a star that is visible on a sky map

n. Know how to estimate the latitude of the location from a star map with Polaris

o. Be able to estimate the angular distance between two stars

p. Be able to find what month of the year it is

- **i. if you can see the Sun on the sky map**
- **ii. if you can't see the Sun on the sky map but you know what the solar time is**