Option F — Astrophysics

F1. (a) comets have long periods;
the orbits are very elliptical;
many have orbits off the plane of the ecliptic; ***[1 max]***

(b) volume occupied by a star is about $2^3 = 8\,\text{pc}^3$;
so number of stars is $\frac{10^{12}}{8} \approx 10^{11}$; ***[2]***
Accept any answer from 1.0×10^{11} *to* 2.4×10^{11} *(for those using sphere packing) to at most 2 s.f.*

F2. (a) power received (from a star) by an observer (on Earth) per unit area (of the detector);

a measure of the brightness of a star as it appears from Earth (in a relative classification system); ***[2]***

(b) (i) Delta Cephei because it has a larger apparent brightness; ***[1]***

(ii) Delta Cephei is closer;
because although (intrinsically) dimmer, appears brighter; ***[2]***
Award the first marking point only if second is also awarded.

(c) the surface of the star is pulsating / getting larger and smaller;
the luminosity varies because the surface area changes; ***[2]***

(d) (i) locate a Cepheid in the galaxy;
measure period to find luminosity;
distance may be determined from the relation between apparent brightness and luminosity; ***[3]***

(ii) the period is 10 days and so the peak luminosity is
$3000\times3.9\times10^{26} = 1.17\times10^{30}$ W;
correct substitution $d = \sqrt{\frac{L}{4\pi b}} = \sqrt{\frac{1.17\times10^{30}}{4\pi\times7.2\times10^{-10}}}$
$d = 1.1\times10^{19}\ \text{m}\left(=1200\ \text{ly} = 370\ \text{pc}\right)$; ***[2]***

F3. (a) electromagnetic radiation/(blackbody) radiation in the microwave region that fills the universe;
and is received from all directions in the universe / is essentially isotropic / *OWTTE*; ***[2]***

(b) CMB is characteristic of black body radiation at 3 K;
the universe was hot in its early stages;
and has cooled down because of the expansion of the universe; ***[3]***

F4. (a) (most) of the hydrogen fused to helium; ***[1]***

(b) luminosity increases;
the surface area increases; ***[2]***

(c) F is the part of the H-R diagram where white dwarfs are found;
Main sequence stars that end up with a mass under the Chandrasekhar limit / 1.4 solar masses will become white dwarfs; ***[2]***

(d) path starting on MS above the sun, leading to the super red giant region and either stopping there or shown curving downwards towards (and below) white dwarfs; ***[1]***

F5. (a) the speed of recession of distant galaxies is proportional to their separation; ***[1]***
Accept answers in terms of distances of galaxies from Earth.
Accept equation with terms defined.

(b) at the time of the Big Bang any two points were essentially at zero separation;
now a time T later they are separated by a distance d and are moving with a relative velocity of $v = Hd$;
assuming a constant rate of expansion $\frac{d}{T} = Hd$ from which we deduce that $T = \frac{1}{H}$;
*Award **[1 max]** for correct answer without accompanying reasoning.* ***[3]***

Option G — Relativity

G1. (a) (i) 1.90 c; ***[1]***

(ii) $u = \dfrac{u' + v}{1 + \dfrac{u'v}{c^2}}$;

correct substitution to get $u = \dfrac{c + 0.900\,c}{1 + \dfrac{c \times 0.900\,c}{c^2}}$;

$u = c$; ***[3]***

Do not accept bald answer $u = c$.

*Award **[1 max]** for use of incorrect formula* $u' = \dfrac{u - v}{1 - \dfrac{uv}{c^2}}$ *leading to answer* $u' = c$.

G2. (a) (i) time is $\dfrac{6.0\,\text{ly}}{0.80\,c} = 7.5\,\text{y}$; ***[1]***

(ii) calculation of gamma factor $\gamma = \dfrac{1}{\sqrt{1 - 0.8^2}} = \dfrac{5}{3} = 1.67$;

to get time $= \dfrac{7.5}{\gamma} = 4.5$ y;

or

calculation of gamma factor $\gamma = \dfrac{1}{\sqrt{1 - 0.8^2}} = \dfrac{5}{3} = 1.67$;

length contraction of 6.0ly to get $d = \dfrac{6.0}{\gamma} = 3.6$ ly and so time is $\dfrac{3.6}{0.80\,c} = 4.5$ y; ***[2]***

(b) (i) the length of an object in its rest frame / length measured by (inertial) observer with respect to whom object is at rest; ***[1]***

(ii) $L = \dfrac{40}{\gamma}$;

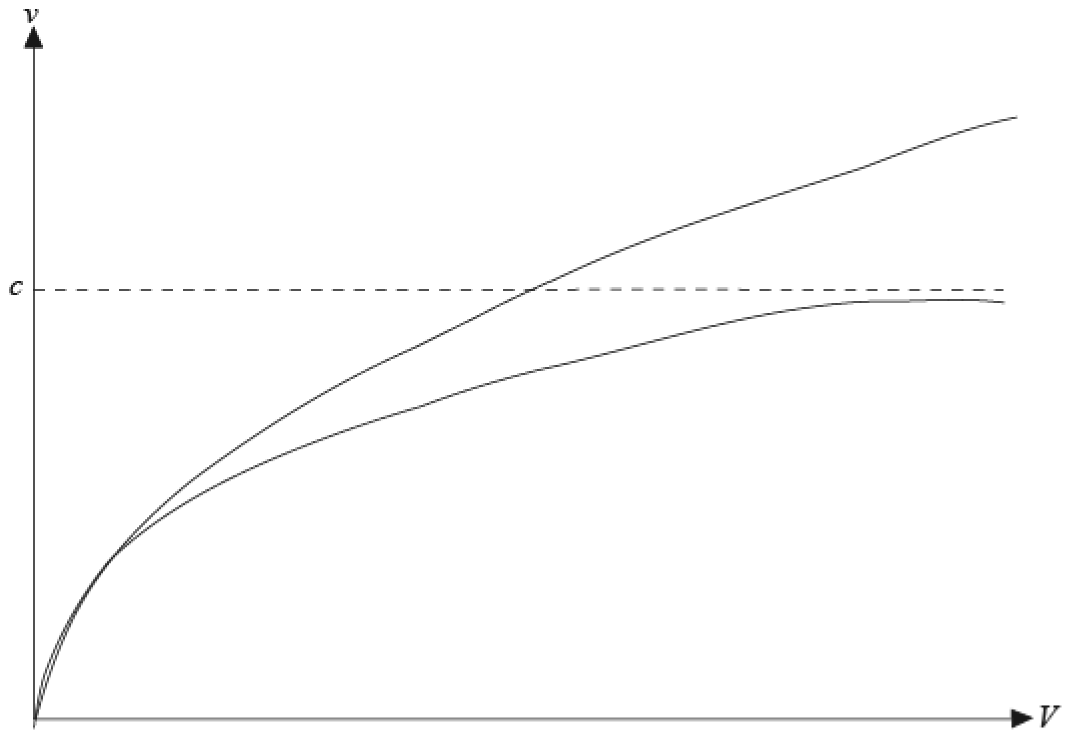
$= 24$ m; ***[2]***

(c) (i) from Tom's point of view both signals travel at the same speed (and have been emitted simultaneously);
so since the front of the station moves towards the signal, the front gets the signal first; ***[2]***
*Award **[1]** for the correct answer without explanation or incorrect explanation.*
Beware of the incorrect argument that Tom travels towards the front mirror.

(ii) arrivals of reflected signals are simultaneous for Jerry (because he is in the middle of the space station);
since arrivals occur at the same point in space they are simultaneous for all other observers as well, including Tom; ***[2]***
*Award **[1]** for the correct answer without explanation or incorrect explanation.*

G3. (a) calculation of gamma factor from $\gamma = \frac{1}{\sqrt{1-0.998^2}} = 15.8$;
total energy of proton is then $E = 15.8 \times 938 = 14.8\,\text{GeV}$;
hence electrical potential energy is $(14.8 - 0.938) = 13.9\,\text{GeV}$;
and so accelerating voltage is $V = 13.9\,\text{GV}$; ***[4]***

(b) curve that is identical to Newtonian curve for small velocities / curve that is below Newtonian curve;
and approaches speed of light asymptotically;
as in the following graph:



[2]

G4. total energy of the two Y particles is 3520 MeV;

so total energy of one of them is $\frac{3520}{2} = 1760$ MeV;

$E^2 = \left(m_0c^2\right)^2 + p^2c^2 \Rightarrow \left(m_0c^2\right)^2 = 1760^2 - 1490^2 = 8.775 \times 10^5$;

$m_0c^2 = \sqrt{8.775 \times 10^5}\ \text{MeV} = 937\,\text{MeV}$; ***[4]***

G5. (a) the radius from within which nothing can escape to the outside / the distance from the black hole where the escape speed is equal to the speed of light; ***[1]***

(b) the black hole is likely to increase in mass due to material falling into it;

since $R = \frac{2GM}{c^2}$ the radius is likely to increase / reference to radius being proportional to mass; ***[2]***

(c) (i) any <u>curved</u> path from observer to spacecraft that does not cross the event horizon; ***[1]***

Do not accept paths that start straight and then curve around event horizon.

(ii) the black hole curves / “warps” spacetime;

Radio signal follows <u>shortest distance</u> / geodesic of the curved spacetime; ***[2]***