Self-assessment questions for *An Introduction to Astrobiology*

Question 1

This question relates to Chapter 1.

(a) Carbon is the only element that can form molecules of sufficient size to perform some of the functions necessary for life as we know it.

Carbon can form chemical bonds with many other atoms.

Carbon can form compounds that readily dissolve in liquid water. *An Introduction to Astrobiology*, page 3.

Carbon can also form hydrophobic compounds.

(b) Chirality is a chemical property of a compound or molecule such that its isomers can be separated into left-handed and right-handed forms (in other words the mirror images of a chiral compound/molecule may not be superimposed).

Life exhibits a preference when it comes to the use of chiral molecules. For example, life on Earth uses only the left-handed forms of amino acids for producing proteins.

UVCPL light destroys one form of molecules more readily than the other forms and it is this process which is thought to have been responsible for creating an excess of left-handed molecules in the solar nebula from which life on Earth subsequently arose. [*An Introduction to Astrobiology*, pp. 24–27].

(c) Minerals could have played following key roles in the development of life on Earth:

(1) <u>Protection</u> – by acting as hosts for assembling chemical systems thereby protecting them from dispersal and destruction.

(2) <u>Support</u> – by providing mineral surfaces that could have acted as a support structure for molecules to accumulate and interact.

(3) <u>Selection</u> – by aiding in selecting certain biologically useful minerals.

(4) <u>Catalysis</u> – by catalyzing certain biologically important elements and compounds from their inert forms to more reactive forms facilitating biological reactions. [*An Introduction to Astrobiology*, p. 33–34.]

Question 2

(a)

$$T_e^{\,4} = \frac{L}{4\pi R^2 \sigma}$$

Rearrange Eq. 1 to solve for T_e:

$$T_e = \sqrt[4]{\frac{L}{4pR^2 s}}$$

Inserting values for L (1.19 x 10^{18} W), π (3.14), R (6.30 × 10^6 m) and σ ($5.67\times10^{-8}Wm^{-2}K^{-4}$)

$$T_e = \sqrt[4]{\frac{1.19\times10^{18}W}{4\times3.14\times(6.30\times10^6 m)^2\times5.67\times10^{-8}Wm^{-2}K^{-4}}}$$

Therefore,

$$T_e = \sqrt[4]{\frac{1.19\times10^{11}K^4}{2.83}}$$

Therefore,

$T_e = 453K$ or 180 ^{o}C

(b) There are three competing views as to the origin of the Earth's water. [*An Introduction to Astrobiology*, p. 60.]

First, that the Earth accreted as a dry body and its water was subsequently added through cometary impacts.

Second, that the Earth's water was directly derived from the solar nebula.

Third, that the Earth inherited its water from water-bearing minerals in the un-degassed interiors of planetary embryos.

Although comets contain significant quantities of water, the ratio of two stable isotopes of hydrogen (deuterium/hydrogen or D/H ratio) in comets (e.g., 1 P/Halley and Hyakutake) is greater than the D/H ratio in terrestrial water, Also accept alternative phrasing of statement such as the Earth and comets seem to have different hydrogen isotope ratios implying that the Earth did not obtain the bulk of its water by cometary impacts.

However, this is based on measurements of only two comets, which may not be representative of all comets. So it is possible but as yet not testable. [*An Introduction to Astrobiology*, Box 2.4, p. 60]

It also seems unlikely that the Earth scavenged volatiles such as water directly from the solar nebula because relative concentrations of other volatiles, such as Ne, Ar, Kr, and Xe, were much higher in the solar nebula than they are now in Earth's atmosphere. [*An Introduction to Astrobiology*, Box 2.4, p. 60]

Since we find hydrated minerals in meteorites such as carbonaceous chondrites, it is plausible that water-bearing grains became incorporated in planetesimals, planetary embryos and eventually the Earth. A major uncertainty in this model is whether water-bearing planetesimals could have formed at 1 AU or whether they could only have formed at distant parts of the solar nebula, much further away than region in which Earth was accreting. [*An Introduction to Astrobiology*, pp. 59–61.] (248 words)

(c) Plate-tectonics plays a significant role in recycling CO_2 and other atmospheric constituents between atmosphere, hydrosphere, and the Earth's interior, thereby regulating the level of greenhouse gases in the Earth's atmosphere, critical for maintaining habitability of the Earth. In the early Solar System it is estimated that there was about five times more heat being produced in the Earth's interior than there is today and, therefore, in the early Solar System when the solar luminosity was much reduced compared to the present day, plate-tectonics could have played a major role in regulating the surface temperature on Earth by bringing additional heat from the Earth's interior. [*An Introduction to Astrobiology*, pp. 56–58.] (104 words)

Question 3

This question relates mainly to Chapter 3.
(a) *can be answered mostly with reference to An Introduction to Astrobiology, pp. 96–99.*

The Viking life detection instrument package consisted of three experiments which were:

1) The Pyrolitic release experiment (PR) which tested for carbon fixation.

In this experiment Martian soil was incubated in a simulated atmosphere of CO_2 and CO (carried from Earth) labelled with radioactive ^{14}C.

A xenon arc lamp provided simulated sunlight.

After 5 days, the atmosphere was removed and the soil sample heated to 625 ^{o}C to break down any organic material and the resulting gases were passed through a ^{14}C detector to see if any organisms had ingested the radioactive CO_2.

2) The Gas Exchange experiment (GEX), which tested for metabolic production of gaseous by-products in the presence of water and nutrients as produced during respiration.

The soil was incubated for at least 12 days in a simulated Martian atmosphere of CO_2, with helium and krypton added.

Gases that might be emitted from organisms consuming the nutrient were then detected by a gas chromatograph – this instrument could detect CO_2, O_2, CH_4, H_2, and N_2.

3) The labelled release experiment (LR), which tested for metabolic activity.

This experiment injected Martian soil with a nutrient consisting of distilled water and organic compounds.

The organic compounds had been labelled with radioactive ^{14}C.

After moistening, the sample was incubated for at least 10 days and any micro-organisms should consume the nutrient and give off gases containing the ^{14}C, which would then be detected.

Both GEX and PR experiments produced positive results even with the control samples indicating that non-biological processes were operating on Mars.

Only the LR experiment appears to have met the criteria for life detection but the results remain ambiguous.

This is primarily because even though the control sample produced negative results, the LR experiment on Martian soils initially showed rapid increase in the amount of labelled gas release (as if biological processes were at work) but subsequent experiments showed opposite pattern (i.e., decrease in labelled gas release initially followed by a slow increase), confounding researchers.

The gas chromatograph-mass spectrometer (GCMS) on board the Viking lander was capable of detecting traces of organic molecules, failed to detect any organic compound in the Martian soil which provided further support to those scientists who strongly questioned the existence of life on Mars. However, perchlorate (later found by Phoenix) would destroy (oxidize) organic molecules, and produce chloromethane and dichloromethane, both of which were found by the Viking GCMS but dismissed at the time as contaminants from cleaning solvents.

(b) *can be answered mostly with reference to An Introduction to Astrobiology, pp. 118–120.*

- It is always difficult to find compelling evidence of a microbial origin for such simple structures which might equally be chemical and mineralogical artefacts.

- Convincing fossils of 3.9 Ga age are extremely rare on Earth and very hard to find even in systematic searches of well-exposed regions and well-preserved rocks. So, It would be surprising if a sample of little more than 20 rocks (an updated number is 50 for total number of Martian meteorites) from Mars should include one containing fossils.

- No attempt was made to compare the carbonate microstructures with non-biogenic mineral structures that could be mistaken for fossil bacteria.

- Carbonate and other materials in veins could have crystallized at high temperatures (200 to 500 degrees C) at the moment of the impact that ejected ALH 84001 into space so it is unlikely that structures and compounds within them are fossils.

- Tiny crystals of the iron sulfide mineral greigite in the carbonate globules could have been produced by non-biological processes such as those occurring in oceanic sediments by natural chemical processes.

There are alternative theories for the origin of magnetite crystals in ALH 84001. The sceptics argue that the crystallographic and morphological evidence is inadequate to support the inference of former life on Mars.

(c) *can be answered mostly with reference to An Introduction to Astrobiology, pp. 123–125.*
Some factors that militate against the development of life on Mars are:

- The Martian atmosphere is predominantly composed of CO_2 with very low concentration of oxygen.

- The thin Martian atmosphere and low concentration of ozone allows exposure of Martian surface to high levels of harmful UV radiation not conducive to life.

- Oxidation due to surface peroxides on Mars means that the dry dusty soil on the surface is unlikely to be a suitable habitat for life.

Main considerations for landing site selections for any missions designed to search for Martian life are:

- Appreciable concentration of material indicating the possibility of biota.

- Environment such as ancient hydrothermal springs where microbial material could have been fossilized rapidly to preserve organic molecules.

- Other aqueous environments such as evaporite deposits, lakes, and glaciers could have provided habitats for life so should be ideal landing site candidates.

- An area with thin dust cover should be preferred over an area with thick dust cover, which could be masking much of the underlying geological features, indicative of habitats for life.

- A large target area in order to accommodate any landing uncertainties as it is not yet possible to land on Mars with perfect targeting precision.

Question 4

This question relates to Chapter 4.

(a) *A good answer should cover the following points:*

Evidence:
high density shows that there must be a rocky interior at relatively shallow depth (*An Introduction to the Solar* System, p. 81), which could be a source of nutrients/chemical energy.
Magnetic field could be produced by convection within (conducting) ocean below the ice. (*An Introduction to Astrobiology*, p. 140)
Orbital resonance with Io an Ganymede (4:2:1) likely to cause tidal heating (hence ocean below ice &/or water-rock reactions).
Mobility of the ice shell inferred from spacecraft images, is possible only if there is an ocean below.
Examples are rafts and matrix in chaos areas, consistent with episodes of melt-through where ocean reached the surface.
Thinness of ice inferred from raft height and crater morphology. (*An Introduction to Astrobiology*, p. 147)

(b) *A good answer should cover the following points (from An Introduction to Astrobiology*, pp.159–163):
Sub-ice ocean would be warm enough for life (or vents would provide warmth for life).

Chemically-enriched plumes of warm water would be vented at the ocean floor.

This is the setting where life may have begun on Earth.
Because the last common ancestor here is similar to heat-loving chemosynthetic organism at hot vents (*An Introduction to Astrobiology*, p. 39).

And is likely to be a favourable setting for life to originate elsewhere (such as Europa).

Energy source would be chemosynthesis.
Done by exploiting a low-temperature redox reaction that is kinetically inhibited.
Such as:
Methanoenesis (reduction of carbon dioxide).
Reduction of an oxidised metal (e.g. iron).
Using H_2/ H_2S/CH_4 as the reducing agent.

Balanced equations such as *An Introduction to Astrobiology*, equations 4.4, 4.5, 4.6 could be used to illustrate this.
Or oxidation using O liberated radiolitically from water by decay of ^{40}K.

Question 5

This question relates mainly to Chapters 2, 3 and 8.

(a) The Infrared Telescope Facility (IRTF) self-evidently uses infrared (so does Keck, which is mentioned on *An Introduction to the Solar System*, p. 239 though IR is not stated) Methane "is a strong absorber of infrared" (*An Introduction to Astrobiology*, p. 272; also Fig 8.7) so IR spectroscopy is needed (or very useful) to detect methane.

(b) "Organisms release methane as they digest nutrients" [Press release para. 4]. Methane is a possible product of respiration [*An Introduction to Astrobiology*, p. 96, also Eq. 4.5] Methane is "quickly destroyed in the Martian atmosphere". [Press Release, para. 2]

The relevant other species (*An Introduction to Astrobiology*, Table 3.2) are (particularly) carbon dioxide and oxygen.

(The carbon in) methane is reduced, whereas (the carbon in) carbon dioxide is oxidized. [*An Introduction to Astrobiology*, Box 3.4]

Oxygen and methane are a redox pair. [*An Introduction to Astrobiology*, p. 116, p. 275]

So are oxygen and carbon dioxide, and (by extension of the logic) so are methane and carbon dioxide.

Identification of out of equilibrium redox pairs indicates the possibility of biochemistry/metabolism. [*An Introduction to Astrobiology*, p. 265, p. 275]

Alternative explanation is 'geology'.

Such as active volcanism, conversion of iron oxides to serpentine, release of ancient methane trapped in clathrates.

A biological origin of methane could be determined by isotopic measurements [last paragraph of the Press Release] because living processes favour light C (^{12}C favoured over ^{13}C, delta ^{13}C negative) [see also *An Introduction to Astrobiology*, pp. 69–70 and p. 116] and also light H (H preferred to D).

(c) Plumes of methane were found [localized rather than global] and these occurred during warmer seasons (spring/summer) over places where there is evidence (from other data) of ancient ground-ice or flowing water. [paras. 9 and 10]
[19,000 tonnes in one plume does not merit an extra mark, because the question asks only for spatial and temporal distribution]
Release mechanism: vaporization (=sublimation) of ice blocking fissures, allowing underground methane to escape. [para. 9]

(d) [Press Release para. 6] 'Far below the surface where it is warm enough for liquid water'. These are some kind of extremophile.
Specifically, the depth implies pressure – hence piezophile (or barophile – there is no real difference between these terms, despite the implication in *An Introduction to Astrobiology*, Table 2.2).

Question 6

This question relates mainly to Chapter 6 but also to Chapters 7 and 8.

(a) The radial velocity method cannot determine the tilt of an exoplanet's orbit (*An Introduction to Astrobiology*, p. 224, p. 227).

If inclination is 90 degrees (i.e. if we see orbit edge-on), then M$\sin i$ = M, but if the inclination is less then $\sin i$ is <1 so M has to be greater.

It is unlikely that the orbit is exactly edge on.

Statistically (for random orbital inclinations), the vast majority of exoplanets will have masses with a factor of two above their M$\sin i$ values. [*An Introduction to Astrobiology*, p.240]

So in this case the mass will probably be in the range 0.45 M_J to 0.9 M_J (which is approx 2/3 M_J).

(b)

(i) Using the equation in Box 6.2

$m = -2.5\log(b/b_0)$

so $\log(b/b_0) = -m/2.5$

and thus $b/b_0 = 10^{-m/2.5}$

so $b = b_0 \times 10^{-m/2.5}$

Substituting value for b_0 from Box 6.2, and 7.77 for m, we have

$b = 2.29 \times 10^{-8}\ \text{W m}^{-2} \times 10^{-7.77/2.5} = 2.29 \times 10^{-8}\ \text{W m}^{-2} \times 10^{-3.108}$

$= 2.29 \text{ x } 10^{-8} \times 7.798 \times 10^{-4}\ \text{W m}^{-2}$

$= 1.786 \times 10^{-11}\ \text{W m}^{-2}$ extra sig figs retained for subsequent calculations
$= 1.79 \times 10^{-11}\ \text{W m}^{-2}$

(ii)

Equation 6.3: $b = \dfrac{L}{4\pi d^2}$

Re-arranging Equation 6.3

$L = b \times 4\pi d^2$ (d is distance from Earth)

And inserting value of b calculated in (i) and d given in the question,

$L = 1.786 \times 10^{-11}\ \text{W m}^{-2} \times 4\pi(1.63 \times 10^{18}\ \text{m})^2$

$= 5.962\times 10^{26}$ W m^{-2} m^{2} = 5.96×10^{26} W

(c)

(i)

We first have to calculate the brightness of HD212301 seen from HD212301b.

Using Equation 6.3: $b = L/(4\pi d^2)$ (d = distance between planet and star)

In this case d is 0.036 AU (given in question), which is 5.40×10^{9} m (using 1 AU = 1.50×10^{11} m in Appendix B Table B2)

Substituting values, $b = 5.96\times 10^{26}$ W/(4π (5.40×10^{9} m)^{2})
$= 1.626 \times 10^{6}$ W m^{-2}
$= 1.6 \times 10^{6}$ W m^{-2} to 2 sig figs

Now use Equation 6.4 to calculate L, substituting value of surface area of Jupiter (p204, final paragraph and answer to Question 6.2):

$L = AbS = 0.7 \times 1.63 \times 10^{6}$ W m^{-2} $\times 1.54 \times 10^{16}$ m^{2}

$= 1.8 \times 10^{22}$ W $= 2 \times 10^{22}$ W (only 1 sig fig is justified, as albedo is given to only 1 sig. fig)

(ii)

Using equation 6.5, $b = L/(2\pi d^2)$ (d = distance from Earth)

$= 1.8 \times 10^{22}$ W /(2π(1.63×10^{18} m)^{2})

$= 1.1 \times 10^{-15}$ W m^{-2}
$= 1 \times 10^{-15}$ W m^{-2} only 1 sig fig as luminosity had only 1 sig fig [because of 1 sig fig albedo. If a 2 sig fig albedo was used, then 2 sig figs should be quoted here]

(An alternative method would be to use the ratio between the luminosities of planet and star, and to multiply the star's brightness by this number).

Question 7

This question relates to Chapters 6 and 9.

(a) The Drake equation considers the rate at which broadcasting civilizations appear and how long they broadcast. The rate at which they appear is estimated from: the rate at which stars form; the proportion of stars that have planetary systems; the average number of planets in habitable zones; the probability of life arising, becoming intelligent and broadcasting.

The rate at which stars form and abundance of planetary systems are well known. Other terms (especially the life terms) are debatable. But ‘reasonable’ values suggest that (intelligent) life could be abundant (you could have earned credit by inserting a worked example using credible values for the terms).

The Fermi paradox arises from a calculation of the time to colonise the Galaxy using foreseeable technology, [as on *An Introduction to Astrobiology*, p. 298] showing that at a rate of 10 light years per century would take a million years to cross the entire Galaxy.

(b) The Fermi paradox is “if intelligent life is not rare (and could colonize the Galaxy in a ‘short time’) how come we haven’t already noticed it?”.

Possible explanations include:

The probability of life starting is extremely low.

The probability of intelligence arising is low.

civilizations (or advanced life) do not survive for long enough, because of natural disasters (impacts, gamma-ray bursts, super-volcanoes) or wars advanced life does not broadcast for very long, or becomes so advanced that it has no interest in us. We could be looking in the wrong part of the spectrum/with the wrong technology.

Question 8

This question relates to Chapter 9.

(*a*) SETI: Search(ing) for extraterrestrial intelligence
CETI: Communicating/ion with extraterrestrial intelligence

(*b*) Hydrogen is ubiquitous, and so the hydrogen frequency is an obvious frequency to choose.
It occurs in the radio spectrum, where the Sun is faint so our signal would be relatively strong.
It occurs in the radio spectrum to which our atmosphere and/or the atmosphere of the habitable planet receiving our signal is/would be transparent.
However there are many natural sources of hydrogen emission, so we need a way to make our signal stand out.
By placing the frequency where there is little natural emission but related to the hydrogen frequency by a factor that intelligence would recognise.
We multiply or divide our transmission frequency by a dimensionless, universal constant.

In this case we use pi, which seems an obvious choice:
452 MHz = 1420MHz/pi
4461 MHz = 1420 MHz × pi
[*IA* pp. 282–283, 291]

(*c*) We need to search either side of the exact frequency where the signal would be if radial velocity were zero.
Plus any two from:

Rotation of the galaxy/movement of stars is likely to cause a Doppler shift so that the hydrogen line can be anywhere from 1419 to 1421 MHz 4462 MHz is within the natural range to which the transmitted frequency could be shifted due to radial velocity.

Likely to be in the range −150 to +150 km/s.
[*An Introduction to Astrobiology*, p.283]