Physics: B.1, B.3
Higher level
Paper Example

Thursday 25 September 2025

75 minutes

Student name

Citrinitas

Instructions to candidates

- Write your name in the box above.
- Do not open this examination paper until instructed to do so.
- A graphic display calculator is required for this paper.
- Answer all questions.
- Answers must be written within the answer boxes provided.
- Unless otherwise stated in the question, all numerical answers should be given exactly or correct to three significant figures.
- The maximum mark for this examination paper is **[48 marks] + [9 bonus marks]**.
- Bonus marks do not count toward total. The bonus question is for practice purpose only.

Q:	1	2	3
Marks:	/13	/27	/8

Total
/48

14 pages

Answers must be written within the answer boxes provided. Full marks are not necessarily awarded for a correct answer with no working. Answers must be supported by working and/or explanations. Solutions found from a graphic display calculator should be supported by suitable working. For example, if graphs are used to find a solution, you should sketch these as part of your answer. Where an answer is incorrect, some marks may be given for a correct method, provided this is shown by written working. You are therefore advised to show all working.

1. [Maximum mark: 13]

[ideal gas law]

(a) You might see people write the ideal gas law in one of the two forms:

$$PV = Nk_BT,$$

or

$$PV = nRT.$$

Identify the meaning of every variable in these 2 equations. [2]

P = pressure

kB = Boltzmann's constant

V = volume

n = number of moles

N = number of molecules

R = ideal gas constant

T = temperature

(b) What are the assumptions of ideal gas law (list 3)? [3]

Classical regime (far from absolute 0).

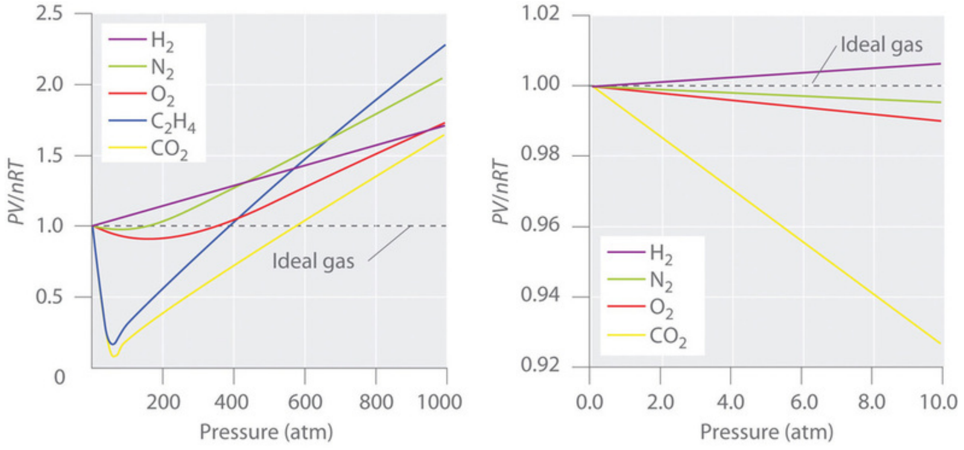
Thermal Equilibrium,

Particle volume negligible.

elastic collision

no intermolecular forces.

(c) Here are some experimental data of real gases, what can you notice from the diagrams. State one observation. [1]



(a) *PV/nRT* at high pressures **(b) *PV/nRT* at low pressures**

Figure 1: Real gases measured at 273 K.

Answer any observation would earn 1 pt.
This question just helps you to do 1 (d).

(d) To model the behavior of real gases, the van der Waals correction applies upon the ideal gas law:

$$P = \frac{RT}{V/n - b} - \frac{a}{(V/n)^2},$$

where a and b are constants. What are the constants corresponding to? Sate and explain your reasoning. (Hint: You may want to rearrange this formula so that one side equals to nRT.) [4]

Rearranging $\left(P + \frac{an^2}{V^2}\right)(V - nb) = nRT$

RHS is the same as idea gas law

In LHS, correction is applied on P and V.

Think about why we need to correct P and V terms with the assumptions of ideal gas removed.

Answer: The constant a accounts for intermolecular attractive forces between gas molecules. [1 pt] These attractive forces reduce the observed presure, so an^2/V^2 is added to correct it [1 pt] The constant b accounts for the finite volume of gas molecules [1 pt] since the term $V - nb$ represents the effective volume available for molecular motion (excluded volume correction). [1 pt].

(e) The total internal energy U of a ideal gas can be described by the equipartition theorem.

$$U = \frac{3}{2} N k_B T.$$

Derive the ideal gas law, starting from this formula. [3]

(i) Option 1: Do the question directly

ideal gas $\Rightarrow$ $U = K = \frac{3}{2} N k_B T = \sum_i^N \frac{1}{2} m v_i^2 = \frac{1}{2} \underline{mN} \langle v^2 \rangle$ [1 pt]

so ignore Potential energy.

total mass of the gas

$$\frac{mN}{V} = \rho$$

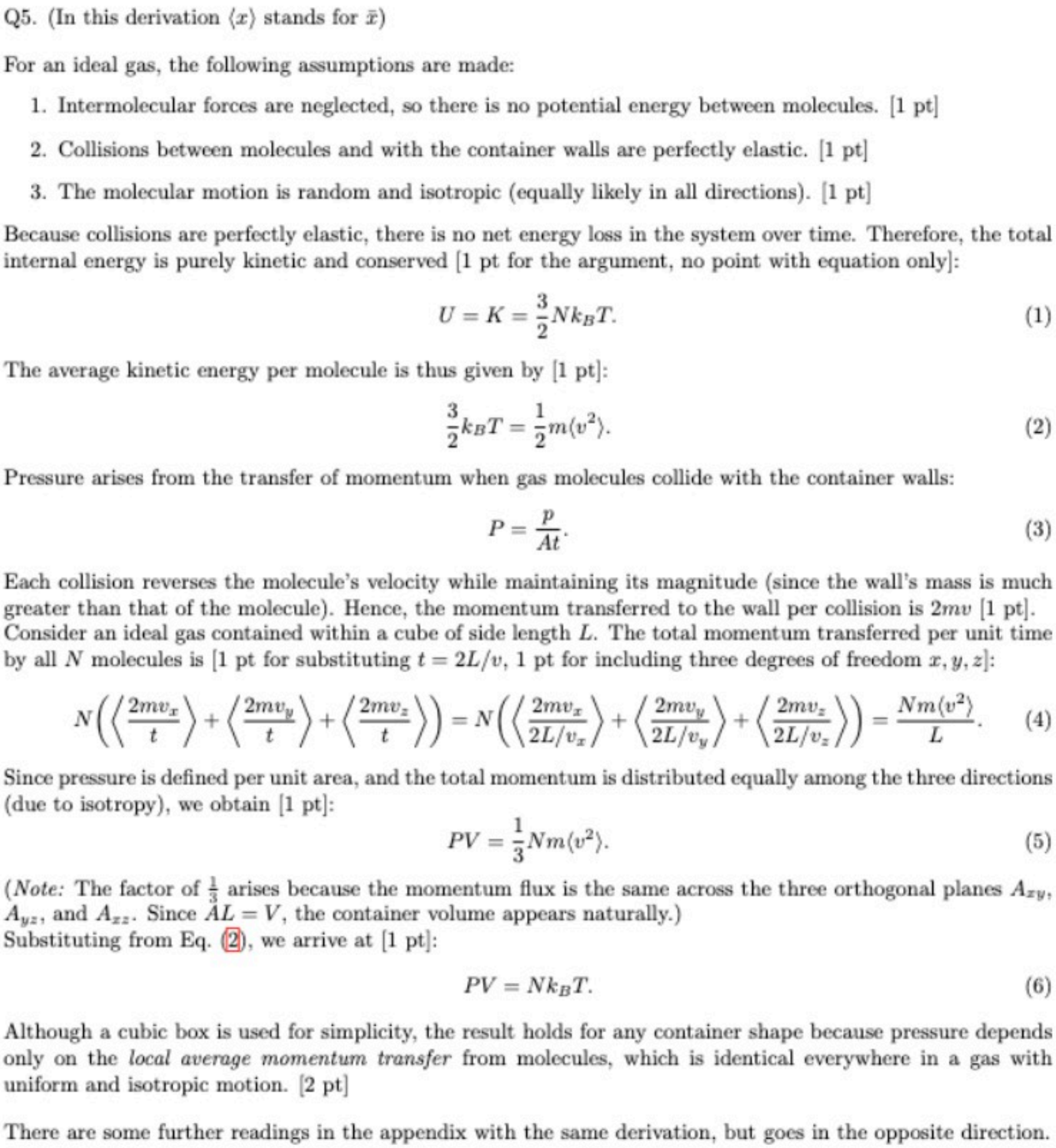
$$P = \frac{1}{3}\rho \langle v^2 \rangle = \frac{1}{3} \frac{mN}{V} \langle v^2 \rangle$$ [1 pt]

$$3PV = mN \langle v^2 \rangle$$

$$= 3 N k_B T$$

$PV = N k_B T$ as the question requires. [1 pt]

(ii) Option 2: (Bonus!) Include derivation of pressure's relationship with the average translational speed of molecules. Do no use that expression directlyl. Sate all the assumptions you used. (Hint: Pressure is momentum transfer per unit area per unit time on the container walls.) (Another hint: think about the derivation of $\bar{E_k} = \frac{3}{2}k_BT$ on oxford IB physics 2014 edition page 109.) [+9 extra marks]



Q5. (In this derivation $\langle x\rangle$ stands for $\bar{x}$)

For an ideal gas, the following assumptions are made:

1. Intermolecular forces are neglected, so there is no potential energy between molecules. [1 pt]
2. Collisions between molecules and with the container walls are perfectly elastic. [1 pt]
3. The molecular motion is random and isotropic (equally likely in all directions). [1 pt]

Because collisions are perfectly elastic, there is no net energy loss in the system over time. Therefore, the total internal energy is purely kinetic and conserved [1 pt for the argument, no point with equation only]:

$$U = K = \frac{3}{2}Nk_BT. \tag{1}$$

The average kinetic energy per molecule is thus given by [1 pt]:

$$\frac{3}{2}k_BT = \frac{1}{2}m\langle v^2\rangle. \tag{2}$$

Pressure arises from the transfer of momentum when gas molecules collide with the container walls:

$$P = \frac{p}{At}. \tag{3}$$

Each collision reverses the molecule's velocity while maintaining its magnitude (since the wall's mass is much greater than that of the molecule). Hence, the momentum transferred to the wall per collision is $2mv$ [1 pt]. Consider an ideal gas contained within a cube of side length L. The total momentum transferred per unit time by all N molecules is [1 pt for substituting $t = 2L/v$, 1 pt for including three degrees of freedom x, y, z]:

$$N\left(\left\langle\frac{2mv_x}{t}\right\rangle + \left\langle\frac{2mv_y}{t}\right\rangle + \left\langle\frac{2mv_z}{t}\right\rangle\right) = N\left(\left\langle\frac{2mv_x}{2L/v_x}\right\rangle + \left\langle\frac{2mv_y}{2L/v_y}\right\rangle + \left\langle\frac{2mv_z}{2L/v_z}\right\rangle\right) = \frac{Nm\langle v^2\rangle}{L}. \tag{4}$$

Since pressure is defined per unit area, and the total momentum is distributed equally among the three directions (due to isotropy), we obtain [1 pt]:

$$PV = \frac{1}{3}Nm\langle v^2\rangle. \tag{5}$$

(*Note:* The factor of $\frac{1}{3}$ arises because the momentum flux is the same across the three orthogonal planes A_{xy}, A_{yz}, and A_{zx}. Since $AL = V$, the container volume appears naturally.)
Substituting from Eq. (2), we arrive at [1 pt]:

$$PV = Nk_BT. \tag{6}$$

Although a cubic box is used for simplicity, the result holds for any container shape because pressure depends only on the *local average momentum transfer* from molecules, which is identical everywhere in a gas with uniform and isotropic motion. [2 pt]

There are some further readings in the appendix with the same derivation, but goes in the opposite direction.

2. [Maximum mark: 27]

[states of matter and heat transformations]

(a) To measure the heat capacity of an object, all you usually have to do is to put it in thermal contact with another object whose heat capacity you know. As an example, suppose that a chunk of metal is immersed in boiling water (100 °C), then is quickly transferred into a calorimeter containing 250 grams of water at 20 °C. After a minute or so, the temperature of the contents of the calorimeter is 24 °C. Assume that during this time no significant energy is transferred between the contents of the cup and the surroundings. The heat capacity of the cup itself if negligible.

(i) How much heat is gained by the water? [2]

$\Delta T_w = 4\ K$

$Q_w = 0.25kg \cdot C_w \cdot 4K = C_w = 4181J$

I don't know what Cw is given on your formula sheet, just whatever that value is, that's the answer

(ii) How much heat is lost by the metal? [1]

$|Q_m| = |-C_w| = |-4181J| = 4181J$

(iii) What is the heat capacity of this chunk of metal? [2]

$\Delta T_m = 76K$

$C_m = \frac{|Q_m|}{\Delta T} = \frac{4181J}{76K} \simeq 55.0\,JK^{-1}$

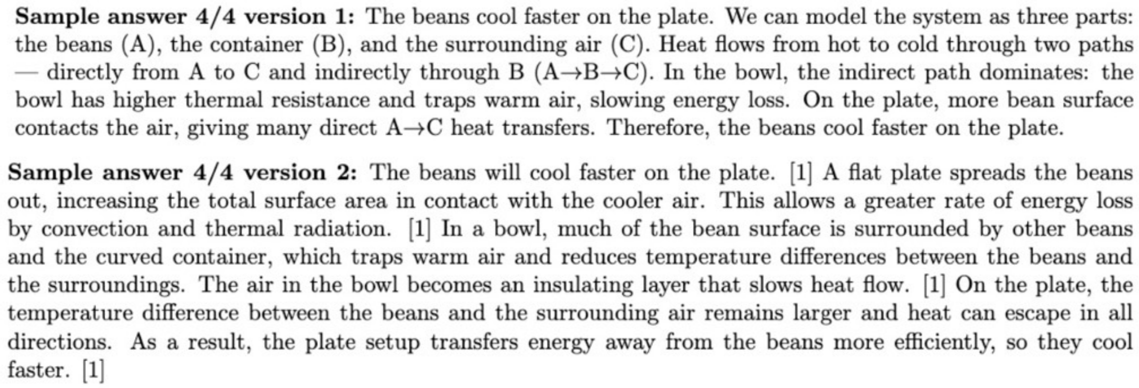
(iv) If the mass of the chunk of metal is 100 gram, what is its specific heat capacity? [2]

$100g = 0.1kg$

$c_m = 55.0\,JK^{-1} / 0.1kg$

$= 550\,JK^{-1}kg^{-1}$

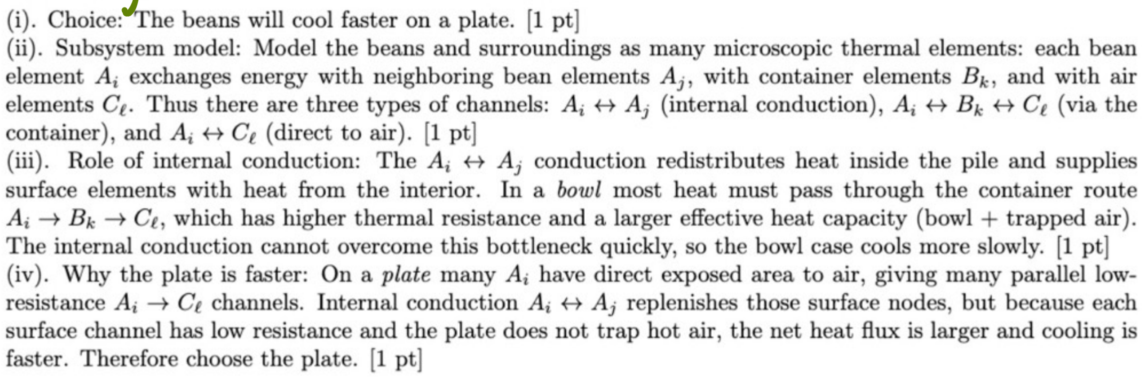
(b) Suppose that you have some steaming boiled beans. There are two containers that you can choose from: a plate (very flat, without concavity) and a bowl. Which container would you choose if you want to cool the beans faster? Explain. [4]



Sample answer 4/4 version 1: The beans cool faster on the plate. We can model the system as three parts: the beans (A), the container (B), and the surrounding air (C). Heat flows from hot to cold through two paths — directly from A to C and indirectly through B (A→B→C). In the bowl, the indirect path dominates: the bowl has higher thermal resistance and traps warm air, slowing energy loss. On the plate, more bean surface contacts the air, giving many direct A→C heat transfers. Therefore, the beans cool faster on the plate.

Sample answer 4/4 version 2: The beans will cool faster on the plate. [1] A flat plate spreads the beans out, increasing the total surface area in contact with the cooler air. This allows a greater rate of energy loss by convection and thermal radiation. [1] In a bowl, much of the bean surface is surrounded by other beans and the curved container, which traps warm air and reduces temperature differences between the beans and the surroundings. The air in the bowl becomes an insulating layer that slows heat flow. [1] On the plate, the temperature difference between the beans and the surrounding air remains larger and heat can escape in all directions. As a result, the plate setup transfers energy away from the beans more efficiently, so they cool faster. [1]

A bit beyond IB version. (an alternative of version 1.).



(i). Choice: The beans will cool faster on a plate. [1 pt]
(ii). Subsystem model: Model the beans and surroundings as many microscopic thermal elements: each bean element A_i exchanges energy with neighboring bean elements A_j, with container elements B_k, and with air elements C_ℓ. Thus there are three types of channels: $A_i \leftrightarrow A_j$ (internal conduction), $A_i \leftrightarrow B_k \leftrightarrow C_\ell$ (via the container), and $A_i \leftrightarrow C_\ell$ (direct to air). [1 pt]
(iii). Role of internal conduction: The $A_i \leftrightarrow A_j$ conduction redistributes heat inside the pile and supplies surface elements with heat from the interior. In a *bowl* most heat must pass through the container route $A_i \to B_k \to C_\ell$, which has higher thermal resistance and a larger effective heat capacity (bowl + trapped air). The internal conduction cannot overcome this bottleneck quickly, so the bowl case cools more slowly. [1 pt]
(iv). Why the plate is faster: On a *plate* many A_i have direct exposed area to air, giving many parallel low-resistance $A_i \to C_\ell$ channels. Internal conduction $A_i \leftrightarrow A_j$ replenishes those surface nodes, but because each surface channel has low resistance and the plate does not trap hot air, the net heat flux is larger and cooling is faster. Therefore choose the plate. [1 pt]

(c) Explain briefly why molecules solid sates are relatively motionless compared to the molecules in fluids. [2]

In solids, molecules are fixed or can only vibrate about equilibrium due to strong intermolecular forces. [1 pt]
In fluids, weaker intermolecular forces allow molecules to move or flow freely. [1 pt].

(d) Your 200 gram cup of tea is boiling-hot (assume 100 °C). About how much ice should you add to bring it down to 65 °C? (Assume that the ice is initially at -15 °C. The specific heat capacity of ice is 2.1 J/~~k~~g·°C.) 2.1 J/g·°C [4]

$\Delta T = 35\,K$ $m_w = 0.2\,kg$

to bring water temperature down to 65°C, water must loss $Q = m_w C_w \Delta T = 0.2 \times 4181 \times 35 = 29267\,J$

$Q = m_i\,[\,C_w \times 65 + C_i \times 15 + L_f\,]$

$m_i = 29267 / [\,4181 \times 65 + 2100 \times 15 + 3.34 \times 10^5\,]$

$\simeq 0.0459\,kg$

(e) When spring finally arrives in mountains, the snow pack may be 2 meters deep, composed of 50% of ice and 50% of air. Direct sunlight provides about 1000 watts/m^2 (1 watt = 1 J/s) to earth's surface, but the snow might reflect 90% of this energy. Answer the following questions to estimate how many weeks the snow pack should last, if direct solar radiation is the only source of energy.

(i) Calculate the energy required to melt 1 m^3 of snow (50% of ice and 50% of air). [2]

$E = mL_f$

$= \rho_i V_i \simeq 920 \times \frac{1}{2} \times 3.34 \times 10^5 \simeq 1.54 \times 10^8 J$

(ii) Estimate the energy absorbed from sunlight per second per m^2. [1]

Absorbed power $= 100 W/m^2$

$= 100 J/s.m^2$

(iii) Hence, estimate the time for melting. [4]

$$\frac{1.54 \times 10^{8} \times 2\ \mathrm{J/m^2}}{100\ \mathrm{J/s.m^2}} \cdot \frac{1}{60^{2} \times 24 \times 7}$$

$\simeq 5.08$ weeks

(f) Why isolated systems tends to evolve towards thermal equilibrium overtime? Explain by dividing the system into subsystems based on temperature gradient. [3]

An isolated system can be thought of as made up of subsystems at different temperatures [1 pt] Heat flows from the hotter parts to the coder parts until all subsystems reach the same temperature. [1 pt] When no temperature difference remain, the system is at thermal equilibrium. [1 pt]

3. [Maximum mark: 8]

[Blackbody radiation] Stars can be approximately modeled as blackbodies that emit a continuous spectrum of electromagnetic radiation. The Sun's surface temperature is about 5800 K, and its blackbody spectrum peaks in the green region of the visible spectrum (around 500 nm).

(a) Explain why stars can be modeled as blackbodies. [1]

Although stars are not perfect black-bodies they are capable of emitting and absorbing all wavelengths of electromagnetic radiation.

(b) Using Wien's displacement law, describe what happens to the wavelength of peak intensity as the surface temperature of a star increases. [1]

$\lambda_{max} \propto 1/T \Rightarrow$ As temperature increases, wavelength of peak emission decreases.

(c) The Sun’s peak emission is in the green part of the spectrum, yet the Sun appears white or yellowish to the human eye. Explain why. [1]

Even though the peak intensity is at green wavelength, blackbody emission also includes significant red and blue light at about 5800 K. The combined effect of all visible wavelengths appears white or yellowish

A distant star has a radius R = 2.0 R_{sun} and a surface temperature of 10,000 K, where the Sun’s radius is $R_{sun} = 7.0\times10^2$ m and its surface temperature is $T_{sun} = 5800$ K.

(d) Derive an expression for the ratio of luminosities of the star and the Sun. [2]

$$\frac{L}{L_{sun}} = \frac{AT^4}{A_{sun}T^4_{sun}} = \frac{R^2T^4}{R^4_{sun}T^4_{sun}} = 4\frac{T^4}{T_{sun}^4}$$

(e) Calculate this ratio for the given data. [1]

$$4\left(\frac{100}{58}\right)^4 \simeq 35.3$$

(f) Explain qualitatively why even a small increase in temperature leads to a large increase in luminosity. [1]

Because $L \propto T^4$

(g) Describe one assumption made in applying the Stefan–Boltzmann law to stars and comment on its validity. [1]

Assumption: Stars are perfect blackbodies. with uniform surface temperature

Validity: it approximates the behavior, but in reality absorption lines and non-uniform temperature distributions cause small deviations.

END OF EXAM