Answer THREE questions
The numbers in square brackets indicate the provisional allocation of maximum marks per sub-section of a question.

Gravitational acceleration on Earth's surface	9.78	ms^{-2}
Mean molecular weight in Earth's atmosphere	29	kg kg-mol^{-1}
Gas constant per kg-mole	8314	JK^{-1}kg-mol^{-1}

1. What is meant by hydrostatic equilibrium in an atmosphere? Show that the variation of pressure p with altitude z in an atmosphere is given by:

$$p = p_0 \exp\left[-\int_{z_0}^{z} \frac{m_r g dz}{RT}\right]$$

Where
p_0 is the pressure at a reference altitude $z=z_0$
R is the perfect gas constant per kg-mol
T is the temperature in Kelvin
m_r is the molecular weight in kg per kg-mol
g is the acceleration due to gravity
Define the scale height and explain why the contents of the bracket cannot be integrated immediately. **[8]**

Obtain an expression for the variation of pressure with altitude in an isothermal atmosphere, assuming g and m_r are constant with altitude. **[2]**

Assuming that the pressure of the Earth's thermosphere remains constant at an altitude of 200km, but that the temperature varies from 800K to 1200K over the 11 year solar cycle, calculate the ratio of the gas densities at an altitude of 450km from solar maximum to solar minimum. Assume that the thermosphere above 200km is isothermal and that g and m_r are constant with altitude. **[8]**

How does this result affect the orbits of spacecraft at 450km? **[2]**

2. Describe briefly the principal driver of circulation systems in planetary atmospheres. **[1]**

What are the five main circulation systems? Give a brief description of each. **[10]**

State which of the five circulation systems are observed in the atmospheres of each of the planets Venus, Earth and Mars. **[6]**

Describe briefly the large-scale shape of cloud formations in the Venus and Jupiter atmospheres as observed by spacecraft. What additional effects to the basic five circulation systems make these so different and why? **[3]**

3. Classical theory of the formation of ozone in the stratosphere is based on the balance of five chemical reactions:

(1) $O_2+h\nu_2$	$\Rightarrow$	$O+O$	J_2
(2) $O_3+h\nu_3$	$\Rightarrow$	O_2+O	J_3
(3) $O+O+M$	$\Rightarrow$	O_2+M	k_1
(4) $O+O_2+M$	$\Rightarrow$	O_3+M	k_2
(5) $O+O_3$	$\Rightarrow$	$2O_2$	k_3

where J_2 and J_3 are dissociation rates per molecule per second and k_1, k_2 and k_3 are the reaction rates.

Write down equations giving the rate of change of concentrations of O_2 and O_3. Show that in equilibrium the concentration n_3 of O_3 is proportional to the concentration n_2 of O_2 as follows:

$$n_3^{\,2} = n_2^{\,2}\left(\frac{J_2 k_2 n_m}{J_3 k_3}\right)$$

where n_m is the concentration of species M. **[9]**

Draw a rough sketch of the variation of ozone density with height both as predicted by these equations and as observed, indicating the height of the peak in each case. In what other important way does this theory disagree with observation? **[3]**

Discuss four major reasons why these equations are inadequate to describe the concentration of ozone in the EarthÕs stratosphere. **[8]**

4. Describe the layers in the atmosphere of Jupiter as determined from the profile of the variation of temperature with pressure. Discuss the processes which contribute to the heating and cooling in each layer. **[12]**

How did the Galileo entry probe contribute to our knowledge of these layers? **[6]**

Discuss the potential significance of the observation that the relative abundance of helium is only half the solar abundance. At which other gas giants might this be important too? **[2]**

5. Show that, in order for a planet or planetary satellite to have a significant atmosphere, its surface temperature T_s must obey the inequality

$$T_s \ll \frac{2GMm}{3ka}$$

Where *k* is Boltzmann's constant, *G* is the gravitational constant, *M* the mass of the planet, *m* the mass of a gas molecule and *a* the planetary radius. **[4]**

Putting

$$IV = \frac{2GMm}{3kaT_s}$$

we can compile the following values of the inequality value *IV* based on the present atmospheric composition and surface temperature of various planets and satellites:

Planetary body	*IV*
Mercury	6.6
Io	70
Mars	200
Earth	520
Venus	580
Neptune	960
Saturn	1200
Jupiter	2600

Use this table to make a quantitative estimate of how much less T_s should be in the first equation for the planetary body to have a significant atmosphere. **[4]**

If Jupiter has a rocky core whose radius is 20% of the present radius and whose mass is 4.5% of the present mass, show that it would have been big enough to attract and hold an atmosphere of hydrogen and helium from the solar nebula. **[5]**

What alternative mechanisms could have provided the terrestrial planets, whose rocky cores did not reach this mass during the formation of the solar system, with their atmospheres? Which was the dominant mechanism? Which types of gases are the most abundant now? **[7]**

END OF PAPER