

## Solutions to Homework Problem Set 6

### 6.1 Atmospheres

Mercury does not have an appreciable atmosphere. It is small with a low escape velocity, and it is close to the Sun with very high temperature during its day. As a result, Mercury cannot retain any gas particles to form an atmosphere. All other terrestrial planets have appreciable atmospheres.

**Temperature and Pressure** The Earth's atmosphere has an average surface temperature of about  $14^{\circ}$ . Mars has a thin and cool atmosphere of an average surface temperature below zero celsius degree and average surface pressure of less than 1% of the Earth's atmosphere pressure at sea level. Venus has a dense and hot atmosphere with an average surface temperature of over  $400^{\circ}$  and average surface pressure 90 times Earth's atmosphere pressure.

The difference is a result of the distance to the Sun and different greenhouse effects on the three planets.

In terms of the height-temperature profile, in general, the bottom of the atmosphere is warmer than upper layers, because the atmosphere is transparent to sunlight (dominant in visible wavelengths) and solar energy deposits at the surface, heating the atmosphere from the bottom. However, the Earth's atmosphere also exhibits inversions in the temperature profile in stratosphere and thermosphere because certain gas elements ( $O_3$ , O and N atoms) in those layers absorb shortwave-length radiations from the Sun.

**Evolution - greenhouse effect** All three atmospheres started from  $CO_2$ , water vapor,  $SO_2$  etc by volcano outgasing. These are greenhouse gases which trap (outward) infrared radiation by the planets thus keep the planet warmer than without greenhouse gases. With different initial temperatures, atmospheres on the three planets then evolved differently.

On the Earth, the distance to the Sun is such that the temperature allows for water in liquid state (oceans), which can dissolve  $CO_2$  or lock  $CO_2$  into rocks. Evaporation, volcanoes, and plate tectonics then send these gases into the air. This way, greenhouse gases are recycled between atmosphere, water, and rocks, and the greenhouse effect is in check. As a result, the surface temperature is raised by about 40 degrees.

On Venus, the higher surface temperature due to its closer distance to the Sun drives water vapor and  $CO_2$  (from water and rocks) into the atmosphere, which enhances the greenhouse effect and raises the planet's surface temperature. The higher temperature further drives more greenhouse gases into the air to lead to still higher temperature. This is the runaway greenhouse effect which raises the Venus's surface temperature by more than  $400^{\circ}$  and produces a thick dense atmosphere.

On Mars, the lower surface temperature due to its being farther away from the Sun and quicker cooling of the planet keeps water as ice and  $CO_2$  trapped in rocks. No drastic geological activities (such as plate tectonics) works to release greenhouse gases into the air. As a result of this runaway icehouse effect, the atmosphere on Mars is thin and cool.

**Composition** At the present, more than 95% of the atmosphere on both Venus and Mars is of CO<sub>2</sub>, while the Earth's atmosphere consists 20% of molecular oxygen and about 80% molecular nitrogen.

At the start, all three planets had atmospheres of similar composition: CO<sub>2</sub>, water vapor, SO<sub>2</sub> etc outgassed from volcanoes. On the cold Mars, water is kept as ice below the surface other than in the atmosphere. On the hot Venus, water vapor in the air was cracked down by ultraviolet radiation. So on both planets, CO<sub>2</sub> dominates the air composition. On the Earth, the large body of liquid water allows for life to develop on the planet. Photosynthesis by plants and biochemical processes by certain bacteria have vastly changed the atmosphere composition into molecular oxygen and nitrogen gases with very little CO<sub>2</sub> remaining in the air.

### **Surface features**

Surface features in the four planets can be compared in terms of cratering, volcanism, plate tectonics, and water.

Mercury has the oldest surface, which is heavily cratered. Mountains and basins on Mercury are largely features by impact cratering. Scarps may be produced when the planet was cooling down and shrank. Mercury is small and lack of internal energy, which cannot drive significant geological activities to renew its surface.

Venus has a relatively young surface characterized by vast gentle smooth plains of lava flows and volcano hills. Geological features like ridges also formed by lava flows. Volcanism has been, and probably still is, active on Venus because of its hot molten interior. No evidence of plate tectonics is found on Venus probably because Venus is hot, molten, and plastic, and lacks rigid crustal plates.

Mars's surface is divided into a cratering old highlands in the southern hemisphere and smooth young lava-covered lowlands north of the equator. (The exact reason for such crustal dichotomy pattern remains unclear.) Mountains on Mars are volcano or cratering mountains. The presence of large-scale volcano mountains and old cratering surface indicates no plate tectonics on Mars. Mars, however, exhibits geological features (channels, riverbeds, gullies, flood islands, mud flash etc.) indicative of water flow or erosion in the past. Mars has polar caps made of dry ice and ice water, and water ice is believed to be present below the surface elsewhere on the planet. Mars does not have active plate tectonics and strong volcanism (compared with Venus and Earth) perhaps because of its small size thus less internal heat and thicker crust (compared with the Earth).

The Earth's surface is young, largely reshaped by abundant geological activities driven by plate tectonics. Large mountain ranges, ocean rifts, gulfs, earthquake and volcano belts, are results of plate tectonics and are located at plate boundaries (or subduction zones) where plates collide, separate or rub against each other. Most significantly, the Earth's surface is dominated by a large body of liquid water, oceans. The Earth's surface also bears signatures of weathering, such as wind and water erosion, and life activities such as vegetation.

The Earth is the only planet with active plate tectonics because of its internal heat, molten interior, convective athenosphere (all these owing to the large size of the Earth), a thin and rigid crust (perhaps because of formation of the Moon taking away most of the Earth's rocky crust), and the presence of a large body of liquid water (due to its distance to the Sun and surface temperature) allowing for plate floating.

In short, Mercury has the oldest surface, followed by Mars, Venus, and Earth, in the same order as their sizes. The major reason is that larger planets have more internal energy to drive geological activities.

6.2 (a) From the energy balance equation, we can derive the mean surface temperature of a planet to be

$$T_p = \left( \frac{(1-a)R_s^2}{4d^2} \right)^{1/4} T_s$$

where  $a$  is the albedo of the planet,  $d$  the distance between the Sun and planet,  $T_s$  and  $R_s$  the radius and surface temperature of the Sun. Given that  $T_s = 5800$  K,  $R_s = 6.95 \times 10^5$  km, and for Venus,  $d = 1.082 \times 10^8$  km and  $a = 0.59$ , there is

$$T_p = \left( \frac{(1-0.59)(6.95 \times 10^5 \text{ km})^2}{4(1.082 \times 10^8 \text{ km})^2} \right)^{1/4} \times 5800 \text{ K} = 263 \text{ K}$$

This is much lower than the mean surface temperature on Venus (733 K), so the greenhouse effect on Venus must be much stronger than on the Earth.

(b) Without an atmosphere, there would not be the greenhouse effect to significantly raise Venus' mean temperature by over 400 K degrees. It is likely that the surface albedo of Venus would be smaller as in the case of Mercury and the moon. But even with an albedo  $a = 0.10$ , it can be shown that the mean surface temperature would be around 320 K degrees only. On the other hand, there would be a sharp difference between the day and night temperatures, since a day or a night on Venus is as long as 117 days.

6.3 Evidence of past and current water on Mars can be summarized as the following: (a) erosion features by past water flow, such as gullies, dried riverbeds, flood-carved islands, and sedimentary rock layers found from high resolution images of Mars' surface; (b) minerals dissolved in liquid water, as revealed by spectral observations; (c) neutron (deficiency) measurements revealing presence of ice water beneath Mars' surface.

6.4 (a) Mars' diameter is  $D = 6794$  km. To view Mars as a disk, i.e., its angular size has to be  $\alpha = 60''$ , we can use the small angle formula to find the desired distance from the Earth

$$d_0 = 206265 \frac{D}{\alpha} = 206265 \times \frac{6794 \text{ km}}{60''} = 2.33 \times 10^7 \text{ km} = 0.16 \text{ AU}$$

The shortest distance between Mars and Earth occurs when Mars is at the favorable opposition. At the most favorable opposition, Mars is closest from the Sun, or 1.381 AU away from the Sun,

and Earth is fartherest from the Sun, or 1.017 AU from the Sun, then the distance between Mars and Earth is  $d = (1.381 - 1.017) \text{ AU} = 0.364 \text{ AU}$ . This is more than twice the desired distance. So Mars never gets close enough to be resolved as a disk.

(b) The Earth's diameter is  $D = 12,756 \text{ km}$ , less than twice Mar's diameter. So even at the shortest distance, an astronaut on Mars cannot resolve the Earth as a disk. The distance between the Earth and moon is  $D = 384,400 \text{ km}$ , which is about 30 times the diameter of the Earth. Therefore, at favorable oppositions, viewed from Mars, the angular distance between the Earth and Moon is a lot larger than  $60''$ . In fact, even when Mars and the Earth are fartherest from each other, or  $d = (1.666 + 1.017) \text{ AU} = 2.683 \text{ AU}$ , the angular distance between the Earth and moon as viewed from Mars would be

$$\alpha = 206265 \times \frac{384400 \text{ km}}{2.683 \text{ AU} \times 1.5 \times 10^8 \text{ km/AU}} = 197'' > 60''$$

So the Earth and moon can be seen as well separated objects.

6.5 (a) The rotation velocity at the equator ( $V_{rot}$ ) is tangential to the equator and the magnitude is written as

$$V_{rot} = \frac{2\pi R}{P}$$

where  $R$  is the radius of the planet. From the data table of Mercury,  $R = 2440 \text{ km} = 2.44 \times 10^6 \text{ m}$ , and  $P = 58.646 \text{ days} = 58.646 \text{ days} \times 24 \text{ hrs/day} \times 3600 \text{ sec/hr} = 5.07 \times 10^6 \text{ sec}$ , there is:

$$V_{rot} = \frac{2\pi \times 2.44 \times 10^6 \text{ m}}{5.07 \times 10^6 \text{ sec}} = 3.02 \text{ m/s}$$

(b) At the two edges of the planet, the magnitude of line-of-sight component of the rotation velocity is the maximum, which is just  $V_{rot}$  (given that the inclination of Mercury's equator to the line-of-sight direction is zero). Using the Dopplershift equation, there is

$$\Delta\lambda = \lambda_0 \frac{V_{rot}}{c}$$

where  $c$  is the speed of light  $c = 3.00 \times 10^8 \text{ m/s}$ , and  $\lambda_0$  is the observing wavelength  $\lambda_0 = 12.5 \text{ cm} = 0.125 \text{ m}$ . Therefore,

$$\Delta\lambda = 0.125 \text{ m} \frac{3.02 \text{ m/s}}{3.00 \times 10^8 \text{ m/s}} = 1.26 \times 10^{-9} \text{ m} = 1.26 \text{ nm}$$

So the Dopplershift produced at this wavelength by rotation motion at the edges is 1.26 nm. At the approaching edge, it is a blueshift with reflected radio waves of shorter wavelength, and at the receding edge, it is a redshift with reflected radio waves of longer wavelength.