NOTES FOR PLANETARY ATMOSPHERES LAB

The focus of this lab is the calculation of planetary surface temperatures taking into account distance from the Sun, planetary albedo, and atmospheric optical depth.

Part I of the lab describes the relevant concepts and equations necessary for the lab. The main point to stress is the **balance of energy** – if energy were not radiating from the planet at the same rate solar energy is arriving, the surface would warm or cool until equilibrium was reached.

If the planet was radiating too fast, the surface would cool and the rate of radiation would slow. If the planet wasn't radiating fast enough, the surface would warm and the rate of radiation would speed up. In either case, an equilibrium is reached. This is exactly true for a non-rotating body. However, all the planets rotate. Here are some useful values:

Planet	Sidereal Day	Solar Day	Revolution Period
Merury	59 days	179 days	88 days
Venus	-243 days*	117 days	225 days
Earth	23.93 hours	24 hours	365 days
Mars	24.62 hours	24.65 hours	687 days

For Earth and Mars, the rotation is fast enough that Equation 1 is a good approximation. The nighttime temperature drop is small compared to the daytime temperature. For Mercury, Equation 1 is not a good approximation and the dayside bakes and the nightside freezes. (Question 1 addresses Mercury's dayside temperature.) For Venus, its very thick atmosphere and very fast global winds maintain a roughly constant temperature between day and night. (* Note: Venus rotates in the opposite sense from Earth.)

There may be some confusion between the difference between a face-on sphere (πr^2) and the total area of a sphere ($4\pi r^2$). In addition, the low temperatures of the polar regions arises from the difference between half a sphere ($2\pi r^2$) and a face-on sphere (πr^2). This is due to the geometry of a sphere, with the polar regions presenting less surface area than the equatorial regions, area $\propto$ cos(latitude). Thus the polar regions receive less heating, and thus are colder, than the equatorial regions. You may want to go into this in introductory remarks, but for the purposes of the lab, we are ignoring the effect of latitude on temperature. We are only concerned with global averages.

The concept of **albedo** used here is the Bond albedo, the ratio of the total energy scattered from the planet to the total energy incident on the planet. Perhaps the easiest real life example of albedo is the difference between a white shirt and a black shirt on a hot, sunny day.

The **greenhouse effect** is misnamed. In a greenhouse, air warmed by the ground is physically trapped inside and heat is primarily lost by conduction to the outside. In an atmosphere, it is the infrared radiation which is trapped by atmospheric opacity. Energy can only be lost to space by radiation, and it is this process that is slowed by the prominent infrared absorption features of water vapor and carbon dioxide. Without gases that have infrared absorption bands, an atmosphere would provide very little warming effect.

The importance of **Step 1** is to notice that Venus would be roughly habitable and Earth would be frozen without the natural greenhouse effect of the atmosphere. Since Mars' atmosphere is so thin, its greenhouse warming is slight.

Step 2 involves some speculation on reasonable atmospheric parameters for the early Venus, Earth, and Mars. It is assumed that all three planets started out with a sizable carbon dioxide atmosphere and large oceans. Initially, these atmospheres were probably maintained by a combination of volcanic activity and bombardment. In this step, it is important for the students to note that Venus is close to 373 K, and Mars is well below 273 K, while Earth is in between.

Step 3 leads the students through the idea of catastrophic climate change on Venus and Mars. The theory of climate change on these two planets involves a feedback loop. It has been found that highlighting the idea of feedback is enough to jumpstart their thinking.

For Venus, the effect is termed *runaway greenhouse effect*, where the initial high temperature leads to rapid evaporation of the planet's oceans, which increases the amount of water vapor in the atmosphere, which increases the atmosphere's infrared optical depth, in turn increasing the temperature. This process runs away, with the final climate very hot and all the planet's oceans evaporated. Long-term loss of hydrogen from the atmosphere explains the absence of water in Venus' atmosphere now.

For Mars, the process is called *reverse runaway greenhouse*, where the initial low temperature causes any water vapor in the atmosphere to freeze out, lowering the atmospheric optical depth and thus the temperature. This process runs away, but does not have as dramatic an effect on the temperature as is the case for Venus.

In the middle, Earth is between the freezing and boiling points of water, so neither of these processes happened. However, Question 3 addresses an additional puzzle.

Question 1 involves the difference between the Sun-facing area and the radiating area in the derivation of Equation 1. For very slow rotating bodies, only half the surface radiates, $2\pi r^2$, so the area on the right hand side decreases by two. As everything else in Equation 1 stays the same, T increases by a factor $2^{1/4} = 1.19$, to offset the decrease in radiating surface area. As Mercury's T_e is already large, an increase of 19% in the temperature is large!

Additionally, you can calculate the sub-solar temperature, the temperature of the surface where the Sun is at the zenith for long periods. For this purpose, Equation 1 is modified by making the intercepting and radiating area to be the same, say 1 m^2. This has the effect of increasing T by a factor of $4^{1/4} = 1.41$, to offset the decrease in the radiating area. Thus, the subsolar temperature is very high, 40% greater than T_e.

Question 2 is just a bit of historical astronomy.

Question 3 is an important look at one of the most pervasive astronomy myths.

Question 4 can also be turned around to look at the future. As the Sun ages and moves up the giant branch, its luminosity will increase, so the radius of habitable planetary climates is constantly moving outward from the Sun, or any other star. For the last part of this question, thickening the atmosphere is probably the best solution, since the formation of surface ice will only increase the albedo. Although, clearing of the large amount of cloud cover by some mechanism, perhaps precipitation, could decrease the albedo.

Question 5 can be extended to discuss the ancient history of Mars. There is ample evidence of liquid water on Mars billions of years ago. It was cold then too. So how did liquid water ever exist on Mars? The ideas proposed involve a lot of CO_2 (as much as 5 atm), but run into problems of their own. This much CO_2 will readily dissolve in water or combine with rock, depleting the atmospheric optical depth. The problem of liquid water on Mars is still an ongoing topic of research.

Question 6 is a fun look at all those science fiction novels about Mars. It has a strong connection to Question 4.