Name:______________________________
Date:_______________________________

15 The Volcanoes of Io

15.1 Introduction

During this lab, we will explore Jupiter's moon Io, the most volcanically active body in the Solar System. The reason for Io's extreme level of volcanic activity is due to the intense tidal 'stretching' it experiences because of its proximity to Jupiter, and due to its interaction with the moons Europa and Ganymede. The regions of the surface where molten lava from the interior comes up from below are very hot, but in general the rest of the surface is quite cold (about -172^oC $= -279^o$F) since Io is 5.2 AU from the Sun. Regions of different surface temperatures emit different amounts of thermal (blackbody) radiation, since the amount of thermal energy emitted is proportional to the temperature raised to the 4th power: T^4. We will use *infrared* observations, obtained with the Galileo spacecraft in the late 1990's, to determine the temperatures of some of the volcanic regions on Io, and estimate the total amount of energy being emitted by the volcanoes on Io.

Supplies:

1. Exercise squeeze balls and thermometers
2. Visual and thermal images of regions on Io
3. A map of Io with various features identified by name
4. A transparency sheet for temperature fitting of blackbodies

15.2 Introduction to Io

Io (pronounced eye-Oh) is one of the four large moons of Jupiter discovered by Galileo. Images of these four moons (Io, Europa, Ganymede, and Callisto) are shown in Figure 15.1. Io, Ganymede and Callisto are all larger than the Earth's moon, while Europa is slightly smaller. It is clear from Figure 15.1 that Io appears to be quite different from the other Galilean satellites (especially when viewed in color!): it has few obvious impact craters, and has a mottled surface that is unlike any other object in the solar system. Even before the two Voyager probes first flew past Io back in the late 1970's, it was already known that it was an unusual object. The Voyager images of Io certainly suggested that it was covered with volcanoes and lava flows, but it was not until an image showing an erupting volcano, also shown in Figure 15.1, that the case was clinched. From the imaging data, astronomers estimate that there may be as many as 200 volcanoes on Io!

Why does Io have so many volcanoes? It has to do with a process called "tidal heating". As you have learned in the lectures this semester, the gravitational pull on one body by a second massive body raises tides—an example are those caused by the Moon upon the Earth's oceans. As we have also found this semester, the orbits of objects in the solar

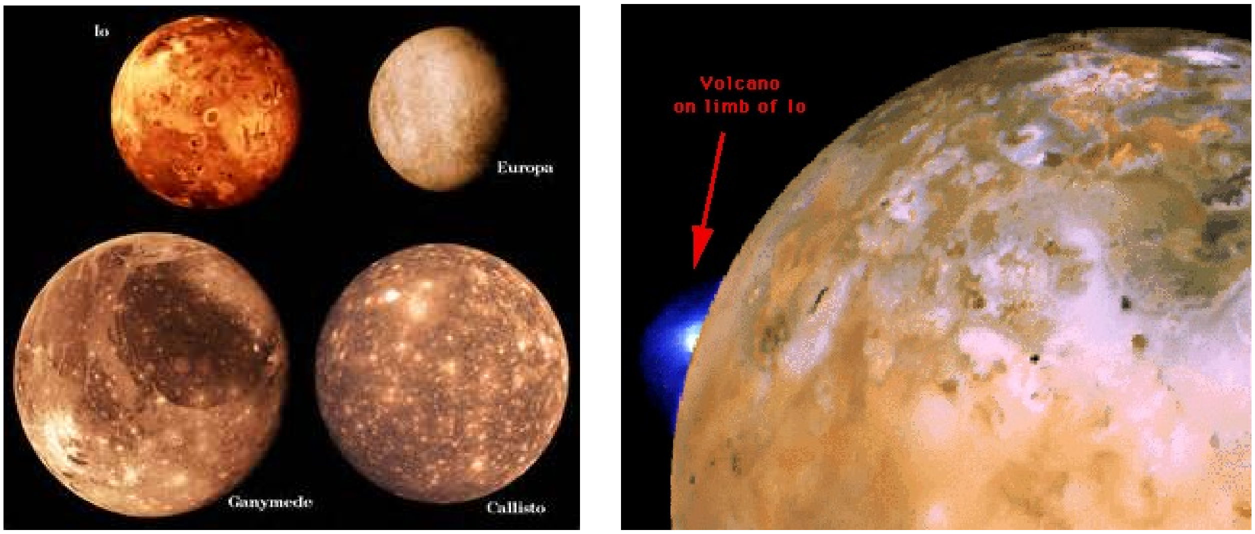
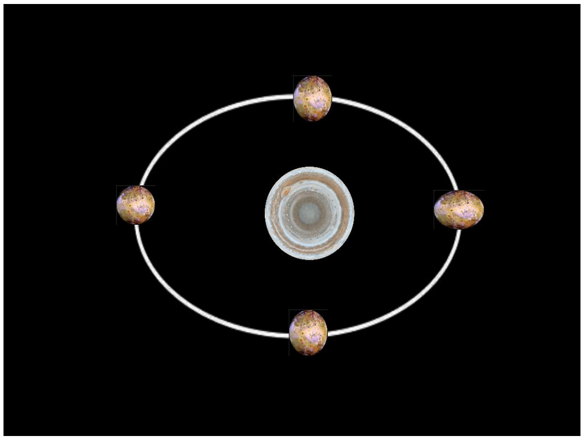


Figure 15.1: Left: The four Galilean moons of Jupiter. Right: An erupting volcano on Io seen in a Voyager image.

system are not perfect circles, but ellipses. That means the distance of an object orbiting a larger body (planet around the Sun, or moon around a planet) is constantly changing. In the case of Io, we have an object that has about the same mass as the Earth's moon, but it orbits Jupiter, an object that has 300 times the mass of the Earth! We have learned that the force of gravity is directly proportional to the mass of an object, Newton's second law: $\mathrm{F} = \mathrm{m}a$. For gravity, Newton's second law is $\mathrm{F} = (G\mathrm{m}_1\mathrm{m}_2)/\mathrm{r}^2$ ("G" is the "gravitational constant"). Thus, even a slightly eccentric orbit, as demonstrated in Figure 15.2, means that large changes in tidal force are felt as Io goes around Jupiter (the $1/\mathrm{r}^2$ term in the equation). In fact, the surface of Io rises and falls by about 100 meters over an orbit! This should be compared to the approximate 0.3 meter rise and fall of the Earth's surface due to the Moon's pull.

The reason that Io's orbit is so eccentric is due to the gravity of Europa and Ganymede. First, let's look at the orbital periods (i.e., the time it takes the moon to orbit Jupiter a single time) of these three moons: P_{Io} = 1.769 days, $\mathrm{P}_{\mathrm{Europa}}$ = 3.551 days, and $\mathrm{P}_{\mathrm{Ganymede}}$ = 7.155 days. It we take the ratios of these orbital periods we get the following answers: $\mathrm{P}_{\mathrm{Europa}}/\mathrm{P}_{\mathrm{Io}} = 2.0$, $\mathrm{P}_{\mathrm{Ganymede}}/\mathrm{P}_{\mathrm{Io}} = 4.0$. What does this mean? Well, it tells you that every 3.551 days Europa and Io will be in the same exact location (relative to each other), and that every 7.155 days Ganymede, Europa *and* Io will be in the same relative places! A diagram of this is shown in Figure 15.2. The term astronomers use for such an arrangement is "orbital resonance". Because of these orbital resonances, the gravitational tug on Io is amplified, as it and Europa (and it and Ganymede) make close approaches on a regular, and repeating basis. Thus, Europa and Ganymede continually pull on Io, making its orbit more eccentric. [Note that we believe that Europa also has considerable tidal heating, and this heating may mean that below its frozen surface, there is a large ocean of liquid water that could support primitive life. This might even be happening on Ganymede.] The tidal heating causes the interior of Io to become molten, and this liquid rises to the surface, where



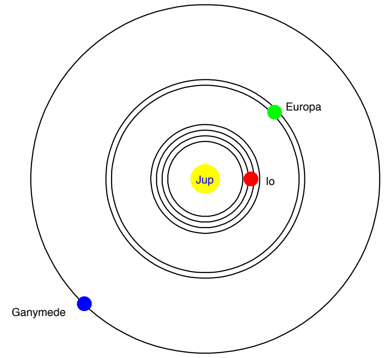


Figure 15.2: Left: Because Io's orbit around Jupiter is an ellipse, the distance is constantly changing, and so is the gravitational force exerted on Io by Jupiter (note that this figure is not to scale, and the ellipticity of the orbit and the shape of Io have been grossly exaggerated to demonstrate the effect). This changing force causes Io to stretch and relax over each orbit. Right: The tidal forces exerted by Europa and Ganymede distort the orbit of Io because the orbits of all three moons are in "resonance": for every four trips Io makes around Jupiter, Europa makes two, and Ganymede makes one. This resonance enhances the gravitational forces of Europa and Ganymede, as these three moons keep returning to the same (relative) places on a regular basis. This repeated and periodic tugging on Io causes its orbit to be much more eccentric than it would be if Europa and Ganymede did not exist.

it erupts in volcanoes. We will return to Io later in this lab, but before we do so, we must cover several complicated topics that will allow us to better understand what is happening on Io.

15.3 The Electromagnetic Spectrum

Before we begin today's lab, we have to review what is meant by the term "spectrum", and "wavelength". As we have discussed in class, light is an energy wave that travels through space. For now, we can use the analogy that waves of light are like waves of water: they have crests, and troughs. The "wavelength" is the distance between two crests, as shown in Fig. 15.3. The energy contained in light is directly related to the wavelength: low energy light has long wavelengths, while high energy light has short wavelengths. Thus, scientists have constructed several categories of light based on wavelength, and which you have certainly heard about: Gamma-ray, X-ray, Ultraviolet, Visible, Infrared, Microwave and Radio. Gamma- and X-rays have very short wavelengths and have lots of energy, so they penetrate through materials, and often damage them as they pass through. Ultraviolet light causes sunburns and skin cancer. Visible light is what our eyes detect. We feel intense infrared light as "heat", microwaves cook our food, while radio waves allow you to listen to music and watch television. The common textbook plot of the electromagnetic spectrum is shown in Fig 15.4. When we break-up light and plot how much energy is coming out at each wavelength, we construct a “spectrum”. A spectrum of an object supplies a lot of information, and is the main tool astronomers use to understand the objects they study.

We can also think of the electromagnetic spectrum as a way to represent temperature. For example, objects that emit X-rays are at temperatures of millions of degrees, while objects that emit visible light have temperatures of thousands of degrees (like the Sun), while infrared sources have temperatures of 100’s of degrees. To understand this concept, we must talk about “blackbody” radiation.

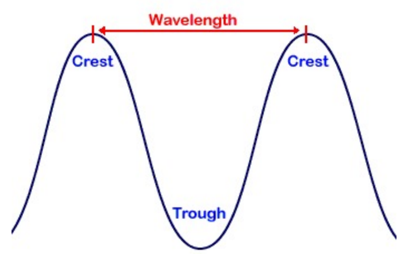


Figure 15.3: The wavelength is the distance between two crests.

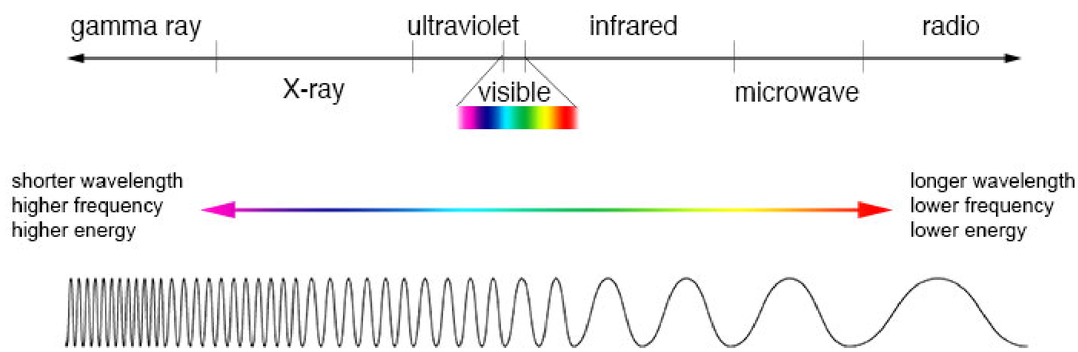


Figure 15.4: The electromagnetic spectrum.

15.4 Blackbody Radiation Review

Let us review the properties of **blackbody radiation**. A blackbody is an object that exactly satisfies the Stefan-Boltzmann law (named for the two scientists who first figured it out), and has a spectrum that is always the same shape, no matter what temperature the source has, as shown in Fig. 15.5. While real objects do not exactly behave like this, many objects come very close and in general we assume that most solar system objects (including Io) are blackbodies.

The Stefan-Boltzmann law states that *the total amount of energy at all wavelengths emitted by a blackbody at temperature T is proportional (“$\propto$”) to the fourth power of its temperature*, which can be written in equation form as:

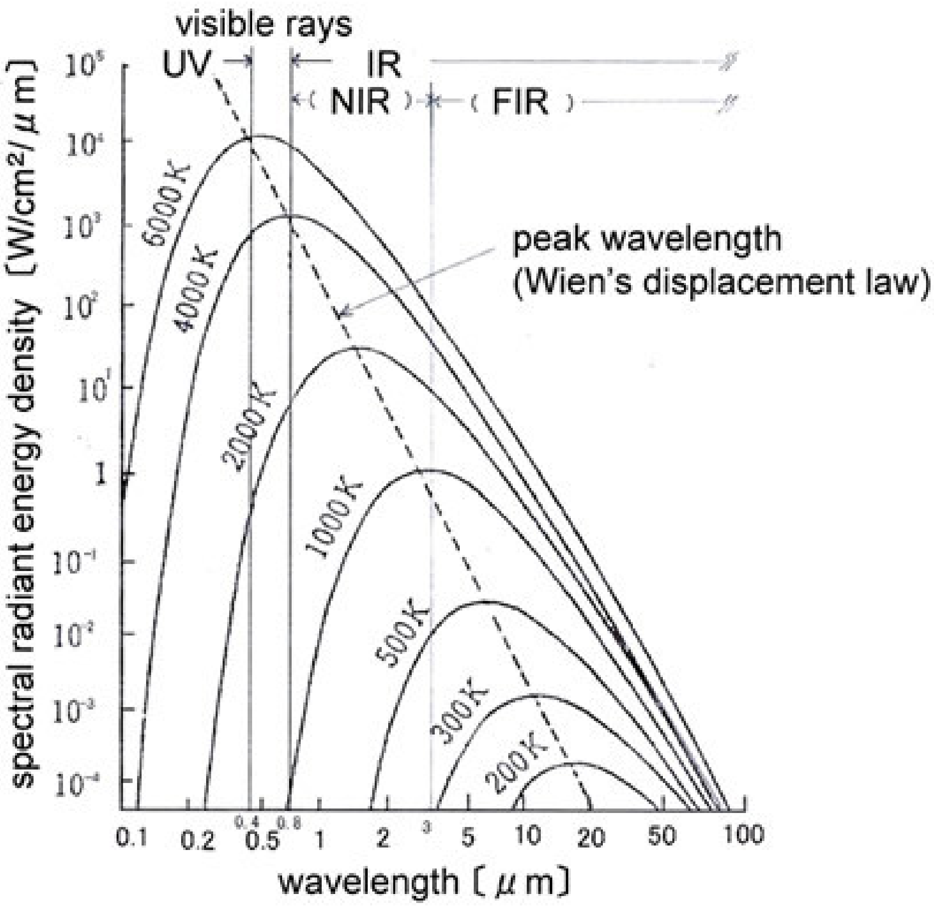


Figure 15.5: The spectra of blackbodies always have the same shape, but the wavelength where the *peak emission* occurs depends on temperature, and can be calculated using the "Wien displacement law" (since Wien is a German name, it is properly pronounced "Veen"). In this particular plot the unit of wavelength is the micrometer, 10^{-6} meter, symbolized by "μm." Note also that the x-axis is plotted as the *log* of wavelength, and the y-axis is the *log* of the radiant energy. We have to use this type of "log-log" plot since blackbodies cover a large range in radiant energy and wavelength, and we need an efficient way to compress the axes to make compact plots. We will be using these types of plots for the volcanoes of Io.

$$E \propto T^4. \tag{3}$$

Here E is the amount of energy emitted by *each square meter* of the object each second. You might be wondering to yourself why we write $E \propto T^4$, instead of $E = T^4$. In fact, the real blackbody equation is $E = sT^4$, where "*s*" is the "Stefan-Boltzmann constant." The Stefan-Boltzmann constant is a special number that makes the equation work, and insures that the output energy is in Watts (or another appropriate energy unit), instead of $^{o}F^4$. You measure the energy of a light bulb in Watts, not the fourth power of degrees Fahrenheit. The actual value of s is 5.6703×10^{-8}. This is a horrible number to deal with, so we will use a technique that does not require us to remember it!

As noted in Fig. 15.5, the Wein displacement law relates the temperature of a blackbody, and the wavelength (λ) of its maximum emission: $\lambda_{max} \times T = 3670$, where 3670 is the value of "Wien's constant" when wavelength is measured in micrometers, and radiant energy in Watts/m^2 (as we will use in this lab).

Definition of Temperature

Before we go any further in understanding blackbodies, we must define the temperature scale that is used in the Stefan-Boltzmann formula, and in Wien's law. In the United States, our weather forecasts use the Fahrenheit scale. This scale was developed around the idea that in our everyday experience, a big number like "100^o F" would be "hot", and "0^o F" would be "very cold." On this scale water boils at 212^o F, and freezes at 32^o F. The Fahrenheit scale is not very easy to work with, in that it has 180^o F between the boiling and freezing point of water (two processes that are easy to observe, allowing accurate calibration). With the development of the metric system, based on powers of 10, a temperature scale was developed where the freezing point of water was defined to be 0^o, and the boiling point was set to 100^o. This is the "Celsius" scale (denoted by "^{o} C"), predominantly used outside the United States.

Both the Fahrenheit and Celsius scales, however, cannot be used with the blackbody energy equation. Why? Because both scales have "zeroes" and negative temperatures. Even in Las Cruces, the temperature often goes to 0^o C or below on the Celsius scale during winter (and once in a while, as in 2010, it goes below zero on the Fahrenheit scale!). Look at our equation again, $E \propto T^4$. If the temperature changes from 3^o C to 0^o C, the amount of energy emitted by a blackbody *would go from positive to zero.* If this object got colder and colder, however, its emitted energy would increase! For example, if its temperature had now dropped to -3^o C, the emitted energy would be the *same* as it was at $+3^o$ C: $E = -3 \times -3 \times -3 \times -3 = 81 = 3 \times 3 \times 3 \times 3$. Do you see why this is? The fourth power (or any even power in the exponent) means that a negative number will turn out positive: $(10)^4 = (-10)^4 = 10{,}000$, because every time you multiply two negative numbers together, the result is a positive number.

If we were to use the Fahrenheit or Celsius temperature scales, our equation would produce nonsensical answers, since it is obvious that a hotter object has more energy than a colder one. Thus, scientists use a scale that has no negative numbers, the "Kelvin" scale. On the Kelvin scale, the temperature at which water freezes is 273 K, and it boils at 373 K (Kelvin has the same size degrees as the Celsius scale, and note also that the little degree symbol, "^{o}", is not used with Kelvin). In our example, 3^o C = 276 K, and 0^o C = 273

K. Now, a drop in temperature by 3 degrees does not cause the emitted energy to go from positive to zero, the energy simply decreases. There is a 0 K, but that temperature is so cold that any object with that temperature *would* emit zero energy (that, in fact, is the definition of 0 K!).

Working with the Stefan-Boltzmann Law

An equation like the Stefan-Boltzmann law is scary to many Astronomy 105 students. Nearly all of you have heard about "squares", such as the area of a circle being πR^2. But, there are many equations in science when the exponent is larger than 2. All an exponent says is that you must multiply the number by itself that many times: $R^2 = R \times R$. Or, $R^5 = R \times R \times R \times R \times R$. Other than the large numbers that come out of the Stefan-Boltzmann law (it is astronomy after all!), there is nothing difficult about understanding how to deal with T^4.

Ok, let's see how to use equation (1) so we can compare the energy emitted by *each square meter* of the surface of two different objects, A and B. We will construct the ratio so we do not have to worry about the value of the Stefan-Boltzmann constant:

$$\frac{E_A}{E_B} = \frac{sT_A^4}{sT_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{4}$$

Do you understand what happened? We had an s on the top and bottom of our equation, but $s = s$, so it cancels out! We also use the property where $T_A^4 \div T_B^4 = (T_A/T_B)^4$ (in math this is called the "Power of a Quotient property").

Let's work an example. Object P has a temperature of 43 K, and object Q has a temperature of 33 K. The objects have the same area. How many times greater is the energy emitted by P compared to the energy emitted by Q? Set-up the equation:

$$\frac{E_P}{E_Q} = \frac{s(43)^4}{s(33)^4} = \left(\frac{43}{33}\right)^4 = (1.3)^4 = 1.3 \times 1.3 \times 1.3 \times 1.3 = 2.86 \tag{5}$$

Now it is your turn:

1. Assume that T_A, the surface temperature of Object A, is 200 K, and T_B, the surface temperature of Object B, is 100 K. The objects have the same area. How many times greater is the energy emitted by A compared to the energy emitted by B? (**2 points**)

2. Object R and Object S have the same temperature. But object R has an area of 4 square meters, and object S has an area of 2 square meters. How much more energy

does object R emit compared to Object S? (**2 points**)

3. Now we are going to go backwards (much harder!): assume that we receive 81 times more energy from Object X than from Object Y. Object X and Y have the same areas. How many times hotter is the surface of X compared to the surface of Y? [Hint: what number multiplied by itself 4 times = 81?] (**2 points**)

We know that the last problem was hard! How does one solve such equations? The key to understanding this is to realize that for every mathematical operation that uses exponents, there is the reverse process of "taking the root". For example, two squared: $2^2 = 4$. What is the square root of 4? $\sqrt{4} = 2$. The square root can also be written as a fractional exponent: $(4)^{1/2} = 2$. This is how we solve the problem above. Here is an example: What is Q, if $Q^4 = 6561$? On a fancy scientific calculator, we just enter this: $(6561)^{1/4} = 9$. But the fourth root is really just two *successive* square roots: $\sqrt{6561} = 81$, $\sqrt{81} = 9 = (6561)^{1/4}$. So you do not need a fancy calculator, got it?

Working with Wien's Law

Unlike the Stefan-Boltzmann law, Wien's Law is very simple. So simple we do not think you need an example on how to use it! [Here is Wien's law again: $\lambda_{\rm max} \times {\rm T} = 3670$]

4. If the temperature of a black body is 1000 K, at what wavelength ($\lambda_{\rm max}$) does it emit its peak amount of energy? (Remember to include the wavelength unit!) (**2 points**)

5. An object is observed to have a blackbody spectrum that peaks at $\lambda_{\rm max} = 37\ \mu$m, what temperature is this object? (Remember to include the temperature unit!) (**2 points**)

15.5 Simulating Tidal Heating

As we noted above, the process of tidal heating is what causes Io to be covered in active volcanoes. In this exercise we are going to simulate tidal heating, where *you* are the source of the energy input. First off, however, have you ever tried to break a piece of wire with your hands? You cannot simply pull it apart with your hands, it is too strong. But we can break it by adding heat. We do this by first folding the wire to create a kink, and then rapidly bending the wire back and forth. The wire becomes very, very hot at the kink, and will eventually snap. What you have done is transfer energy your body generates and focused it on a tiny region of the wire. The intense heat weakens the wire and it snaps (you should try this with a paper clip). This process is what is going on in Io, a stretching/bending of the rock that generates heat.

Exercise #1:

Ok, well Io is not a wire, it is a sphere! While the repeated bending of the wire is *exactly* like the process that is heating Io, it is not very realistic. Let's take this concept to a slightly more realistic level by "stretching" a sphere. Among the materials you were given were two, small exercise squeeze balls and a digital thermometer. We will now use these. To start this experiment, insert the thermometer into each of the balls and record the **Start Temperature**. Make sure the tip of the metal probe reaches the center of the ball (and no further!). Note that it also takes a certain amount of time for the temperature to stabilize at the correct value. Enter these values into Table 15.1.

Now, one member of your group should take a ball in each hand. One of these will be the "control ball", let's call that Ball #1. You will not do anything to Ball #1, except hold it in your hand. But for Ball #2, repeatedly, as rapidly as possible, squeeze this ball as tightly as possible, release, and repeat. *Do this for four straight minutes (one group member needs to be the time keeper!).* At the end of four minutes, as quickly as you can, insert the thermometer into the ball you have been squeezing and record the temperature. Note that it takes quite a few seconds for the temperature to read the correct value, continue to squeeze this ball *with* the thermometer inserted, until the temperature no longer rises. Record this value in the "End Temperature" column for Ball #2. Now, do the same for Ball #1, but do not squeeze, simply continue to quietly hold it in your hand while the thermometer rises to its maximum temperature. Put this value in Table 15.1. [If you cannot repeatedly squeeze Ball #2 for four straight minutes in one hand, go ahead and switch hands, as long as the same ball is the one that continues to get squeezed.]

Take the difference between the End and Start temperatures and enter it into the final column of Table 15.1. (**6 points**)

Answer the following questions: Are the start and end temperatures for both balls different? Why do you think we had you hold onto Ball #1 the entire time you were

Table 15.1: Exercise Ball Temperatures

	Start Temperature	**End Temperature**	**Change in Temperature**
Ball #1			
Ball #2			

squeezing Ball #2? Which ball showed the greater temperature rise? Why did this happen, and where did this energy come from? (**6 points**)

15.6 Investigating the Volcanoes of Io

Now to the main part of today's lab, the volcanoes of Io. Along with the other lab materials, we have supplied you with a three ring binder containing images of Io, along with a large laminated map of Io. Please do not write on any of these items! The first section contains some images of Io taken with the Galileo spacecraft. Just page through them to get familiar with Io (including color versions of the Figures in the introduction of this lab). Io is an unusual place!

Today we are going to look at images and data obtained with three different instruments of the Galileo spacecraft: the Solid State Imager (SSI), the Near-Infrared Mapping Spectrometer (NIMS), and the Photopolarimeter-Radiometer (PPR). The SSI is simply a ("0.6 megapixel") digital camera not unlike the one in your smart phone, and only can detect visible light (technically wavelengths from 0.4 to 1.1 μm). NIMS is also an imager, but it detects near-infrared light, having wavelengths from 0.7 to 5.2 μm (your TA will demonstrate a version of this type of infrared camera during lab). The PPR measures the heat output of objects (not really an imager, though you could make coarse pictures with it), and could detect light with wavelengths from 17 to 110 μm

Let's go back and look at Fig. 15.5. Do you understand why these instruments were included on a mission to Jupiter? The Sun has a blackbody temperature of about 6,000 K, what is the wavelength of peak emission for such a blackbody? This is the light that illuminates the Earth during the day, and all of the other objects in our solar system. Thus, to see these objects, we only need a regular camera (the SSI). But Jupiter is very far from the Sun, and thus it is very cold place. For example, at the surfaces of the Galilean satellites, the temperatures are about 100 K. To measure such cold objects, we need an instrument like the PPR. If there are hot spots on Jupiter or any of its moons (like Io!), they might have temperatures between 500 and 2000 K, and we will need a "near-infrared" camera like NIMS to detect this light.

In the second section of the three ring binder are some NIMS images. The first set of images shows a color picture of Io obtained with the SSI, and two images obtained with NIMS (at 1.593 and 4.133 μm). Note that in the SSI image there are bright and dark regions all over Io. In the NIMS images, however, Io begins to look quite different. In image #5a, at 1.593 μm there is still *some* reflected sunlight (since this is a daytime NIMS image), but by 4.133 μm thermal (blackbody) emission from Io is now strong.

Exercise #2

6. In image #5a, we see that at 4.133 μm there are many bright spots. Returning to Fig. 15.5 (above), estimate the temperature of these bright spots. [Hint: can you see the bright spots at 1.593 μm? What is the hottest blackbody in this figure that has a lot of emission at 4.133 μm, but (almost) none at 1.593 μm?] (**4 points**)

7. In image #5b, around the dark spot near the center of the 1.3 μm image, there is a bright ring. But this ring is very dark at 4.2 μm, suggesting it is very cold. How can it be bright at 1.3 μm, and dark at 4.2 μm? These are daytime images. Can you explain this feature? [Hint: think about snow] (**4 points**)

8. In Fig. 15.6, below, are plotted two blackbodies (energy emitted in Watts vs. wavelength in micrometers). Using Wien's law, what are the approximate temperatures of

each of these blackbodies (one **solid** line, one **dashed**) in "K"? Which one is emitting more total energy? How do you explain this? (**4 points**)

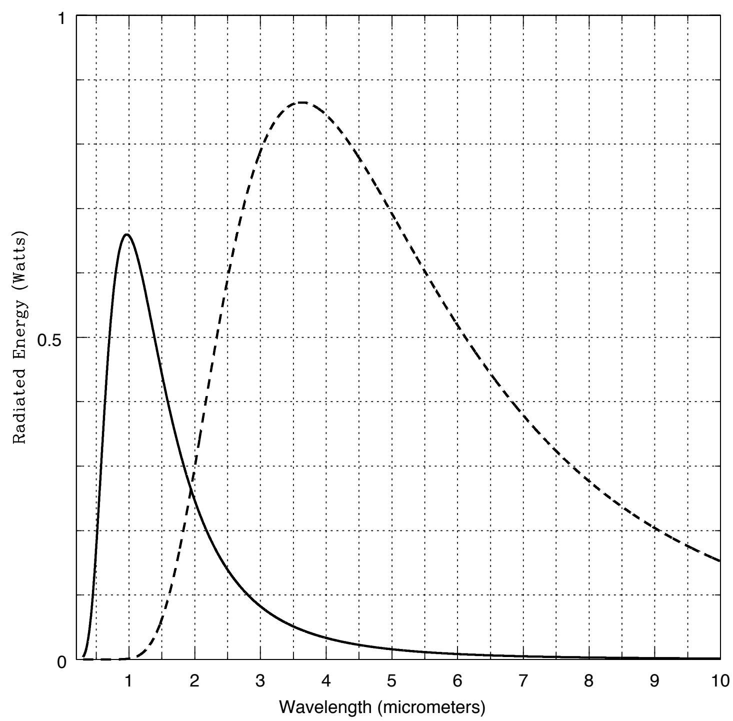


Figure 15.6: The energy vs. wavelength, the "spectra" (spectra is plural of spectrum), produced by two blackbodies with different temperatures.

Exercise #3

In section 3 of the binder, we have some NIMS images of active regions on Io. On these images are some small, numbered boxes, we will be looking at the NIMS + PPR spectra of some of these boxed regions to determine their temperatures. The names of the features on Io are from a variety of mythologies that have to do with deities of fire, volcanoes, the Sun, thunder and characters and places from Dante's Inferno. Named mountains, plateaus, layered terrain, and shield volcanoes are given the terms mons, mensa, planum, and tholus, respectively. The term “Patera” (plural = Paterae) means a bowl, and brighter, whitish regions go by the name “Regio”.

9. Region #1 (Image #6) is a night time NIMS image of a region on Io. In this image, you can see lines of longitude and latitude. It basically runs from 125°W to 132°W in longitude, and from +59° to +71° in latitude. Using the big map of Io, what is the name of this active region? [Note: an SSI image of this region is shown in binder image #4!] (**2 points**)

11. It is clear the NIMS instrument does not make very pretty pictures, it has “poor resolution”. When this camera was built, infrared imaging technology was just becoming possible. The infrared camera that your TA has demonstrated today in class is as good, or better than NIMS! In these NIMS images, redder colors mean hot, and bluer colors mean cool. Compare the Region #1 NIMS image to Image #4 in the binder from the SSI (they have totally different orientations!!!). Can you figure out what is happening? Can you figure out which boxes in the NIMS image cover the hot, glowing lava feature in the SSI image? (**6 points**)

12. The NIMS image of Region #2 is shown as Image #7. Using the large map, what is the name of this region? (**2 points**)

13. In fact, the NIMS image of Region #2 does not cover all of this large feature, does it? In Fig. 15.7 we present the NIMS + PPR spectra of the six boxes shown identified

in Image #7. Using the plastic blackbody overlay, measure the temperatures for *only* boxes 1 and 4. [If you are having trouble doing this, ask your TA for help.] (**4 points**)

Table 15.2: Region #2 Box Temperatures

Box	**Maximum Wavelength (μm)**	**Temperature (K)**
Box #1		
Box #4		

14. The radius of Io is 1,821.3 km, that means that the circumference of Io is (C = 2πR) 11,443.6 km. Since there are 360° in a circle, each degree of *latitude* represents 31.79 km. Assuming the northern half of this glowing ring has the same size as the southern half, what is the total area covered by the hot material of this feature? [Hint: The latitude increases from the bottom to the top of the image (approximately the y-axis of the figure), while the horizontal (x-axis) direction is longitude. Note that the white grid lines are identical in size in the vertical and horizontal directions, thus you can measure both sides of the box in degrees of latitude (note that degrees of longitude only equal degrees of latitude at the equator, and this region is not at the equator!). The degrees of latitude are the small white numbers that run from 9 to 13.]

    The area of a square is simply $side \times side = s^2$. Calculate the area in square kilometers of one white grid box (not the tiny little boxes you measured the temperatures for!). Next, estimate the number of such grid squares *fully* covered by the "hot" reddish regions for the southern half of this feature (this will be a fraction of a grid box for some spots). The total area in square kilometers is the number of boxes covered times the area of one box—find this number. Multiply that result by two, and you have the approximate area of the entire feature. (**6 points**)

15. Now we want to figure out the total energy output of all of the volcanoes on Io. Step 1: In the large map of Io, the paterae are the brown regions. You can see that the volcano you just measured is just about the largest such feature on Io. The average

patera appears to have about 5% (= 0.05) the area of this feature. Estimate the total area covered by *all of the paterae* on Io. [Hint: note what we said in the introduction about the estimated number of volcanoes on Io.] (**4 points**)

Total Volcano Area = Average area × number of volcanoes = ???? km^2

Total Volcano Area = × = km^2

16. Step 2: Figure out the total area of Io. The area of a sphere is $4\pi R^2$. (**3 points**)

17. Step 3: We will assume that the average surface temperature of the non-volcanic regions on Io is the same as that of box #4 on Image #7 that you found above. We will assume that the average temperature of the paterae is the same as that of box #1 on Image #7 that you found above. Now, we are going to use the Stephan-Boltzmann law to calculate how much energy the volcanoes on Io put out compared to the rest of Io. Remember, the Stephan-Boltzmann law was the amount of energy output per unit area (m^2):

$$\frac{E_A}{E_B} = \frac{sT_A^4}{sT_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{6}$$

Since in this problem we have two different emitting areas (total Io area, and area covered by volcanoes), we have to modify this law to explicitly include the area terms:

$$\frac{(Total\ Emitted\ Energy)_A}{(Total\ Emitted\ Energy)_B} = \frac{Area_A}{Area_B} \times \left(\frac{T_A}{T_B}\right)^4 \tag{7}$$

So,

$$\frac{(Total\ Emitted\ Energy)_{Volcano}}{(Total\ Emitted\ Energy)_{Io}} = \frac{(Area)_{Volcano}}{(Area)_{Io}} \times \left(\frac{T_{\#1}}{T_{\#4}}\right)^4 \tag{8}$$

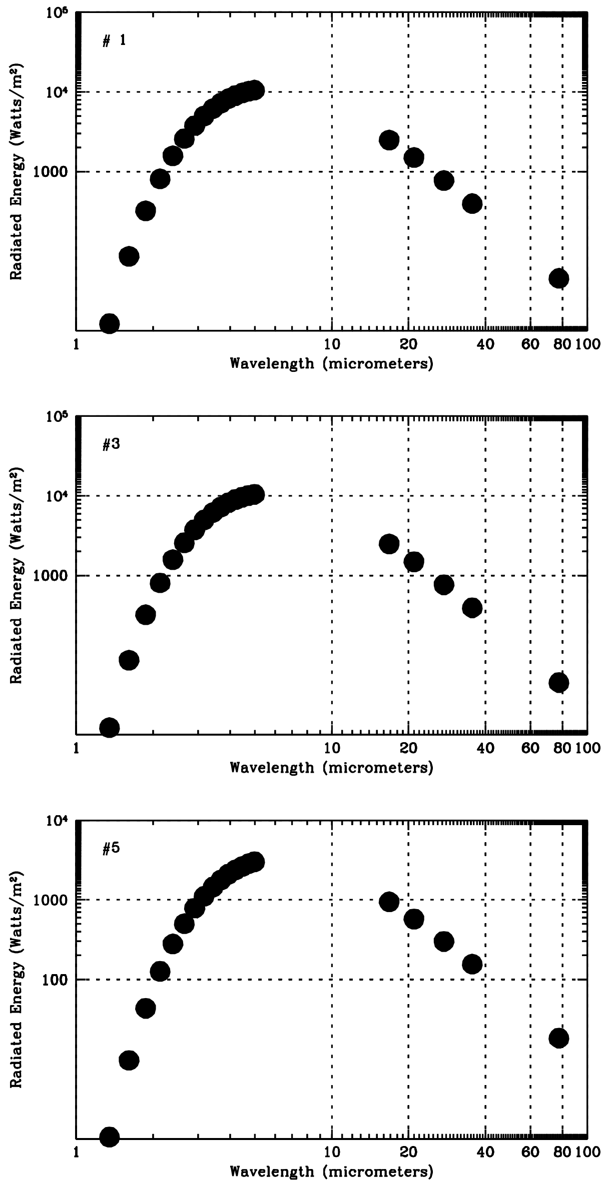


Figure 15.7: The blackbody spectra of the six boxes shown in Image #7. Be careful, these plots have *log* wavelength on the x-axis.

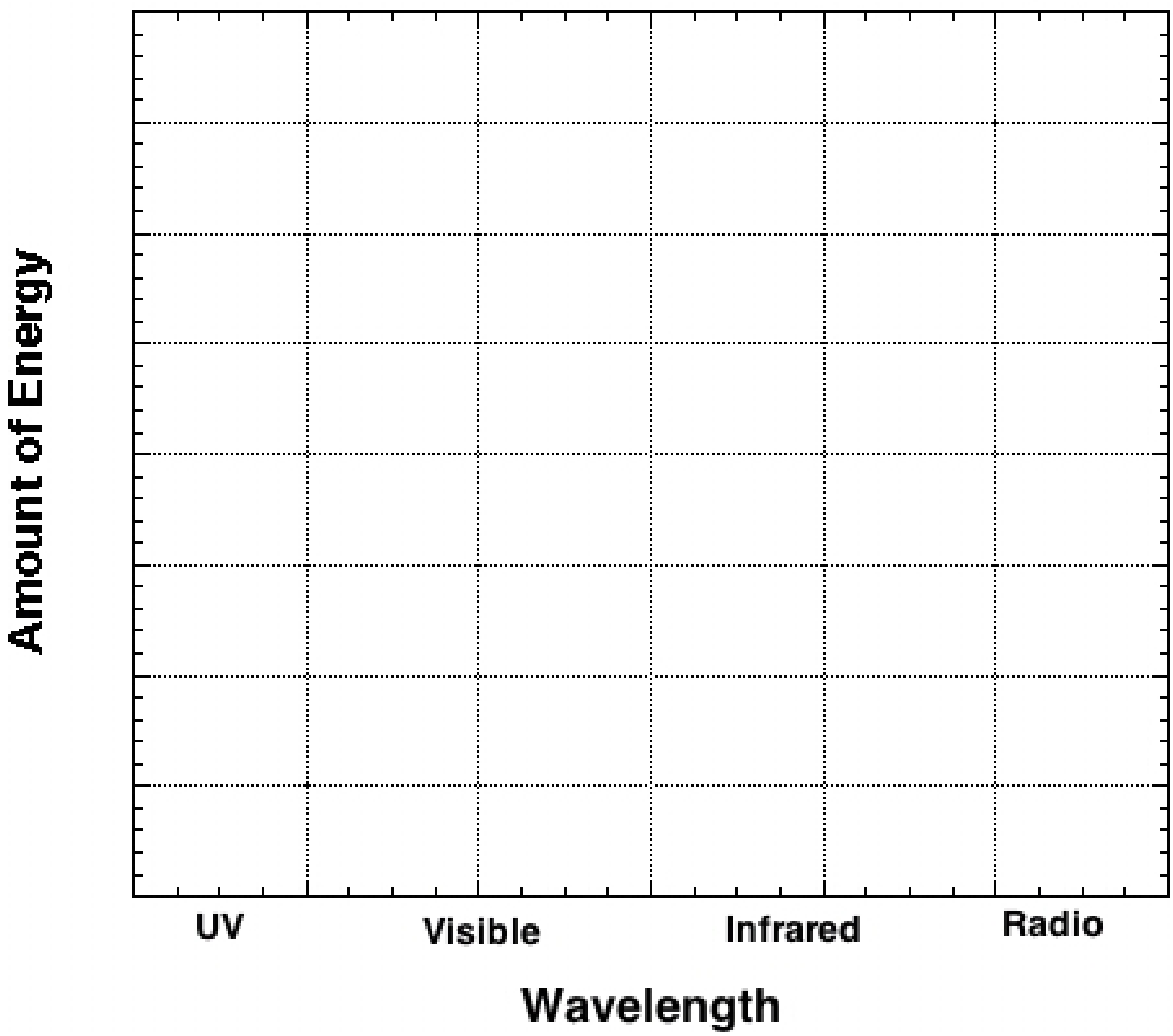
$$\frac{(Total\ Emitted\ Energy)_{Volcano}}{(Total\ Emitted\ Energy)_{Io}} = \tag{9}$$

The volcanoes on Io put out how much more energy than the total *for all of* Io? Do you find this surprising? Note that the Sun is far away (5.2 AU), and cannot heat-up Io very much. Thus, gravitational heating can be very important. This process is probably going on elsewhere in the solar system (such as with the moons of Saturn). What does this mean for the possibility of life existing on/inside these moons? (**4 points**)

Name:________________________________
Date:_________________________________

15.7 Take-Home Exercise (35 points total)

1. In the graph below, draw two curves indicating the blackbody curves (energy as a function of wavelength) emitted by i) a hot object (T = 6,000 K), and ii) a cool object (T = 1,000 K). Both objects have the same area. You will be graded on the *relative positions* of these two curves with respect to one another, as well as which one emits more energy. Label the y-axis with the appropriate numbers, and identify the blackbody curves! (**10 points**)



2. If Europa and Ganymede were further from Jupiter (had larger orbits), but Io remained where it is, would you still expect Io to experience volcanism? Explain. (**10 points**)

3. The colorful volcanic features we have studied in this lab involve the chemical element sulfur. It is not expected that molten sulfur gets any hotter than $\sim$ 350 Kelvin or so on Io's surface. As you have found out, however, many spots on Io's surface have been determined to possess temperatures that are much hotter, some as hot as 1800 K! It is believed that such regions must consist of molten rock (silicates, like lava here on Earth) and not molten sulfur.

   a) How many times greater would the flux from such a rock-lava region be compared to the flux emitted by the colder regions of Io (such as you measured in Exercise #3, question #13). (**3 points**)

   b) At what wavelength would the maximum (peak) energy emission occur from this 1,800 K region? (**2 points**)

c) Returning to Figure 15.5, would this very hot lava be detectable with the SSI? Explain. (**5 points**)

4. Jupiter has several moons that are much, much smaller than Io and that orbit even closer to Jupiter than Io. Give a brief explanation of why these moons do NOT show evidence of volcanism [Hint: think of a man-made satellite in Earth orbit, even a *big* one such as the International Space Station]. (**5 points**)

15.8 Possible Quiz Questions

1. Why does Io have volcanoes?
2. What does the term "orbital resonance" mean?
3. What is a "blackbody"?
4. What is Wien's law?
5. What does the term "patera" mean?

15.9 Extra Credit (ask your TA for permission before attempting, 5 points)

Orbital resonances are found elsewhere in the solar system. For example, the shaping of Saturn's ring system, or the relationship between Neptune and Pluto. Type-up a one page discussion of how orbital resonances affect the appearance of Saturn's rings, or how the Neptune-Pluto orbital resonance gives us insight into the processes that shaped the formation of our solar system.