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16 Heat Loss from Io

16.1 Introduction

With this lab, we will explore two concepts we have discussed in class. Jupiter's moon Io is the most volcanically active body in the Solar System, due to the intense tidal 'stretching' it experiences because of its proximity to Jupiter and its orbital characteristics related to the orbits of 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 surface is quite cold since Io is 5.2 AU from the Sun. These regions of different surface temperatures emit different amounts of thermal (blackbody) radiation, since the quantity of energy emitted is proportional to the temperature raised to the 4th power (T^4). We will use observations, obtained with the Voyager spacecraft in the late 1970's, of the quantity of energy emitted by various locations on Io's surface to determine the temperatures of these surfaces. This is the reverse of what we have generally discussed this semester, where we know the temperature and determine something about how much radiation is emitted. By knowing the temperature of the lava/molten material, we can make a good guess as to the composition of the lava.

Supplies:

1. One wide-angle view and one close-up image of Io's surface obtained with the Voyager 1 spacecraft in 1979
2. A map of Io's western hemisphere with various features identified by name
3. A transparency sheet with circles of different diameters drawn on it

16.2 Blackbody Radiation Review

Io's surface is covered with volcanoes and the deposits erupted by these volcanoes. The white regions on Io's surface show spectral absorption features (visible wavelengths at which Io does not reflect much sunlight) of sulfur dioxide (SO_2). Sulfur dioxide is white when solid, and when heated enough it changes to gas (just like water, though the freezing/evaporating temperatures for SO_2 will be different than for water).

The surface colors on Io are consistent with sulfur volcanism. When sulfur is heated, it changes from pale yellow to orange to brown to black as the temperature increases. Laboratory studies indicate that the blackest structures on Io should be hottest, assuming they are sulfur. We will test this prediction today.

For this lab, we are going to look at data returned by an instrument on the *Voyager* spacecraft, which flew by Jupiter and its moons in 1979. The Infrared Spectrometer and Radiometer (IRIS) was mounted on the same part of the spacecraft (the instrument platform) as the visible light camera. This means that both instruments had the same view of Io's surface at any given time. While the camera took images using the sunlight **reflected** by the surface (just like when you take a snapshot), the IRIS measured the thermal infrared radiation **emitted** by the surface. We will use this information to learn about the temperature of the surface of Io.

First, we need to review the properties of **blackbody radiation**. A blackbody is an object that exactly satisfies the Stefan-Boltzmann law and Wien's law. While generally real objects do not exactly satisfy these laws, many objects come very close and in general we assume that most solar system objects (including Io's surface) are blackbodies. Answer the following questions to re-familiarize yourself with these laws.

1. How does the total amount of radiant energy (or flux) emitted by a blackbody depend on its temperature ? How does the wavelength at which most of the energy is emitted depend on its temperature? (**5 points**)

   One rule that was briefly discussed in class is that **the flux of energy at all wavelengths emitted by a black body at temperature T is proportional to the fourth power of its temperature**, which can be written as:

$$F \propto T^4. \tag{1}$$

   Here F (flux) is the energy emitted by each square meter of the object each second. Using equation (1), let's compare the flux emitted by each square meter of the surface of two different objects, A and B. We will construct the ratio:

$$\frac{Flux_A}{Flux_B} = \frac{T_A^4}{T_B^4} = \left(\frac{T_A}{T_B}\right)^4 \tag{2}$$

2. 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. How many times greater is the flux from A compared to the flux from B? (**5 points**)

3. Now, assume that we receive 81 times more flux from Object X than from Object Y. How many times hotter is the surface of X compared to the surface of Y? (**5 points**)

16.3 Temperature of Io's Volcanoes

As indicated above, we can suitably approximate the surface of a planet or a moon as a blackbody. Using the above equations and temperature determination techniques, and IRIS observations, we can determine the temperatures of some of the volcanoes on Io's surface. You will be filling **Table 16.1** as you go along.

Within your lab package you will find two *Voyager* camera images of a region on Io's surface. One of these images is a wide-angle view (covers a large area) in which you can see several dark regions, and the other image is a close-up in which you can see two features, one dark and one bright, that are readily apparent in the wide-angle image.

4. Determine the location, in the wide-angle view image, of the two features you can see in the close-up view. [You should have the GREEN corner of each image in the lower left as you look at them]. The black feature in the close-up image is called *Mihr Patera* (Patera means pancake). Find Mihr Patera on the map provided along with the images and write down its latitude and longitude on Io. (**5 points**)

As Voyager's visible camera was taking the images you have in front of you, its infrared-sensitive instrument, IRIS, was also looking at the same location on Io's surface. However, IRIS had much lower spatial resolution than the imaging camera. It only measured the total amount of energy emitted from a large circular region each second.

Overlay your transparency sheet on the wide-angle image. Match the green edges on your wide-view photo and on your transparency, and point the arrow upwards, to determine which circular Areas (A, B, C, D, E) correspond to the various features on the wide-angle image. The circles on the transparency show the IRIS field of view ("footprints") over the same area as the photograph.

Now, let's determine how hot the surfaces are within these circular areas. We assume that area A is completely covered with ice composed of sulfur, and that all regions within this circular area are at the same temperature. The amount of emitted energy received from Area A by IRIS corresponds to a surface temperature of $\sim$ 125 Kelvin. [If we calculate a surface temperature for Io based upon the reflectivity of the ice, distance from the Sun, etc., we arrive at a temperature of $\sim$ 125 K, so the IRIS measurements are very reasonable.]

5. Looking at just the Energy values in Column 2 of Table 16.1, which areas do you conclude contain warmer surface temperatures than the surface temperatures within Area A? Why do you conclude this? What distinguishes these areas, at visible wavelengths, from their neighbors in the wide-angle image? (**10 points**)

To determine the temperatures of these regions, we will make the following assumption: *for those regions that contain both bright and dark regions, we will assume all the emitted energy IRIS received came from the dark regions.* We can safely make this assumption because of the T^4 dependence of energy emission, and since through our knowledge of the surface composition (sulfur), we are quite confident that darker regions will be warmer than brighter regions.

We now want to determine how much (maybe all?) of the area within a circular field-of-view is producing the flux received by IRIS. We will do this by counting squares (picture elements, or pixels). For circular regions containing both bright and dark pixels, count up the number of dark pixels. For regions of uniform brightness (*e.g.,* Area E), assume the entire circular area produces the flux measured and count the total number of pixels contained within the circle.

Thus, for Area B, we will count the number of pixels that the dark circular feature covers. For Area C, count the pixels that cover the large dark feature, for Area D count the pixels covering the dark portions, and for Area E assume that the surface is equally bright everywhere. Write the number of pixels you count for each area in Column 3 of Table 16.1. (**6 points**)

Now we know i) the relative amount of energy coming from each circular area, and ii) how many pixels of area generated the flux that was measured.

We can now calculate temperatures (finally). We know that the amount of energy emitted is proportional to T^4. We will use the following equation:

$$\left(\frac{T_x}{T_A}\right)^4 = \left(\frac{E_x}{E_A}\right) \times \left(\frac{Pixels_A}{Pixels_x}\right) \tag{3}$$

Here E_A is the energy measured at site A, $Pixels_A$ is the number of pixels that cover site A, and T_A is the temperature measured at site A. The 'x' subscript corresponds to areas B, C, D, or E.

- Use Equation (3) and the values in Columns 2 and 3 from Table 16.1 to calculate the ratio (raised to the 4th power) of the surface temperature in the area of interest to the surface temperature in Area A. Place these values in Column 4 of Table 16.1. (**8 points**)

- Take the square root TWICE of the values you just place in Column 4 to obtain the ratio of the surface temperature of the area of interest to the surface temperature within Area A. Place these values in Column 5 of Table 16.1. (**8 points**)

- Multiply the values you just placed in Column 5 by the temperature of Area A, and you will have determined the surface temperature within the areas of interest. Place these values in Column 6 of Table 16.1. (**8 points**)

- To put these temperatures into units that you are more familiar with, convert the temperatures you just calculated from Kelvins to degrees Fahrenheit using the following formula, where F the temperature in Fahrenheit and K is the temperature in Kelvins:

  $$F = ((K - 273.15) \times 1.8) + 32 \tag{4}$$

  Place these new temperature values in Column 7 of Table 16.1. (**5 points**)

Additional workspace – SHOW ALL OF YOUR WORK HERE:

Area	Energy	Area (# pixels)	$(T_x/T_A)^4$	T_x/T_A	T_x (K)	T_x (°F)
A	1.000	132	1.000	1.000	125	
B	4.833	33				
C	4.523					
D	3.560					
E	0.983					

Table 16.1: Energy Emitted and Temperature of Io's Surface.

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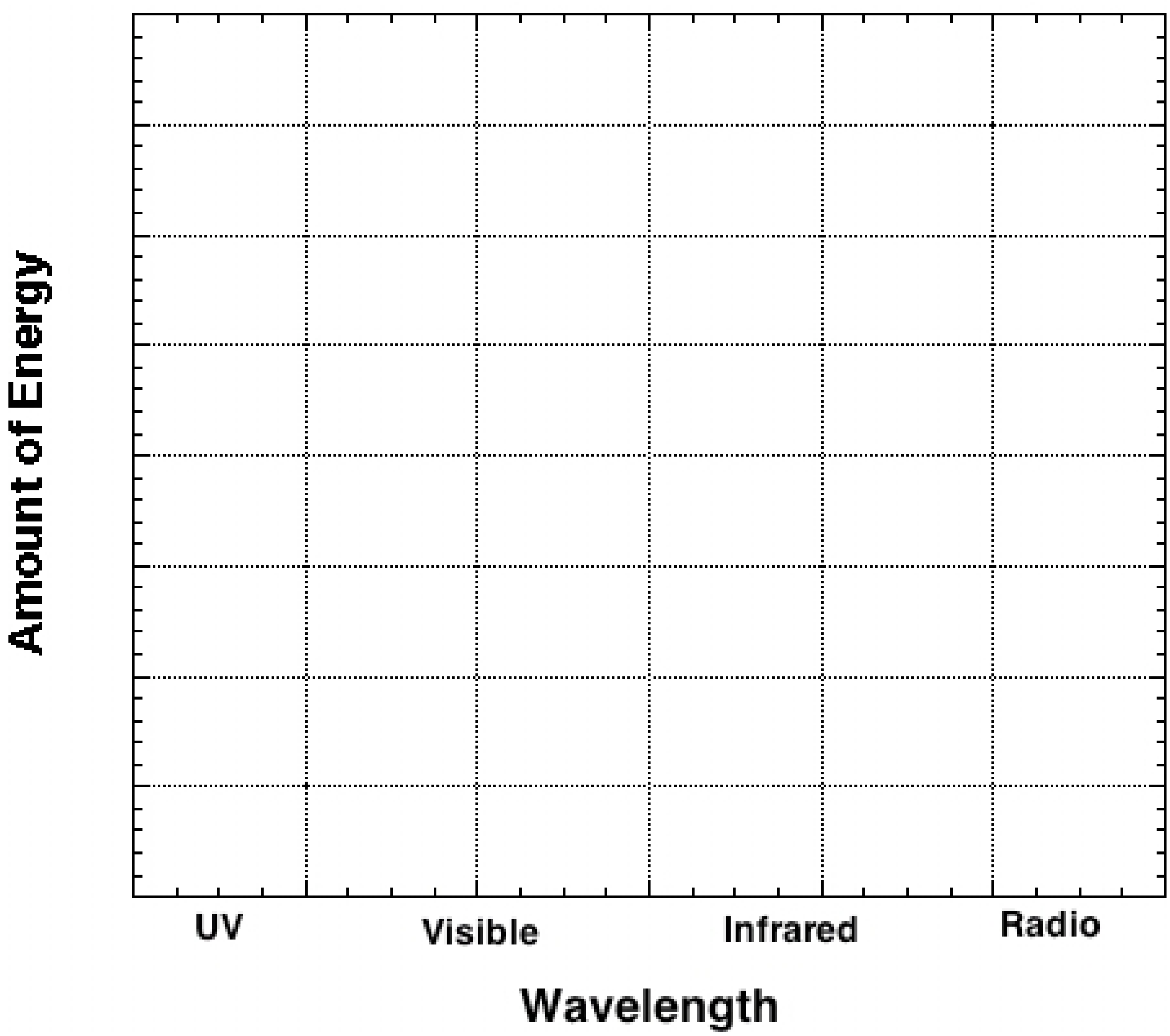
16.4 Take-Home Questions

6. On the graph axes below, draw two curves indicating the blackbody curves (energy as a function of wavelength) emitted by i) a hot area, and ii) a cool area. You will be graded on the *relative positions* of these two curves with respect to one another (in other words, which one – "i" or "ii" – is hotter vs. cooler, and which one has more vs. less energy at the peak). **Be sure to label both curves! (10 points)**



7. If Jupiter's average distance from the Sun was 10 AU instead of its actual value of 5.2 AU, and if Europa, Ganymede, and Callisto were farther from Jupiter, would you still expect Io to experience volcanism? Explain. (**5 points**)

8. The 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. However, some spots on Io's surface have been determined to possess temperatures as hot as 1800 Kelvin. It is believed that such regions consist of molten rock (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 Area A in this lab? [Remember area "A" has a temperature of 125 K.](**5 points**)

   b) Which type of region would you expect you would have a better chance of seeing at visible wavelengths on the night side of Io (not illuminated by the Sun) if you were orbiting overhead? Explain. (**5 points**)

9. How would you change the orbit of the Moon to have it experience tidal heating similar to the kind Io experiences? Explain your reasoning. (**5 points**)

10. Jupiter has several moons that are much smaller than Io and that are closer to Jupiter than Io is. Give a brief explanation of why you think these moons do NOT show

evidence of volcanism. (**5 points**)