

## THE GALILEO MISSION: HOW DO ICY GALILEAN SATELLITES LOOK LIKE

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### 1. THE START OF THE STORY

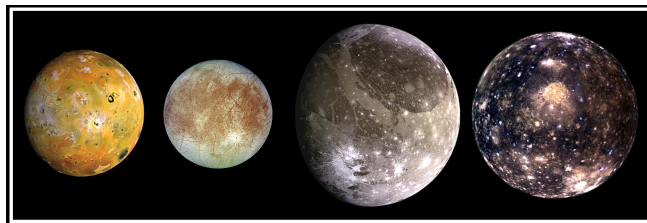
Well before the dawn of space exploration, we had already been asking the question: could there be life beyond Earth? If so, where? The answer cannot be reached so immediately, but in the following article, we will try to contribute the effort to answer this question by analyzing the thermal properties of the Icy Galilean satellites, some of the most astrobiologically interesting targets in the Solar System.

Let us first introduce the Galilean satellites briefly. The four Jovian satellites (**Figure 1**), Io, Europa, Ganymede, and Callisto are often referred to as the Galilean satellites for their discoveries in 1610 by the Italian astronomer Galileo Galilei. Among the four, Io is the most volcanic of them all; Europa has long been hypothesized to host a subsurface salt ocean due to previous studies; Ganymede is the only satellite in the Solar System to have a magnetic field; and Callisto has the oldest surface in the Solar System. The outer three (Europa, Ganymede, and Callisto) are also known as the "Icy Galilean satellites" for their spectroscopically detectable quantities of water ice.

To initiate life, at least three conditions must be satisfied: organic compound, sufficient heat to support biomass, and water, possibly required to be in the liquid form. With these constraints, the Icy Galilean satellites are the few objects left in the Solar System for us to dig in. This was part of the motivation. Then back in the 90's, scientists decided to launch the Galileo orbiter to investigate this neighborhood of Jupiter. Mounted on this orbiter was the Photopolarimeter-Radiometer (PPR), the instrument of our concern, as our research was based on the thermal data collected from the PPR. The orbiter arrived around 1995 and data were sent back to us since 1996. However, due to various logistical reasons, only a small fraction of the PPR data was analyzed and published ever since.

Therefore, one goal for this research is to look through all the PPR thermal data, with a focus on the Icy Galilean satellites. Specifically, we study two of their thermal properties, albedo, the fraction of sunlight being reflected, and thermal inertia, the measurement of how hard it is to change the temperature of an object. Albedo is the property that dominates the daytime temperature variation due to presence of sunlight, while thermal inertia becomes significant during night time – just imagine a pavement that remains warm after sunset, and another one that cools down more rapidly. The latter would have a lower thermal inertia for its easily changed temperature. For this reason, we are expecting to obtain different global temperature variation pattern with and without sunlight from our PPR data.

But you may wonder why we care about the thermal properties of these satellites. The reason lies in the relation between the surface composition of the satellite and their thermal properties. For example, from our mother Earth we know that ice tends to reflect more sunlight than darker rocks and sand. And the thermal anomalies are potential hotspots on these satellites, which is an exciting idea since they indicate the existence of cryovolcanoes, those that erupt volatiles such as water instead of molten rock. The locations of these hotspots can provide potential sites for future missions, such as the Europa Clipper Lander to be launched in the 20's.



**Figure 1.** The Galilean satellites from left to right: Io, Europa, Ganymede, and Callisto ([jpl.nasa.gov](http://jpl.nasa.gov))

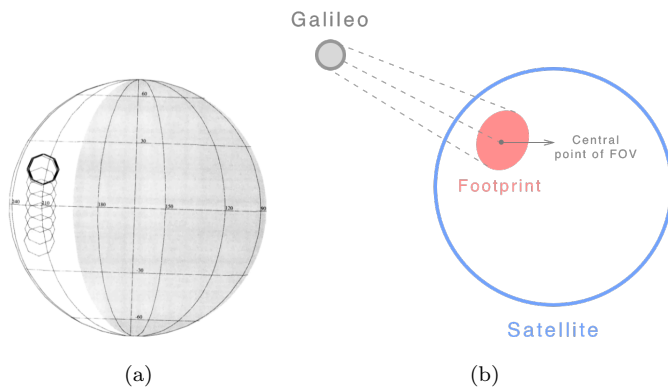
In a plain language, if there is a cryovolcano, we could simply go over, examine the surrounding, possibly dig in for a bit, and learn about the composition along with some other geological features of Europa.

## 2. VISUALIZING THE DATA

We would like to reconstruct the temperature map that the PPR "saw" during its mission. It is then necessary to understand how PPR took data. The logistic of measurement design is illustrated in **Figure 2**. The PPR has an aperture opening of 2.5 radians, which serves as the eye for PPR, and it looks at the surface of the satellite. The area that this eye sees is what we call the footprint as illustrated in **Figure 2b**, and then, PPR measures the temperature for this one footprint. Therefore, the footprint size is dependent on the distance between the spacecraft and the satellite, and consequently, the resolution of our temperature map depends also on the distance between spacecraft and satellite. Another thing to notice is that the spacecraft moves at a relatively slow speed, so consecutive footprints have overlaps as seen in **Figure 2a**. For these overlapping area, an average of the flux is calculated, and then converted to brightness temperature for temperature visualization.

## 3. GETTING READY WITH OUR MODEL

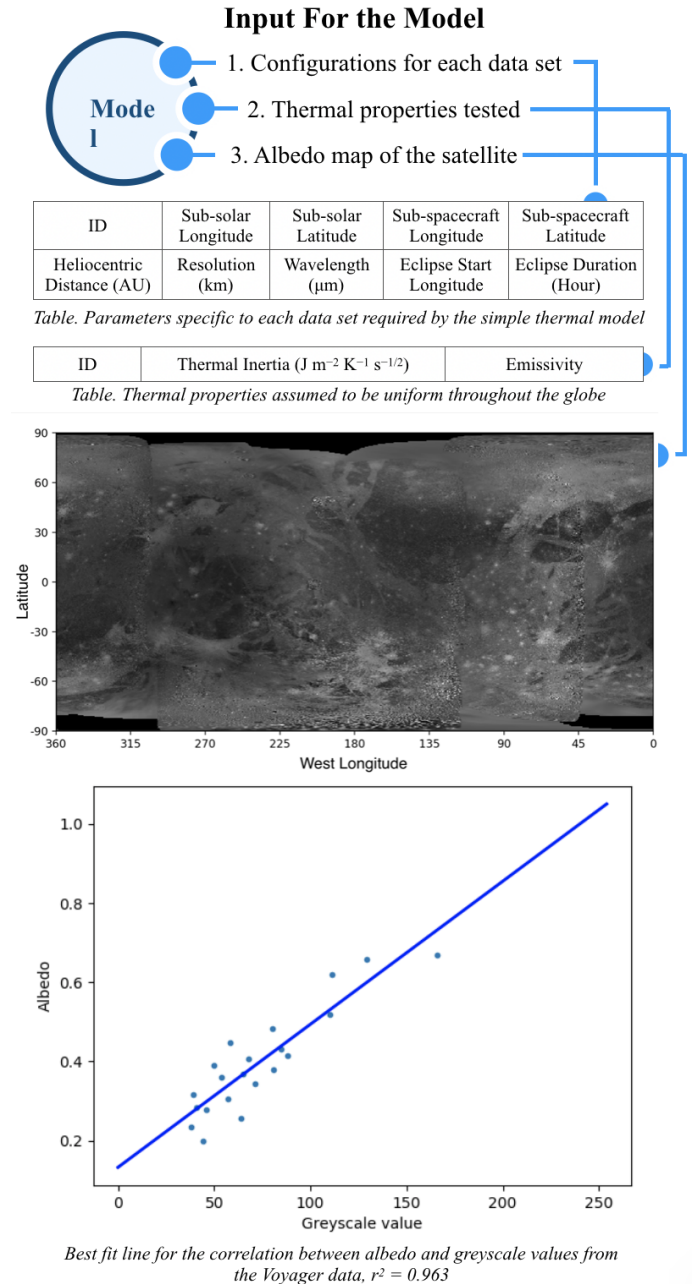
From previous studies, there were one-layer, two-layer (vertically homogeneous), and two-component (laterally homogeneous) models fitted to the Voyager and ground based observations. However, these models gave predictions on Ganymede that are 10K lower than the PPR observations. Therefore, in order to better grasp the overall pattern of the satellite, we run our simulation using the global thermal diffusion model, which has provided consistent results when used to study Europa as well as several other Solar System objects such as moon



**Figure 2.** (a) The overlapping of the footprint when Galileo orbiter is taking measurements; (b) illustration of footprint of measurement of Galileo orbiter.

and Mars.

There are three sets of input the model requires for each simulation (detailed in **Figure 3**): spacecraft configurations of the data set we want to run the simulation with, global thermal inertia, and albedo map of the satellite. These parameters will determine the amount of sunlight received by the satellite and how much of it is being absorbed. The satellite model starts out cold and evolves for several model days until the temperature equilibrates, giving us the final result of the simulation.



**Figure 3.** Three sets of input required for running the model. Albedo measurements are from the Voyager mission.

During our initial runs, we assume that thermal inertia is uniform globally and only albedo varies locally. For this, we need to albedo map. We take the measured albedo from the Voyager data, weighted them according to solar flux at their wavelengths, and correlate them with the grayscale values at each measured point. Then, with the correlation obtained, we propagate to the entire grayscale map to obtain an albedo map. Using the albedo map and uniform thermal inertia, there are two immediate conclusions.

First, even during daytime, the albedo only accounts for partial local temperature variations. As seen in **Figure 9**, the pattern matches roughly between data and pattern, and crater Tros, the darker spot in the upper left of the map, can be identified. However, the residual for this crater in **Figure 9c** reveals that data is much colder than the model, indicating that we need to include local variation of thermal inertia.

Second, in **Figure 10** the observation took place during noon, but the data does not correspond to the albedo map at all. In fact, this measurement was done during a full eclipse on Ganymede, where Jupiter blocked off sunlight entirely. Areas of low thermal inertia experiences sudden drop in temperature, and makes it easy for us to characterize the thermal inertia.

#### 4. FIT FOR THE PPR OBSERVATIONS

To characterize local thermal inertia variation, we run the model over a range of thermal inertia values to fit

with our measurement. The resulting thermal inertia map for Ganymede can be found in **Figure 4**, where region 1 comes from our eclipse data.

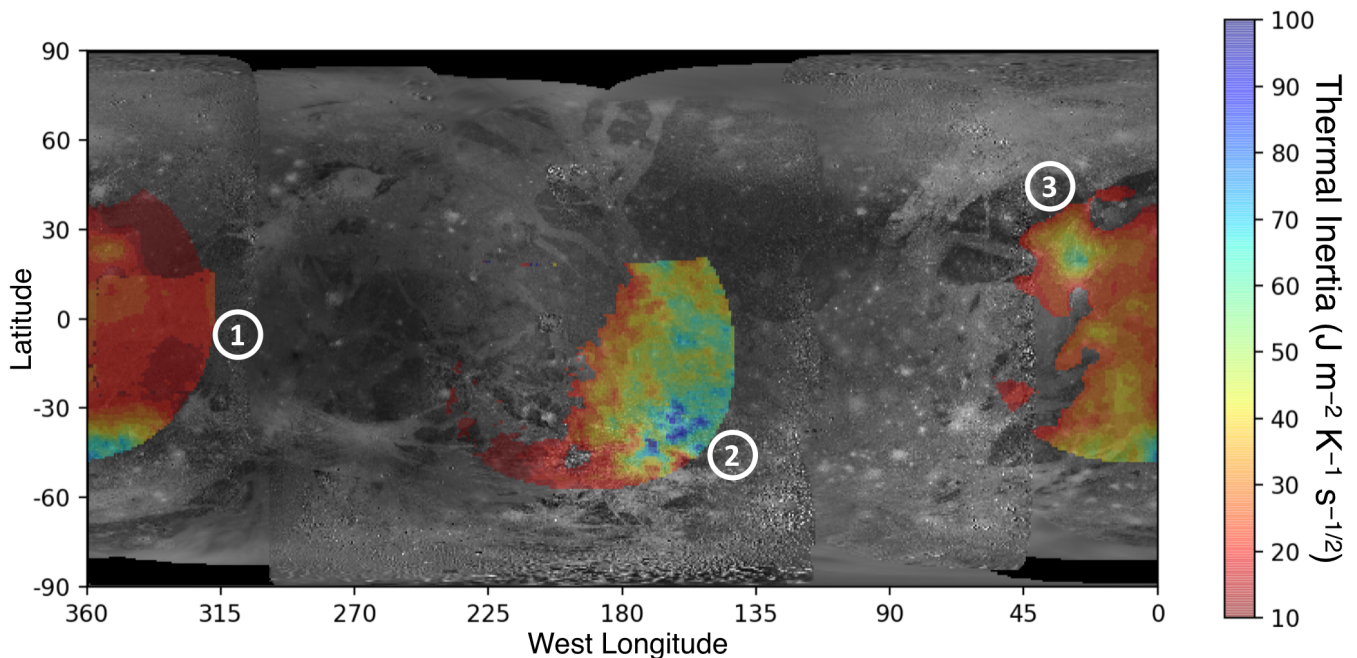
To the right of this map, you could point your finger to region 3, where the crater Tros locates. The map indicates that thermal inertia is locally high around the crater, and such feature can also be found in region 2, where multiple craters form a series of locally high thermal inertia cluster. To cross reference with previous literatures, this is a feature that has been observed previously on other celestial objects such as Mars and our moon.

However, one concern remains for this fitting. The PPR data contains noises and artifact that has few documentation, making it difficult to settle an uncertainty for our thermal inertia map. Therefore, we have to compare data with future projects and missions, and see if the overall pattern are consistent.

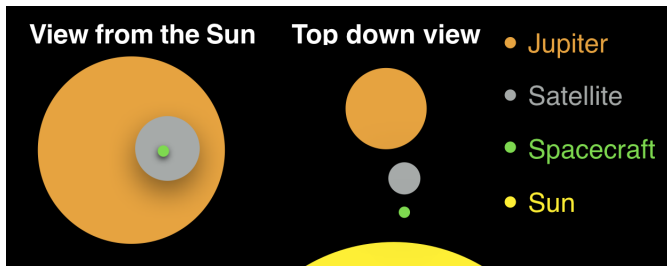
## 5. ANOMALIES

### 5.1. *Stripe Feature*

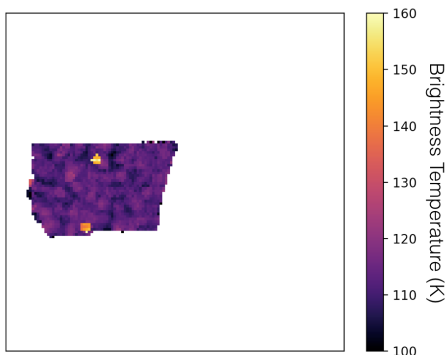
For certain observations such as **Figure 11** and **Figure 12**, a feature, called "stripe", can be found in the residual maps. During these observations, there is a similar relative positions between Jupiter, the spacecraft, and the Galilean satellite, which is illustrated in **Figure 5**, where Jupiter is in the left side of the background when spacecraft is taking measurement.



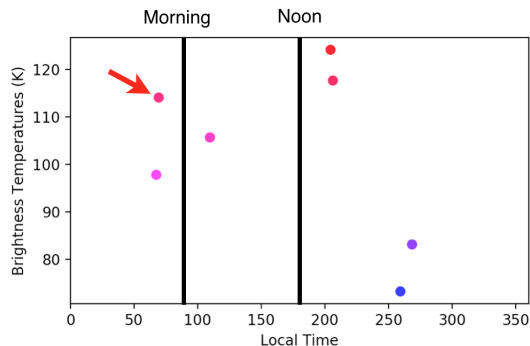
**Figure 4.** Thermal inertia map of Ganymede masked on the albedo map



**Figure 5.** The relative positions of Galileo orbiter, Galilean satellite, and Jupiter in which the stripe-style noise occur in the data.



**Figure 6.** Potential hotspots from the Europa observation: E12EHOTSPT01.

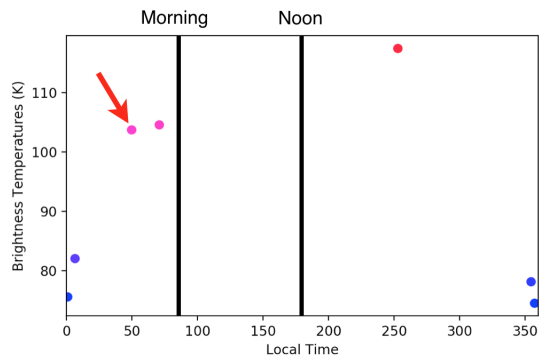


**Figure 7.** Measurement for region around the upper hotspot in **Figure 6** at various local Europa times; the red arrow points at the one where we see the hotspot.

We conjecture that the PPR has picked up radiations emitted by Jupiter since the brighter stripes in **Fig 11** and **Fig 12** are to the left side where Jupiter is at. It is worth noticing for future missions to avoid a similar relative positions, or to implement systematic corrections while processing the data.

### 5.2. Hotspots

Another type of anomaly can be found in **Fig 6**, of which we refer to as the "hotspot", which could potentially be cryovolcanoes. From preceding studies, there



**Figure 8.** Measurement for region around the lower hotspot in **Figure 6** at various local Europa times

is strong evidence for Europa to have subsurface ocean, and active cryovolcanism was found previously with the Hubble telescope. Probing directly into such regions might provide clues for the composition of Europa as well as the subsurface ocean, which can consequently be a stride to evaluate the habitability of Europa.

If a region is truly a hotspot, it should remain hot all the time comparing to the surrounding, and exhibit reasonable heating and cooling according to the amount of sunlight received. Temperature of the "hotspots" throughout the day are plotted in **Fig 7** and **Fig 8**.

For the upper hotspot (**Figure 7**), there is another temperature point at the same local Ganymede time where the temperature difference between the two measurements is around 15K. Additionally, there is a point between morning and noon line that has a lower temperature than our upper hotspot. It should not be hotter before sunlight appears.

For the lower hotspot (**Figure 8**), there is another measurement right next to it with a similar temperature, but both of the measurements are in the stripe region described in previous section, making the data 20K hotter than expectation, and modifying thermal inertia in a reasonable range does not correct for the residual. Additionally, in **Figure 8**, the same conclusion follows as the upper hotspot point when comparing the hotspot to measurements at local time 0 (midnight). These two measurements are much colder.

Although the detection of a hot spot would be exciting, there is not enough evidence to claim the 2 points in **Figure 6** as hotspots.

## 6. THE BIGGER PICTURE AND WHAT'S NEXT

In this research, we studied the thermal properties with the PPR data, identified partial thermal inertia of the Ganymede, and examined the potential hotspot of Europa. As the Europa Clipper Lander will be launched in a few years, the study of Europa's thermal properties

can become especially helpful. They relate to the geological activities and the composition of the satellite. When Clipper Lander arrives, we will have a better sense of the environment of Europa, and can better evaluate for its habitability. We would really get to know if Europa satisfy the three essentials for origins of life as claimed in previous literatures. However, moving around on other celestial objects is very hard. NASA's Mars Curiosity Rover travels only 200 meters per day. So it is necessary to have in mind where to look at before we launch and command the lander where to go, and knowing more about the potential hotspot sites would help us identify

areas to examine, saving us resource and time when we send a probe over for on-site investigation.

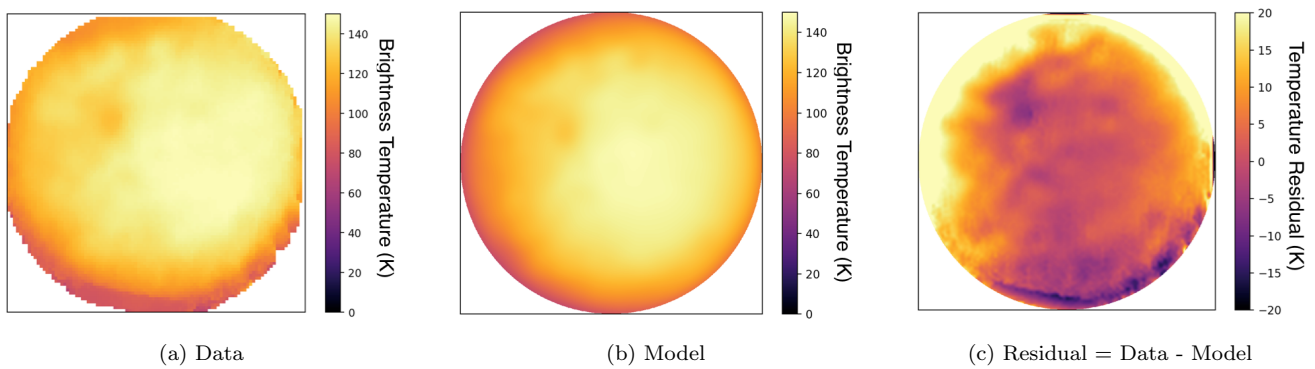
In the end, is there life beyond Earth or is there a place other than Earth we can live on? Hold the breath until Clipper arrives.

## 7. ACKNOWLEDGEMENT

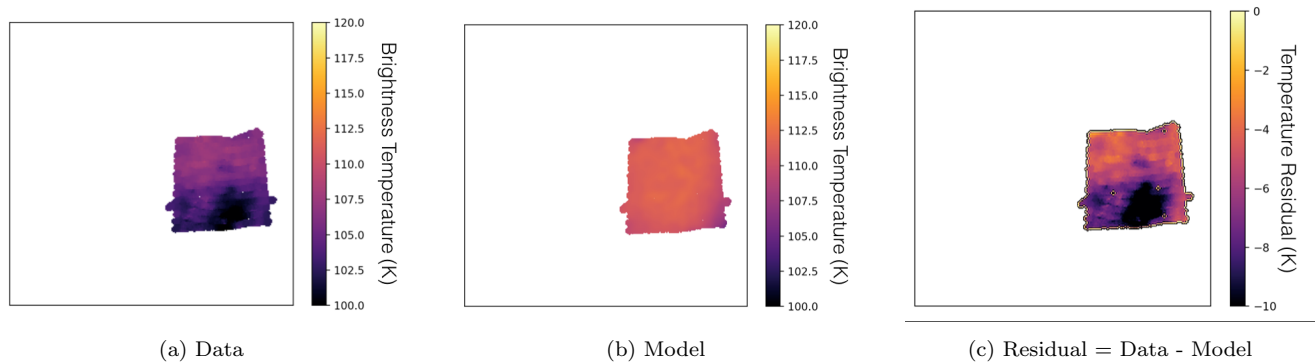
I would like to thank Dr. Michael Brown and Samantha Trumbo for their mentorship, the Student-Faculty Programs and the National Science Foundation for funding this project, and the PPR team for acquiring the data.

## APPENDIX

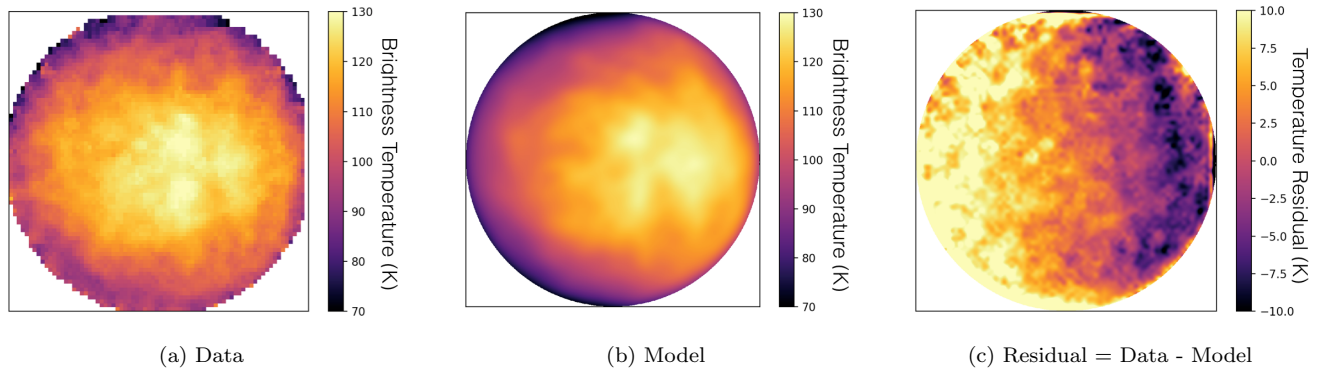
### A. DATA, MODEL, AND RESIDUAL



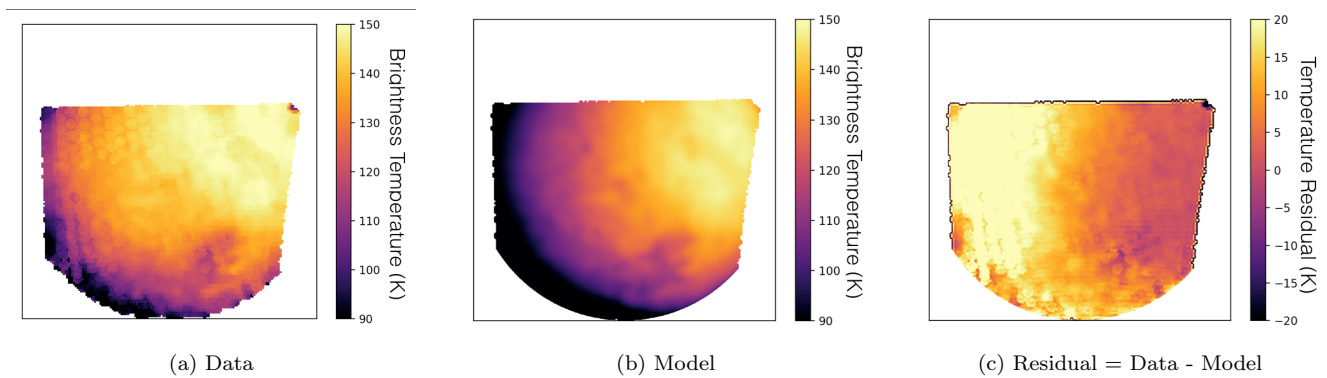
**Figure 9.** Daytime Ganymede data vs. model. A positive residual means that data is hotter than the model at that region.



**Figure 10.** Noon-time Eclipse Ganymede data vs. model



**Figure 11.** Daytime Europa data vs. model



**Figure 12.** Daytime Ganymede data vs. model

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