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Thermal properties of Europa and Ganymede from spatially resolved ALMA observations

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Abstract

The surfaces of icy worlds encode information about the exogenic and endogenic processes that alter these bodies' surface environments and subsurface conditions. We present maps of the thermal emission from the leading and trailing hemispheres of Europa and Ganymede at a spatial resolution of ∼1/10th of a satellite diameter, based on observations at wavelengths of 0.87-3.0 mm from the Atacama Large Millimeter Array (ALMA). Observations at these wavelengths probe the very shallow subsurface (∼cm depths), and provide information on thermal properties such as emissivity and thermal inertia, which in turn depend on the density, heat capacity, and thermal conductivity of the material [7]. We derive emissivities and thermal inertias for the leading and trailing hemispheres of both satellites from thermal modeling, and discuss implications in terms of global surface properties and of localized regions with anomalous thermal properties.

1. Introduction

The leading and trailing hemispheres of the galilean satellites are subject to different external processes, with fast-moving particles in the Jupiter system incident on the trailing sides. Both Ganymede and Europa show strong hemispheric differences in surface albedos, with large regions of warmer, darker terrain as well as cooler, ice-rich regions [5, 1, 6, 2]. Measurements of the subsurface properties of both hemispheres can determine how deep these asymmetries go and whether they extend beneath the solar skin depth.

2. Observations

We observed the leading and trailing hemispheres of Europa, Ganymede, Callisto in 2016-2017 with the Atacama Large Millimeter Array (ALMA). Continuum observations were made at frequencies of 100, 240, and 345 GHz (Bands 3, 6, and 7 respectively); these frequencies were chosen to bracket the solar skin depth, as coarsely constrained by past observations [4]. The calibrated visibility data provided by ALMA were phase calibrated using self-calibration procedures based on a realistic source model and imaged using the Common Astronomy Software Applications (CASA) package, resulting in improved signal-to-noise and reduced image artifacts over the standard calibration. The brightness of the flux calibrator was calculated from measurements on surrounding days, resulting in corrections to the default pipeline flux calibration of up to 15%. The result of these procedures is a calibrated brightness temperature map of the leading and trailing hemisphere of each satellite at all three frequencies, with ∼10 spatial resolution elements across the satellite in each map.

3. Thermal Model & Retrievals

The observations are interpreted using a custom thermal conduction model that numerically solves the heat equation, an approach that has been standard in interpreting planetary surface temperatures for many decades (e.g. [7]). We fix the surface albedos for all satellites using bolometric albedo maps derived from a combination of full optical albedo maps and normal albedos for isolated regions on the surface.

The thermal inertia and emissivity of the surface are fit for simultaneously using a Monte Carlo retrieval method, which yields uncertainties on the input parameters as well as their joint probability distribution, the latter of which provides crucial information for interpreting these degenerate parameters. Localized regions where thermal properties differ from the surrounding area are identified and their thermal properties fit for.

4. Example: Ganymede Leading Hemisphere

The observation of Ganymede's leading hemisphere at 240 GHz is shown in Figure 1, along with an example high-resolution thermal model. The residuals panel demonstrates that this example model (Γ=55 J/m^2/K/s$^{1/2}$) provides a reasonable match to the morning-afternoon temperature gradient but overpredicts polar temperatures. Indeed, no model that assumes uniform thermal properties across the surface is able to match the data, as was previously noted in analyses of mid-IR data [3]. We will discuss variants on these uniform thermal models and implications in terms of surface materials.

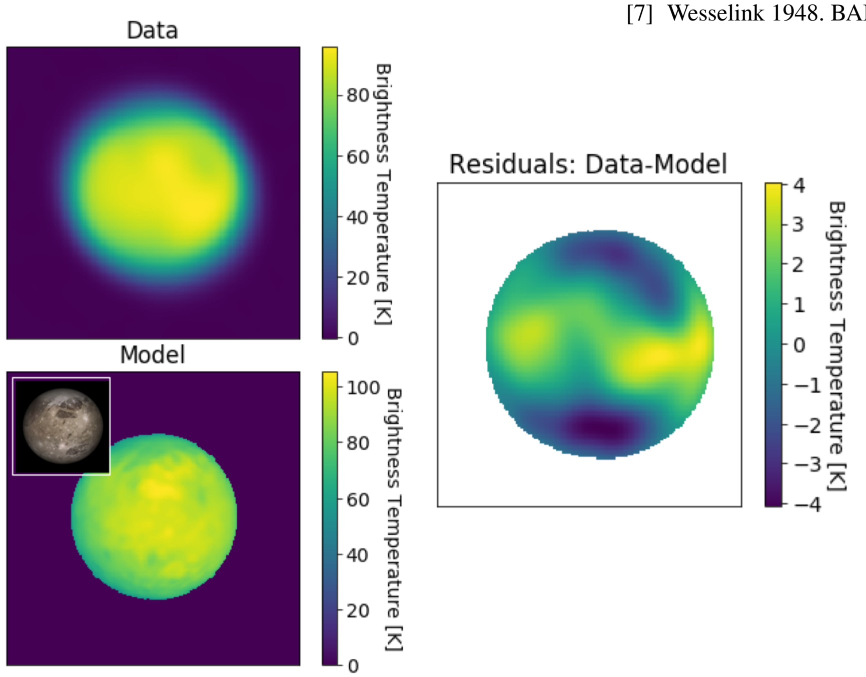

Figure 1: Ganymede Leading Hemisphere: Data and model for 240 GHz observations of Ganymede's leading hemisphere, centered at 63°W. A thumbnail of Ganymede's surface appearance at optical wavelengths, derived from spacecraft maps and projected to the viewing geometry matching the observations, is shown as an inset in the model panel. The residual map shown on the right is the difference between the data and the model after convolution of the model with the point spread function.

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