SPATIALLY RESOLVED THERMAL PROPERTIES OF (15) EUynomIA FROM HIGH-RESOLUTION ALMA DATA Y. Phua¹, K. de Kleer¹, S. Cambioni², M. Shepard³, ¹Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA ²Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, ³Commonwealth University (yphua@caltech.edu)

Introduction: The process of differentiation in planetesimals is central to understanding their thermal and geochemical evolution following their accretion. Asteroid (15) Euynomia, the largest S-type asteroid in the main belt (mean diameter: 270 km; semimajor axis of 2.644 AU) has been suggested to be at least partially differentiated, based on the compositional heterogeneity of its surface and its dynamical family members. On one hemisphere the surface is made up of Fe-rich olivine, similar to stony-iron meteorites, while the other hemisphere is more basaltic and dominated by pyroxene [1, 2]. However, confirmation of this claim and evaluation of the degree of differentiation remains yet to be established.

Ground-based observations that can characterize the spatial heterogeneity of the lithology and mineralogical composition of Euynomia can shed light on the extent to which Euynomia is differentiated. While it is currently impossible to obtain spatially resolved observations of asteroids at infrared wavelengths from ground-based telescopes existing today, previous works have shown that the Atacama Large Millimeter/submillimeter Array (ALMA) can spatially resolve main-belt asteroids at millimeter wavelengths [3, 4]. In this work, we follow the approach in [3, 4] and model the 1.3 mm thermal emission data acquired with ALMA to understand the thermal and dielectric properties of Euynomia's surface. We derive the area-by-area fits of thermal inertia and dielectric constant of Euynomia at ~30 km resolution. With this analysis, we aim to complement the existing knowledge on the compositional and regolith properties of Euynomia based on visible, near-infrared, mid-infrared, and microwave measurements [1, 2, 5], and further our understanding on the formation and evolution of not only Euynomia but of whether the largest S-type asteroids could be partially differentiated objects.

Methods: Observations: Euynomia was observed with ALMA on 2019 June 13 between 08:59 and 12:06 UTC. The dataset covers half of Euynomia’s rotational period, and a total of 24 images were produced from the interferometric data with a time resolution of ~5 minutes. The angular resolution was 0.03°, corresponding to a resolution of 33 km at Euynomia, which was at a distance of 2.51 AU from the Sun and 1.83 AU from Earth at the time of observation.

Model parameters: We model the observations to determine (1) the thermal inertia, which measures the material’s resistance to temperature change in response to changing insolation, and (2) the dielectric constant, which governs the interactions of electromagnetic wave emissions — in this case, at millimeter wavelength — with solid materials. The surface bulk density was calculated from the radar albedo [6, 7] to be 1.64 g cm⁻³ and specific heat capacity assumed to be 500 kg J K⁻¹ K⁻¹, an average value of meteorites [8]. The thermal skin depth, given by \((P/\pi)^{0.5} \Gamma/\rho C\) \((P:\) rotation period, \(\Gamma:\) thermal inertia, \(\rho:\) bulk surface density, \(C:\) specific heat capacity), was calculated for each thermal inertia value. The electrical skin depth, which sets the depth to which thermal emission is observed from, was fixed at 13 mm (10 times the wavelength, typical for rock).

Thermophysical model for area-by-area fits of thermal inertia and dielectric constant: We used the model described in [4] to fit variable thermal inertia and dielectric constants across the surface of Euynomia. This model fits thermal emission curves at each facet of the asteroid shape model by relating the viewing geometry of each facet to the observed ALMA pixel.

Results: The goodness of fit of the model for each combination of input parameters (Fig. 1b) was determined by the reduced \(\chi^2\) value. The high value of minimum \(\chi^2\) (>10) in several regions indicates a relatively poor fit of the model to the data. This is likely due to observations 13-24 suffering from deteriorating weather conditions, resulting in a larger ALMA beam (~60 km), potentially causing a larger mismatch between the shape model and the ALMA images. The results presented below are therefore preliminary, even though we observed a consistent trend when only considering observations 1-12 that cover only east of 0°.

Thermal inertia: The area-by-area best-fit thermal inertia ranged the entire parameter space from ~10 (dust) to 1000 (bedrock). While the map of thermal inertia (Figure 1c) shows regional trends, with the eastern hemisphere (east of 270°) broadly of higher thermal inertia (~100) than the western hemisphere of thermal inertia ~10, the thermal inertia of the western hemisphere is less than 1σ smaller than the eastern hemisphere.

Dielectric constant: The area-by-area best-fit are better constrained than the thermal inertia (that is, it has lower uncertainties) and varies from ~5 to ~20. Similar to the thermal inertia map, the best-fits of dielectric constant also shows regional trends: the eastern hemisphere (east of 270°) appears to broadly be of lower dielectric constant (~7) than the western hemisphere with dielectric constant >10 (Fig. 1c). However, the
dielectric constant of the western hemisphere is also less than 1σ higher than the eastern hemisphere.

**Discussion: Thermal Inertia.** No thermal inertia value has previously been reported for Eunomia. However, our best-fit thermal inertia of Eunomia in the western hemisphere (west of 270°) is consistent with other large main-belt S-type asteroids (mean diameter > 100 km) that are reported to have thermal inertia ~50 (e.g., [10]). While higher thermal inertia would be expected for more metal-rich surfaces, our preliminary results suggest that the thermal inertia differences between the eastern hemisphere and western hemisphere of Eunomia may not be significant. Comparisons of the thermal inertia and dielectric constant maps in this study with the infrared spectra in [1, 2] showing hemispherical compositional dichotomy are still ongoing. However, the lack of significant differences we find between the thermal inertia across the surface of Eunomia suggests that there may not be a straightforward relationship between the thermal inertia and the abundance of olivine or other mineral phases of high metal content on Eunomia.

**Dielectric constant.** As the surfaces of asteroids are less likely to be made of solid rocks and more likely made of porous regoliths, we used the Looyenga-Landau-Lifshitz (LLL) mixing equation to derive the effective dielectric constant as a function of porosity and solid dielectric constant for a mixture of one mineral and vacuum-filled void. The best-fit dielectric constant of ~5 for Eunomia east of 270° can be matched by forsterite, fayalite or pyroxene of 0–30% porosity. This composition is consistent with the expected Fe/Mg-silicate composition based on the S-type taxonomy of Eunomia. The high dielectric constant of ~15 of the western hemisphere cannot be matched by most igneous and sedimentary silicate rocks which have dielectric constants of 6–10 (e.g. [12]), indicating the possibility of higher metal content in this region. For comparison, a dielectric constant of 17-21 was derived for the M-type asteroid (16) Psyche based on the same type of observations [3, 4], so even the most potentially metal-rich portions of Eunomia’s surface are not as metallic as an M-type.


**Figure 1.** Results from the model fitted to 24 observations, shown as maps projected in Mollweide projection. a, time-average of the data minus the model residuals. b, Goodness of fit of the thermophysical model of Eunomia for the ALMA data. c, Area-by-area best-fit thermal inertia. d, The thermal inertia from c. divided by the uncertainty. e, Area-by-area best-fit dielectric constant. f, The dielectric constant from e. divided by the uncertainty.