ARROKOTH'S NEW HORIZONS MEASURED BRIGHTNESS TEMPERATURE PROVIDES CONSISTENT EVIDENCE FOR 0.1-10 MM NEAR SUBSURFACE GRAIN SIZES: POSSIBLE IMPLICATIONS FOR PLANETESIMAL FORMATION MODELS.

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Introduction: During the New Horizons flyby of the bilobate cold-classical Kuiper belt object (KBO) (486958) Arrokoth [1], the spacecraft's REX instrument made several X-band (λ=4.2cm) observations of the planetesimal's backlit side from which a brightness temperature of $T_{b,obs}$ = 29±5 K was derived [2]. Analysis of Arrokoth's surface topography, taken in conjunction with recently uncovered semi-empirical trends between surface slope distribution and body mass, suggest that the body's averaged porosity (p) lies between 0.6 and 0.8 (with $\rho \approx 300$ kg/m^3) [3,4].

The Question: Given Arrokoth's known orbital history, owing to its overall stability given its location in the Kuiper belt, what combination of near surface thermophysical materials and their properties would lead to a brightness temperature T_b equaling $T_{b,obs}$? The problem is complicated by the fact that New Horizons' LEISA IR spectrometer only detected surface methanol [2], possibly only extending down a few mm at most [5]. Furthermore, there were no measurements of the material's thermal inertia (I). Further, the propagation of radio from the interior depends upon the X-band frequency range material properties like the complex dielectric constant ($\varepsilon = \varepsilon' + i\varepsilon''$) and the X-band emissivity $\langle E_{eff} \rangle$, all of which are unknown for Arrokoth.

Methods: A near surface thermal model for Arrokoth is developed based on the recently released 10^5 facet model of the body (`https://pds-smallbodies.astro.umd.edu/datasb/missions/newhorizons/index.shtml`). This thermal solution takes into account Arrokoth's surface re-radiation back onto itself. The solution method exploits Arrokoth's periodic orbital character to develop a thermal response using a time-asymptotic solution method, which involves a Fourier transform solution of the heat equation [2]. The predicted subsurface thermal emission emergent on the day of New Horizons' encounter is then modeled with a radiative transfer framework recently used for Ganymede [6]. This exercise results in a predicted brightness temperature as a function of the several aforementioned unknown thermophysical properties, i.e., $T_b = T_b(\varepsilon, I, \langle E_{eff} \rangle)$. The aim then is find a reasonable bound on various combinations of the four unknowns that yield $T_b = T_{b,obs}$. The details of these combined procedures, as implemented here, are currently in review [7].

Results: Figure 1 depicts the various combinations of ε,I and $\langle E_{eff} \rangle$ that produces $T_b = T_{b,obs,}$ and gives a flavor of the kinds of results we find. While there is weak dependence on ε', there is a wide range of ε'' permitted resulting in a similarly wide range of permitted I values too. Furthermore, outside of water ice and possibly tholins, ε'' values (appropriate for the X-band range) are unknown for materials like methanol and other exotic candidate outer solar system ices. At this point we are left with conjecture: even though H_2O ice was not directly observed on the surface, global evolution models of the solar nebula show that the outer solar system readily contains a plentitude of H_2O ice grains [8]. It is not unreasonable to suppose that the top layers observed by LEISA probed the upper crust that, as recent work to be discussed in this meeting suggests [5], quite possibly consists of radiolytically formed methanol ice. We suppose that the deeper interior (greater than a few cms) consists of H_2O ice grains, which would be readily probed in the X-band. As the predictions displayed in Fig. 1 shows, the $T_b = T_{b,obs}$ is consistent with very small values of $0.001 < \varepsilon'' < 0.02$, which is consistent with similarly measured values for water ice appropriate to other bodies like CG [e.g. 10]. And, indeed, such values of ε'' would, in the X-band, correspond to electric skin depths in the range of 0.5 to several meters.

Given Arrokoth's orbital stability, it is unlikely that the body experienced temperatures in excess of 70K and, as such, these H_2O grains probably have remained amorphous since inception. Implementing models of the effective conductivity of porous amorphous H_2O, following [9], predicts specifically for Arrokoth (with $0.6 < p < 0.8$) values of I=1-20 tiu (tiu ≡ W/m^2/K/s$^{1/2}$), in the temperature range of interest, particularly in the grain-size range of 0.1 to 1 cm (see Fig. 2). The corresponding calculation on the assumption of cubic crystalline ice (to be expected to form if Arrokoth's surface environment exceeded 70K for any appreciable time) would predict values of I > 80 tiu. When cross-referenced against Fig. 1, such high I would correspond to extremely high values of ε'' that are not expected for H_2O. We finally note that the relatively small values of ε'' seemingly consistent with these considerations can be explained also by measurments of tholins under conditions approximating those appropriate for Arrokoth [11]. For these reasons we favor the interpretation that Arrokoth's sub-surface consists of possibly tholin-covered amorphous sub-to-few mm sized H_2O grains with a thermal inertia in the range 1tiu < I <20 tiu. *We emphasize, however, that this is likely not a unique solution to the problem.* When more laboratory work on other outer solar system ices are done (measurements of conductivity, dielectric properties, etc.) a better picture of the range of possibilities explaining Arrokoth should emerge.

Origins Implications: Global evolution modeling of the solar nebula predict grain sizes in the outer nebula to be in the 0.1 to 1 cm range [e.g., 8], like implied by our considerations here. A fuller survey of the planetesimal formation models as well as its relationship to the meteoritic record will be presented in person at the meeting.

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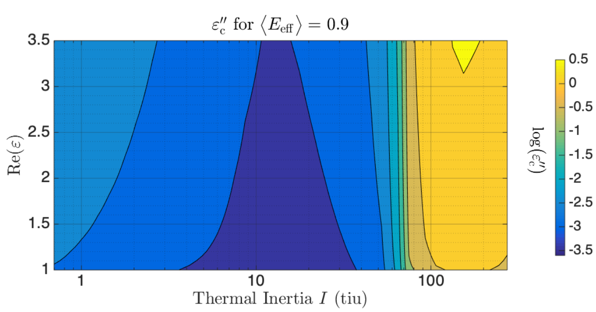

Figure 1: Values of ε'≡Re(ε), ε''≡Im(ε), and I that yield a predicted $T_b = T_{b,obs}$ at <E_{eff}> = 0.9.

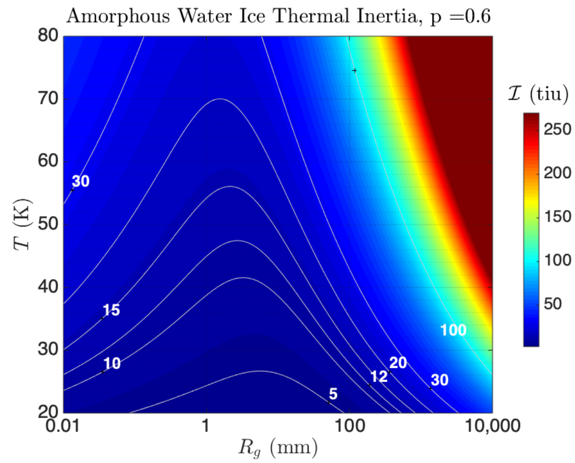

Figure 2: Predicted I for amorphous water ice grains at the temperatures of interest here (10K < T < 50K) following the theory in [9].