TOWARDS A MICROPHYSICAL INTERPRETATION OF THE NEAR-IR SPECTRA OF THE KUIPER BELT OBJECT 2005 FY9.

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Introduction: Recent observations of the Trans-Neptunian Object 2005 FY9 have identified coarse-grained methane ice as the dominant component of the surface [1-3], with the grain size (interpreted as the mean distance between scattering centers) on the order of centimeters [2,3]. Such large grains are indicative that methane ice is present as a low-porosity slab over large portions of the surface. This puts 2005 FY9 into the same class as Triton, Pluto, and the martian seasonal caps, where the main volatile component also forms densified slabs on the surface. What makes the case 2005 FY9 somewhat surprising in this regard is that methane ice is not very volatile at the low temperatures in the outer reaches of the Solar System. However, as discussed below, even at those frigid temperatures low-porosity methane-ice slabs can indeed form by pressureless sintering on timescales comparable to the orbital period, provided the methane grains are sufficiently small. Using a recently developed model of the reflectivity of porous slabs, we will demonstrate that such a model can naturally reproduce the broad absorption features of methane ice (particularly in the 1.7-micron region) that distinguish the near-IR spectra of 2005 FY9 from the spectra of Pluto.

Densification of Porous Methane Ice: Metamorphism of a granular material into a low-porosity layer is expected on thermodynamical grounds, given that zero porosity is the state of minimum surface energy. The kinetics of densification as it applies to Solar System ices has been discussed extensively in a series of publications [4 and references therein]. In the absence of external pressure (e.g., on the optical surface of a planet), densification is driven by surface tension, with the main driving mechanisms being volume and grain boundary diffusion. In pure methane ice at temperatures likely to prevail on 2005 FY9's surface (20-40 K), submicron grains are necessary to produce densification timescales comparable to the orbital period (~ 300 years). Even when longer timescales are considered, only marginally larger grains are allowed (due to the strong grain-size dependence of the densification rate). Note also that the resulting voids would be smaller than the grains, by up to an order of magnitude. Thus, we rather conservatively estimate that the majority of voids in the putative slab will be in the submicron range, although larger outliers are certainly possible (and in fact desirable, see below). This size constraint is important for our spectral modeling.

Spectral Modeling: The simulated spectra have been computed as wavelength-dependent geometric albedo defined as

$$A_p = 4 \int_{\Lambda=-\pi/2}^{0} \int_{L=0}^{\pi/2} \Re(\Lambda, L, 0) \cos\Lambda \cos^2 L dL d\Lambda$$

where Λ and L are the luminance longitude and latitude, respectively. In order to gain insights into the nature of radiative transfer in a strongly forward-scattering medium, the bi-directional reflectance $\Re$ is computed using two approaches: Hapke's model [5] and explicit multiple scattering calculations carried out with the DISORT model [4]. Two basic types of surfaces have been considered: 1. Surface consisting of spherical methane ice grains *in vacuo*, and 2. Surface consisting of a methane ice slab containing spherical voids. In both cases, the optical properties of the particles (i.e., grains or voids) have been computed using a generalized Mie code [6] (which handles the case where the refractive indices for the particle and the surrounding medium have arbitrary complex values), employing the refractive indices for pure methane ice at 30 K [7].

Results: Figure 1 shows the spectra computed using Hapke's and DISORT models for a methane ice layer composed of spherical grains of varying radius. For comparison, we also plot the measured near-IR spectrum [2], normalized to a V-band albedo of 0.6. This value is at the lower end of the range $0.8^{+0.1}_{-0.2}$ estimated from *Spitzer* measurements [8]. We have adopted this rather low value as it allows for a relatively simple fit shown later (Figure 2). Adopting higher values of the visible albedo necessitates going beyond such a simple model, in particular making the medium strongly backscattering [2]. This is certainly plausible, especially if 2005 FY9 exhibits an opposition surge. However, the existing phase curve for 2005 FY9 is rather flat in the limited range of phase angles covered so far [9] and, consequently, we have opted to ignore any opposition-surge effects at this stage.

The Hapke and DISORT models are in qualitative agreement, but quantitative differences are evident in Figure 1. The DISORT model produces more pronounced lows in the regions of strong absorption, presumably through accounting for increased path-lengths in the strongly forward-scattering regime. For 1-cm particles, both models give a flat spectrum in the 1.7-μm region that is a distinct feature in the spectrum of 2005 FY9. This flat spectrum is the basis of the conclusion concerning the likely metamorphosed state of 2005 FY9's surface and has been used as an end-member case in a 2-component granular model that provides a very good fit to the measured spectrum (the other component being a sloping continuum) [2].

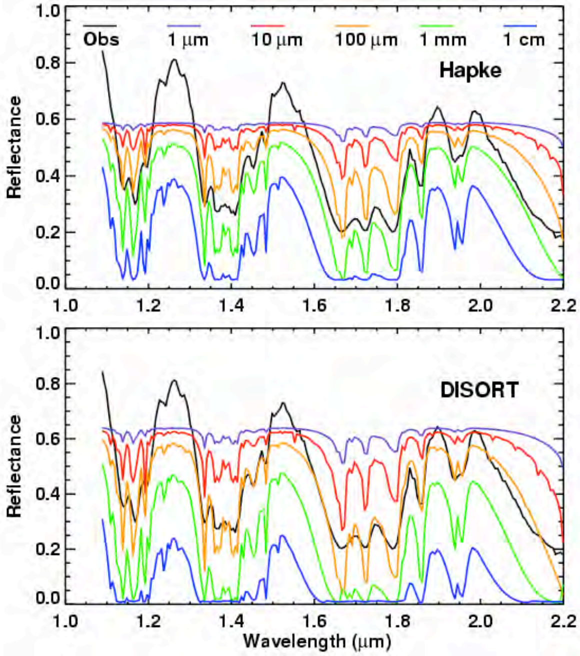

Figure 1: Black line: Measured near-IR reflectivity of 2005 FY9 normalized to a V-band albedo of 0.6. Color lines: Computed physical albedo of a planet covered by a 1-meter deep layer of spherical pure methane ice particles of different radius. The upper and lower panels show albedos computed using Hapke's and DISORT models, respectively.

However, it is clear that centimeter-sized particles are very unlikely to exist on 2005 FY9's surface and they are merely indicative of long path lengths prevailing in a densified slab of solid methane [2,3]. Consequently, our main objective has been to determine whether an end-member spectrum similar to the blue lines in Figure 1 can indeed be obtained using a porous slab model with realistic assumptions about the size of the voids. For this purpose, we have experimented with a wide range of porosities and void sizes consistent with the sizes required to produce a densified slab on "seasonal" time scales comparable to the orbital period. Representative spectra are shown in Figure 2. The main conclusions reached from Figure 2 (and numerous additional runs) are as follows: (1) The slab model can reproduce a flat spectrum in the 1.6-1.8 µm region for small porosities (< 5%) and micron-sized voids that follow a broad size distribution. The spectrum for porosity of 1% closely resembles the 1-cm spectra in Figure 1. (2) Including a distribution of void sizes is necessary for producing flat spectra. (3) A simple 2-component model containing the porous slab and a sloping continuum is capable of producing a semi-quantitative fit to the observed spectra (except beyond 2.2 µm, where additional absorbers have been detected [2]). The remaining discrepancies between the black and red curves in Figure 2 could be a related to (and possibly ameliorated by) subtle effects stemming from the interplay between the assumed porosity, void size distribution, and temperature dependence of the refractive indices for methane ice. (4) We have not been able to obtain a good fit to the spectra scaled to a high visible albedo (> 0.7), without resorting to more complicated multicomponent models or arbitrarily changing the optical properties of the slab (e.g., by making the voids strongly backscattering). The discrepancies were largest away from the absorption peaks and this may indicate, if the albedo is indeed at the high end of the current estimates, that an opposition effect does in fact occur.

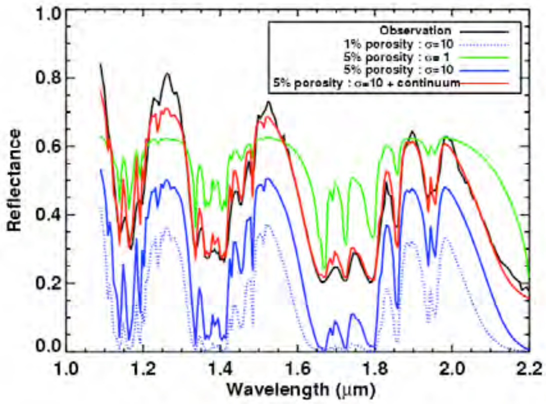

Figure 2: Black line: Measured spectrum of 2005 FY9 normalized to a V-band albedo of 0.6. The color lines represent spectra computed using the DISORT model for a porous slab containing spherical voids. Green line: 5% porosity, with all voids having the same radius of 0.5 µm. Blue lines: Voids follow a lognormal distribution with modal radius of 0.5 µm and mode width of 10. The solid and dashed lines correspond to porosities of 5 and 1%, respectively. Red line: Best fit. It combines in the 90/10% ratio the spectrum computed for 5% porosity and 0.5-µm voids lognormally distributed (i.e., solid blue line) and a sloping continuum determined through least-square fitting.

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