

KINETIC CONSTRAINTS ON THE SIZE OF NITROGEN GRAINS ON TRITON Janusz Eluszkiewicz, 170-25 Caltech, Pasadena, CA 91125.

INTRODUCTION The size distribution and physical state of nitrogen grains have a direct bearing on several issues related to the surface of Triton. Meter-sized grains have been invoked to explain the 2.16- μm absorption feature [1]. Grains smooth on the 80- μm scale may be responsible for the low thermal emissivity inferred from Voyager imaging results [2], although calibration difficulties cannot be excluded. Small ($< 5 \mu\text{m}$) cohesionless grains are called for in the dust-devil hypothesis for the plumes [3], although the authors point out that an involatile substance such as water ice seems to be required. Nevertheless, the issue of grain metamorphism in nitrogen may be relevant even in this case, as nitrogen grains are likely to be intermixed with any involatile material and may provide the very cohesion force whose absence is essential to the dust-devil model.

Unfortunately, the two existing models of grain growth on Triton differ greatly in their estimates of the grain size. According to the model by Zent et al. [4] with the heat of sublimation of solid nitrogen $H = 6.8 \text{ kJ mole}^{-1}$, grains $\sim 1.5 \text{ mm}$ in diameter could form over a Triton season (~ 100 Earth years) at the ambient temperature of $T = 37 \text{ K}$. Their model is based on a direct application of an empirical relationship between the size and age of grains in south polar firn established by Gow [5]. On the other hand, Kirk [6] arrived at a diameter of $\sim 5 \mu\text{m}$ over 100 years at $T = 37 \text{ K}$, using a model in which grain growth is driven by solid-state diffusion.

Both of the above estimates use the relationship

$$\alpha^n - \alpha_0^n = Ate^{-B/T}, \quad n = 2, \alpha_0 = 0 \quad (1)$$

where α is the grain diameter at time t , α_0 is the initial grain diameter, T is temperature, and A and B are constants. Zent et al. calculate B from the sublimation heat and assume A to be equal to the empirical value found by Gow [5]. Some pitfalls involved in this procedure have already been pointed out [6]. Here I will restrict myself to two comments. First, the growth of ice crystals in terrestrial firn occurs in the presence of an inert gas (air), which contributes to an enhancement by several orders of magnitude in the rate of sintering [7]. On Triton, nitrogen grains most likely grow in the absence of any inert gas. Second, the data obtained by Gow correspond to depths where power-law creep may contribute to grain growth by activating additional sintering mechanisms and/or causing densification. Power-law creep is unlikely to be important in the uppermost few meters on Triton [8]. As a result, it is not unlikely the the growth constant A adopted by Zent et al. is overestimated by several orders of magnitude.

On the other hand, Kirk offers in his work a physical basis for Eq. (1). The constants A and B are related to the diffusion coefficient across grain-boundaries D_b' and the surface tension γ . Kirk assumed $D_b' = D_v$, where D_v is the lattice (volume) diffusivity. However, in terrestrial ice $D_b' \gg D_v$ is found [9]. Moreover, Kirk's approach only applies to grain-growth in low-porosity systems [9, 10, 11]. If nitrogen condenses as fluffy frost on Triton, a different growth mode may prevail, as discussed below.

MODES OF GRAIN GROWTH In systems of very low porosity, grain growth is driven by boundary migration [10]. It is often observed that on average whether a grain grows or shrinks depends on the size of the grain: grains with radii $r > r_c$ grow whereas grains with $r < r_c$ shrink. $r_c = r_c(t)$ is "the critical radius". However, an exponent $n > 3$ instead of $n = 2$ in the growth law (1) is usually found [10].

In very porous systems, grain growth is limited by sintering, i. e., the growth of a neck between neighboring grains [11]. Whether a grains grows or not depends on the size of its neighbors and not on any "critical radius". Six microscopic processes have been identified to contribute to sintering [12]. I have calculated the sintering time as a function of the grain diameter α using the equations from reference [12]. The sintering time is defined as the time to reach $x = \alpha/2$, where x is the neck radius. I have used the published values for D_v and γ [references 13 and 14, respectively]. The results are presented in Fig. 1. As discussed in [11], sintering may be the rate-limiting step in grain growth for porosities $> 8\%$.

WARNING The sintering times shown in Fig. 1 are only as good (or as bad) as the material data entering the calculations [12]. The values for D_s and D_b , the surface and along-boundary diffusivity, respectively, are unknown and have been estimated from $D_s = D_v$ and

$D_b = D_{0v} \exp(-2/3 E_v / R/T)$, where D_{0v} and E_v are the preexponential and the activation energy for volume diffusion. A question to be addressed by future experiments is the determination of D_s and D_b . Sintering may in fact be used towards this end and I will be happy to discuss this topic further with any interested reader. In any event, if the values of D_s and D_b assumed here are overestimates of the true values, then the sintering calculations will not be affected in all cases where volume diffusion is the dominant sintering mechanism

IMPLICATIONS A satisfactory model of grain growth must include a simultaneous treatment of densification. Such a model is not yet forthcoming. In [11] it was observed that the average grain diameter grew by a factor of ~ 28 before 8% porosity was reached. If condensing grains on Triton are larger than $\sim 0.3 \mu\text{m}$, then it is quite possible that grains will grow to sizes for which the sintering time exceeds 100 Earth years before densification to 8% porosity occurs. In this case Fig. 1 can be interpreted to give the age vs. size relationship (note that $n \sim 4$ is suggested). Grains no larger than $\sim 10 \mu\text{m}$ can grow at $T = 37 \text{ K}$ over 100 yrs. On the other hand, if the initial grain size is $\ll 0.3 \mu\text{m}$, then full densification may occur on a timescale shorter than 100 yrs. In this case the subsequent grain growth will be driven by grain boundary migration and Kirk's model may apply. If $D_b' = D_b$ and the activation energy for D_b is $2/3$ that for volume diffusion, then with $n = 2$ it is marginally possible that millimeter-sized grains would grow on a seasonal timescale. On the other hand, nitrogen grains smaller than $5 \mu\text{m}$ sinter rapidly, especially at the elevated temperatures. Such grains must therefore be absent from the devil-forming dust, as the latter is required to be essentially cohesionless [3].

SUMMARY AND CONCLUSIONS It is very unlikely that centimeter-sized (or larger) grains grow by thermal metamorphism on the optical surface of Triton on a seasonal timescale. If nitrogen condenses as fluffy frost with the initial grain diameter larger than $\sim 0.3 \mu\text{m}$, then grain growth may be limited by sintering and the resulting grain size at $T = 37 \text{ K}$ over 100 yrs is estimated to be $\sim 10 \mu\text{m}$. If the initial grain size is smaller than $0.3 \mu\text{m}$, then grain growth may be limited by grain boundary migration and the resulting grain size will depend on the across-boundary diffusion coefficient D_b' . Millimeter-sized grains are marginally possible in this case.

If experiments are to be used to study grain growth with application to planetary surfaces, they should include a determination of the various diffusion coefficients involved in grain metamorphism. Sintering measurements may be used to achieve this.

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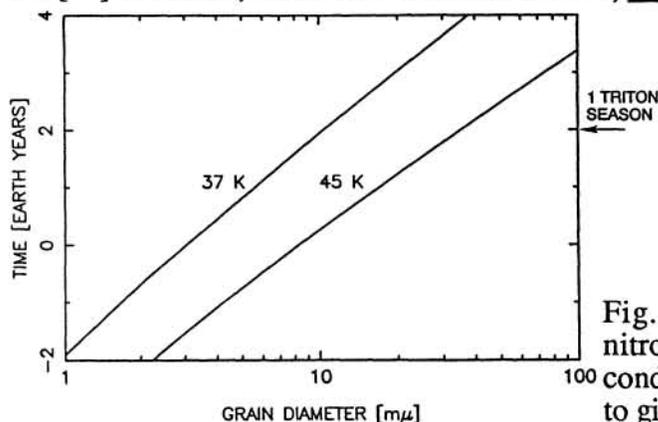


Fig. 1 Sintering time vs. grain size for nitrogen. In porous systems (such as freshly condensed frost) this figure can be interpreted to give the age vs. size relationship.