THERMAL PROCESSES IN SEASONAL AND PERENNIAL N_2 LAYERS ON TRITON AND PLUTO

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Abstract. This work is a continuation of our two previous articles (Duxbury and Brown 1997 and Duxbury *et al.* 1997). Here we extend our convective studies to Tritonian and Plutonian seasonal solid N_2 layers and to Pluto's possibly thick perennial N_2 layer, couple the solar and internal heat sources and evaluate the possibility of eruptive activity on Pluto. For the internal energy supply, a numerical model of conductive-convective heat and mass transport on Triton (expressed mathematically as the Navier-Stokes system in the Boussinesq approximation, Duxbury and Brown 1997) is applied to Pluto's thick perennial N_2 layers. Whether solid-state convection occurs in Pluto's and Triton's N_2 ice (and if it does, then its intensity) depends upon the solid nitrogen grain size and the thickness of the solid N_2 layer. To prove the applicability of our model to Pluto we have computed the average N_2 grain diameter, sufficient for the onset of convection and to obtain $Ra/Ra_{critical} = 5$ as a function of the N_2 thickness in the case of perennial (with dominating Nabarro-Hering creep, volume diffusion) and *seasonal* (with dominating Coble creep) nitrogen deposits. We have also considered the coupled effect of convection and the "super" greenhouse in a seasonal N_2 layer. The "super" greenhouse effect is substantiated by our conclusion that N_2 on Pluto and Triton is likely to form as a transparent layer. (Duxbury *et al.* 1997). We used the constraint on the grain diameters $d_{grain} < 0.3\mu m$ for the fresh N_2 deposits on Pluto and Triton, which we derived from our experiments (Duxbury *et al.* 1997).

thermal
subsurface
modelling

Convection in a seasonal N_2 layer on Triton and Pluto is plausible even without the solid-state greenhouse effect because N_2 on these bodies is so close to its melting temperature of ≈ 63.148 K (at zero pressure) that an upper stagnant layer does not form. We have generalized our conclusion for plausible convection in seasonal layers on other bodies with Van der Waals solids near their melting temperatures (e.g., CH_4 on Titan). We have also proposed a method for estimating the thickness of Pluto's perennial solid N_2 layer during the proposed Pluto flyby mission (Pluto-Kuiper Express).

INTRODUCTION

Pluto is the smallest known planet in the Solar System with an average radius between 1137 and 1206 km (Yoder 1995). A Pluto flyby mission is currently being studied. It will take 10 to 12 years to get to the planet at the outskirts of the Solar System. Having a highly elliptic orbit with an eccentricity of about 0.25 (Yoder 1995), Pluto's aphelion is $\approx$ 50 AU, with an average distance of about 39.48 AU (Yoder 1995). Presently it is near perihelion and its distance from the Sun is slightly less ($\approx$ 29.6 AU) than of Neptune and its largest satellite Triton. What is known about the chemical composition of Pluto's surface comes mostly from the ground-based spectral observations led by Cruikshank (1976, 1980), with the recent important contribution by Owen *et al.* (1993). They found that solid nitrogen is the dominant surface volatile (about 98 %). The derived abundance of solid methane is about 1.5 %, whereas on Triton it is only 0.05 % (Cruikshank *et al.* 1993).

The methane absorption band centers in Pluto's spectrum indicate that much of the CH_4 on Pluto is present as isolated patches of free CH_4, whereas on Triton it is more likely to form a solid solution with N_2 (Schmitt *et al.* 1994; Schmitt and Quirico 1994). Some of the methane on Pluto is also diluted in N_2. The other minor surface volatile constituent on Pluto is solid carbon monoxide (about 0.5 %), which is more volatile than methane but less volatile than nitrogen at Pluto's temperatures. Carbon monoxide is probably present in a form of a solid solution with nitrogen. The second major difference between the surfaces of Pluto and Triton is that, unlike on Triton, carbon dioxide ice has not been detected on Pluto in the near-infrared spectral region.

Usually the absorption feature at 2.148 microns (on which the nitrogen detections on Pluto and Triton were based) is such a weak feature in the reflectance spectrum that the path in solid nitrogen has to be more than a meter in order for nitrogen to be detected at all. Thick nitrogen ice has many interesting implications because of its thermal insulating effect. Solid N_2 (as well as other solids: CH_4, CO, CO_2, whose molecules are bonded by weak Van der Waals forces) in the vicinity of 40 K has much lower thermal conductivity than the water ice. This means that temperatures are elevated at the base of a nitrogen layer.

By virtue of the efficient transport of latent heat of sublimation, the nitrogen-ice surfaces on Pluto and Triton are nearly isothermal. Using ground-based spectroscopy, Tryka *et al.* (1994) estimated the surface temperature of Pluto's N_2 ice to be 40^{+2}_{-2} K, which is close to the current Triton's N_2 surface temperature of 38^{+1}_{-1} (Tryka *et al.* 1993; Grundy *et al.* 1993). The higher mean N_2 surface temperature of Pluto compared to that of Triton can be explained by Pluto's lower overall albedo (thus presently absorbing more solar energy).

The current constraints on the surface pressure on Pluto are 3 to 60 μbar. The lower value was derived from stellar occultation measurements (Hubbard *et al.* 1990, Yelle and Lunine 1989), but was later revised by Stansberry *et al.* (1994), who considered that the occultation measurements did not probe all the way down to the surface. The highest value in the pressure interval is obtained under the assumption that the surface and atmospheric nitrogen are in vapor pressure equilibrium.

The term "geyser" is commonly used for liquid H_2O (and entrained CO_2, H_2S, etc., gases) eruptions on Earth. It may be more correct to call the Tritonian eruptions fumaroles, since they are thought to be nitrogen GAS with dust rising to about 8 km (Smith *et al.* 1990). "Classical" and "super" solid-state greenhouses have been suggested as mechanisms for the solar energy supply to Tritonian geyser-like plumes (Brown *et al.* 1990). At the time the Brown *et al.* (1990) article was published, the existence of a transparent N_2 layer on Triton, required for the "super" greenhouse, was not substantiated by experiments. In our previous work (Duxbury *et al.* 1997) we have proved by experiments and calculations that N_2 on Pluto and Triton is likely to form as a transparent layer. This allowed us to consider here the coupled effect of convection and the "super" greenhouse in a seasonal N_2 layer. Additional conclusion, which we derived from our experiments and which we use here is that $d_{grain} < 0.3\mu m$ for the fresh N_2 deposits on Pluto and Triton (Duxbury *et al.* 1997). At those small grains and low temperatures, Coble creep (boundary diffusion) dominates in seasonal deposits until N_2 grains grow to the critical size. The grain growth at those low temperatures is very slow (Kirk *et al.* 1990).

ESTIMATES FOR PLUTO'S INTERNAL HEAT FLOW

The above mentioned compositional and temperature analogies with Triton made it worthwhile calculating the value of an internal heat flow on Pluto in order to determine the applicability of our Triton model (Duxbury and Brown 1997) for the subsurface convection in Pluto's solid nitrogen. The model was initially developed as an alternative to the solid-state greenhouse mechanism of energy supply to the

Tritonian geyser-like plumes. Speculation about internal energy as a source for Tritonian geysers has occurred (e.g., Smith *et al.* 1990; Kargel and Strom 1990), but detailed models justifying it have not been constructed until now. Previous models of the solid-state convection for different celestial bodies considered only simple parameterized convection in H_2O ice.

Following McKinnon (1989) and Stern (1989), we assume Pluto to be completely differentiated. We adopt the same model of Pluto's internal structure as was suggested for Triton by Smith *et al.* (1989). The model implies a rocky core, overlaid by a water-ice mantle and a surface veneer of volatile (mostly nitrogen) ices. The bulk density estimate for Pluto is very close to Triton's average bulk density of 2.054 g/cm^3 (Smith *et al.* 1989). But even if the densities of these two bodies were equal, Pluto's smaller size may preclude it from having a surface value of the internal heat flow as high as that on Triton, since the surface heat flow is proportional to a body's radius. Hence, separate calculations are needed for Pluto.

Using the conclusions of Stansberry *et al.* (1994), we assume that a strong thermal inversion layer prevented the underlying atmosphere from being sensed by the stellar occultation. Thus, we adopt Pluto's radius of 1150 km, as was derived by Tholen and Buie (1990) from mutual events, rather than 1195 km calculated from the stellar occultation data (Millis *et al.* 1993). We take the value of Pluto's mass from Young *et al.* (1994) astrometrically determined range of $119.08 * 10^{20} - 128.83 * 10^{20}$ kg. The main uncertainty stems from the determination of Charon's orbital semimajor axis. For the average mass from this interval, $\rho_{Pluto} = 1.95\ g/cm^3$. This is consistent with $\rho_{Pluto} = 2.00\ g/cm^3$, derived by Foust *et al.* (1995).

The next formula relates the mass of the rocky core of a body to the body's mean bulk density (Schubert *et al.*, 1986):

$$\frac{M_{core}}{M_{body}} = \frac{1 - (\rho_{water\ ice}/\rho_{Pluto})}{1 - (\rho_{water\ ice}/\rho_{core})},$$

where we assume that $\rho_{core} = 3\ g/cm^3$ is the average rock bulk density, $\rho_{water\ ice} = 1\ g/cm^3$ is the water ice bulk density and $\rho_{Pluto} = 1.95\ g/cm^3$. Thus a rocky core comprises as much as $\approx$ 73% of the total Pluto's mass. This estimate is consistent with the historical considerations of McKinnon and Brackett (1994). Using a collisional formation model with water ice jetting and subsequent ice loss for Pluto, they obtained Pluto's mass ratio: 75% of a rocky core versus 25 % of ice.

We have calculated the range of Pluto's total radiogenic heat flow to be $4.93 * 10^{10} - 8.32 * 10^{10}$ W. The maximum corresponds to the specific (per unit mass) radiogenic heat production of $9.2 * 10^{-12} W/kg$ measured for the lunar samples, and the minimum corresponds to the specific heat production of $5.45 * 10^{-12} W/kg$, measured for chondritic meteorites (Schubert *et al.* 1986). We have calculated the final range of Pluto's internal heat flow at the surface as $2.97 * 10^{-3} - 5.00 * 10^{-3} W/m^2$. Since the total temperature difference across a layer is the same for pure conduction as that for conduction with convection, we equate the calculated heat flow and $\lambda \frac{\partial T}{\partial y}$. The thermal conductivity λ of solid N_2 in the temperature range possible in Pluto's N_2 layer is about $0.2 W/mK$. Hence, the temperature difference across the 1 km N_2 layer is 14.85 - 25 K, which is only slightly lower than the range obtained for Triton. A high temperature gradient in nitrogen ice on these bodies is due to good thermal insulating property of solid nitrogen. The low absolute value of the upper boundary temperature influences the convective model only indirectly through the strongly temperature dependent viscosity of solid nitrogen. In this dependence the proximity of the nitrogen temperature to the N_2 melting temperature is important.

SOLID NITROGEN EQUATORIAL BAND OR POLAR CAPS ON PLUTO?

According to Ward's (1974) calculations, the critical obliquity, above which the minimum of the mean annual insolation per unit area is at the equator rather than at the poles, is about 54 deg. Currently Uranus with the obliquity of 97.86 deg (and its satellites) and Pluto with the obliquity of about 122 deg are satisfying this condition. Probably Mars' obliquity at certain times could have exceeded the critical value, since it was shown that on time scales greater than 10^7 Earth years Martian obliquity behaves chaotically reaching as high as 60 deg (e.g., Jakosky *et al.* 1995). Spencer *et al.* (1996) calculated that the current annual mean insolation at the Pluto equator is about 0.23 J/m^2s, which is slightly less than about 0.26 J/m^2s at the poles.

As shown by Brown and Kirk (1994), *permanent* solid N_2 deposits are stable in the regions of long-term minima in the *absorbed* solar flux. Therefore, for a uniform albedo, a perennial solid nitrogen equatorial "belt" may be expected for Pluto. However, strong surface albedo inhomogeneities were revealed by mutual event observations (Buie *et al.* 1992; Young and Binzel 1993) and by more recent images obtained by Stern *et al.* (1997) in June 1994 using the Faint Object Camera on the Hubble Space Telescope (HST). Owing to these surface albedo inhomogeneities, a perennial nitrogen deposit can be *stable anywhere* on Pluto. There is a discrepancy between the HST images and the mutual event observations (Buie *et al.* 1992). According to the HST images, the brightest spot is on the equator, whereas the mutual events show it on the south cap. A definitive answer to this disagreement will likely have to be preceded by spacecraft exploration. Two spacecraft are currently planned to be launched to Pluto in March 2001.

In order to determine which regions on Pluto have the minimum *absorbed* insolation, albedos at different locations have to be known with much higher precision than they are known today. Especially, because the current annual mean insolation at Pluto's *poles* is *only slightly greater* than that at the equator (Spencer *et al.* 1996), and a darker equator (greater value of (1-A)) may cause the *absorbed* insolation to be higher at Pluto's equator. Nevertheless, the application of our model depends on the thickness of these deposits but not on their locations.

"Old" ice on Pluto may look darker than on Triton because Pluto has more solid CH_4 that darkens with exposure age. This reconciles the existence of a bright permanent polar cap on Triton with the possibility of the existence of dark *perennial* contaminated nitrogen ice on Pluto. Photon and charge particle bombardment of CH_4 inclusions in N_2 ice can produce dark organics, making "old" contaminated nitrogen ice look dark. In this case, only the conductive-convective mechanism of energy supply to the eruptions is feasible.

If the rate of nitrogen condensation is low enough, as appears to be the present case for Triton and Pluto, N_2 condenses as a transparent layer (laboratory experiments and calculations by Duxbury *et al.* 1997). The Pluto albedo maps derived by Buie *et al.* (1992) and Young and Binzel (1993) from mutual events, show that the planet has an extensive bright southern polar cap and a small, or non-existent northern polar cap. (Here we use the angular momentum vector for the definition of Pluto's North Pole). Therefore, it is conventional to speak about N_2 polar caps on Pluto.

REDISTRIBUTION OF INTERNAL HEAT FLOW BY CONVECTION IN N_2 ICE

Our Tritonian model may be applicable to convection in Pluto's upper frozen nitrogen layer provided this layer is thick enough and the grain size is sufficiently small. Therefore, we may expect to observe the nitrogen geyser-like plumes on Pluto as well. Methane geysers are less likely to operate on Pluto because the CH_4 has an equilibrium vapor pressure of about 15 μ bar at 53 K, and about 3 μ bar (the lower estimate for Pluto's lower atmospheric pressure) at 50 K (Brown and Ziegler 1979). This is much higher than the inferred temperature of Pluto's N_2 surface of about 40 K (Tryka *et al.* 1994). However, CH_4 could have a higher temperature, if it is in isolated patches. Creep in CH_4 occurs, if its temperature is greater than $0.6 * T_{melting} \approx 54.4$ K, where $T_{melting} = 90.67$ K. And, if there is a sufficiently thick methane patch at a temperature higher than about 54.4 K, convection is plausible. Our modeling (Duxbury and Brown 1997) was performed for the case of pure N_2 when its basal temperature (63 K) is lower than the melting temperature (63.148 K at zero pressure and increases with pressure, see Scott 1976).

As in any problem with a strongly temperature dependent viscosity, a question arises about the temperature at which to evaluate the parameters (especially viscosity) constituting the Rayleigh number. This is equivalent to the problem of the formation of an icy lithosphere on top of convecting N_2 layers, whose viscosity contrast is large. The viscosity contrast for Pluto's perennial N_2 ice is caused by the temperature difference of about 23 K (for a 1 km layer) between the lower and the upper boundary temperatures. All techniques to take into account this conducting overlayer in a ***single representative*** temperature (at which thermophysical characteristics of a convecting layer are evaluated) were developed either for terrestrial planets or for the H_2O-ice satellites (mostly Galilean and Saturnian satellites). The absence of convection in the H_2O-ice upper layer is substantiated by observations (McKinnon *et al.* 1997) and the fact that water ice on Pluto and Triton is too far from its melting temperature. Here we argue that, though these considerations may be applicable to water-ice mantle convection on Pluto and Triton (McKinnon *et al.* 1997), they are not applicable to convection in nitrogen ice on these bodies.

First, N_2 ice is much closer to its melting point on Pluto and Triton than H_2O ice is on most bodies in the Solar System. Actually, N_2 on Pluto and Triton is in the same vicinity of its melting point as water ice is in terrestrial glaciers. The base of the lithosphere is defined by the *minimum* temperature T_l sufficient for creep to occur on a geological time scale. Creep in solids is caused by self-diffusion, which is a thermally activated process. It is a common phenomenon in solids, at least in the vicinity of their melting points (see experiments by Esteve and Sullivan

(1981) with pure and contaminated N_2). The approach by Ellsworth and Schubert (1983) for the mid-sized satellites of Saturn uses the formula $T_l = 0.6 * T_{melting}$. This formula is based on the creep data for metals that show the occurrence of solid-state creep at temperatures $\geq$ than $0.6 * T_{melting}$. The application of this approach gives the temperature of 37.89 K at the base of the assumed Pluto's N_2-ice lithosphere. This is even less than the lower limit of the spectrally measured temperature of 40^{+2}_{-2} K at Pluto's surface. Hence, we must take $T_l = T_{up}$, where T_{up} is the surface temperature. Though laboratory experiments give $0.6 * T_{melt}$ as the *minimum* temperature ***sufficient*** for creep to occur during laboratory time scales, on GEOLOGICAL time scales creep may occur at lower temperatures. This supports our idea that the very *upper* N_2 layer is convecting on Pluto and Triton. Therefore, we evaluate the thermophysical coefficients in Pluto's N_2 layer at the average of the upper and lower boundary temperatures, as we did for Triton (Duxbury and Brown 1997).

Secondly, from a theoretical standpoint, the bonds between water-ice molecules in a crystalline lattice are strong hydrogen bonds (with the two kinds of H-bonds being randomly distributed, Jichen and Ross 1993). In N_2 ice intermolecular bonds are weaker (electrical) Van der Waals bonds, resulting in lower viscosity.

Thirdly, there are no sufficiently resolved observations of Pluto's surface to draw a conclusion about the involvement of the N_2 surface layer in convection. For Triton's surface there are only Voyager 2 observations in August 1989 (its surface is not resolved from the Earth), thus it is impossible to compare the state of the surface at two different epochs. Moreover, there is some morphological evidence from the Voyager 2 images for diapirism on Triton (cantaloupe terrain, Schenk and Jackson 1993). Presumably, this crustal overturn is driven by compositional layering of Triton's crust, but the authors have noted that thermal convection may also be important as the driving mechanism.

Using the dimensionless formulation corresponding to the formulation from Duxbury and Brown (1997), we have computed that the closest approach to the surface of the $T_{up} + 1\ K$ isotherm is about 16 m for a 1 km layer and $Ra/Ra_{critical} = 5$, where $Ra_{critical} = 1100.65$ (Chandrasekhar 1981). This number is the minimum Rayleigh number required for the onset of convection for the upper stress-free and lower rigid boundary conditions. The minimum is taken with respect to all horizontal wavenumbers. For nitrogen ice the Prandtl number is essentially infinite (cf. the Pr number of 3.6 for liquid nitrogen). This considerably simplifies the hydrodynamic part of the problem by reducing the Navier-Stokes system to the Stokes system.

Even a small decrease in the average grain size gives a significant rise to the ratio $Ra/Ra_{critical}$. Therefore, we investigated Pluto-and-Triton-like conditions that will give the needed $Ra/Ra_{critical}$. The results for thick perennial N_2 layers are shown in Fig. 1. Plots in Fig. 1 present the thickness of a perennial nitrogen layer versus nitrogen grain diameter. These layers are thick enough to start thermal convection (the curves marked by filled circles) and to achieve $Ra = 5 * Ra_{critical}$ in thick N_2 layers (the curves marked by open triangles). A pure conductive thermal gradient of

0.0225 K/m is assumed (no solid- state greenhouse effect). For the grain diameters corresponding to 800 - 1000-m-thick layers on these curves and for Triton's and Pluto's temperatures, Nabarro-Herring volume diffusion dominates (Duxbury and Brown 1997). For the higher pair of curves the volume self-diffusion coefficient of nitrogen ice is assumed to be equal to the average estimate from the measurements of Esteve and Sullivan (1981). For the lower pair the self-diffusion coefficient is taken at the upper limit from the same experimental measurements.

The nitrogen grain size is an important parameter. If we measure the rate of nitrogen grain growth in a laboratory under the Pluto-like conditions, in order to reach a conclusion about the grain size at the end of Pluto's winter season, we need to know the initial grain size. The dynamic viscosity is proportional to the 2nd power (for the Nabarro-Herring volume diffusion creep) or to the 3rd power (for the Coble boundary diffusion creep) of the grain diameter.

CONVECTION IN A SEASONAL NITROGEN LAYER?

Earlier we examined the conditions sufficient for the onset of convection in a thick perennial N_2 ice. It is interesting to note that convection may occur even in a *seasonal* N_2 ice. Though its thickness is much smaller than that of perennial deposits, the sufficient condition $Ra > Ra_{critical}$ may still be satisfied because the initial grain diameter is small and insufficient time elapsed for grains to anneal into larger grains. As we have shown in Duxbury *et al.* (1997), the initial grain size on Pluto (and moreover on Triton) is $< 0.3\mu$m.

At the *small* grain sizes under consideration and at Triton's temperatures Coble (boundary) diffusion creep dominates (a letter by R. Kirk to N. Duxbury dated March 31, 1995). Thus, for Pluto's *seasonal* N_2 layers we have assumed that the dynamic viscosity is proportional to the 3rd power of the grain size instead of the 2nd power as for volume diffusion used for *perennial* layers (Nabarro-Herring creep). We have calculated the nitrogen dynamic viscosity using the grain-boundary diffusion coefficient (Goodman *et al.* 1981):

$$D_b(T) = D_{0b} \times exp(-E_b/(RT)), \quad m^2/s,$$

where the preexponential factor $D_{0b} = D_{0v} = 1.6 \times 10^{-7}\ m^2/s$ (Ashby and Verrall 1978, Eluszkiewicz 1991), $E_b = (2/3) \times E_v = 5.7 \times 10^3$ J/mol is the activation energy for the boundary diffusion (Eluszkiewicz 1991, pp. 19219 - 19220), the universal gas constant R=8.3145 J/(mol K) and T is the temperature.

We used this coefficient in the dynamic viscosity formula for polycrystalline solids with Coble diffusion creep (Raj and Ashby 1971, p. 1121):

$$\eta_b(T_{average}) = \frac{d^3_{grain} k_B T_{average}}{141 \times \delta \times D_b(T_{average}) \times \Omega}, \quad Pa \bullet s,$$

where $\Omega = 4.7 \times 10^{-29}/m^3$ is the N_2 molecular volume, $\delta = 2\Omega^{1/3} \approx 7.2 \times 10^{10}$ m is the width of a nitrogen grain boundary (Eluszkiewicz 1991), $k_B = 1.381 \times 10^{-23}$ J/K is the Boltzmann constant, d_{grain} is the grain diameter (assuming spherical grains), and $T_{average}$ is an average of the upper and lower boundaries temperature.

In our program we calculated $T_{average}$ as a function of the N_2 layer's thickness, of a pure conductive gradient and of the upper boundary temperature. We used the temperature dependence of N_2 thermophysical characteristics from Scott (1976). We used a seventh-order polynomial for the approximation of density, second-order polynomials for the heat resistivity (the inverse of the heat conductivity), and third and second-order polynomials to approximate the N_α and the N_β heat capacity, respectively, as a function of temperature. Note that for a fixed $\nabla T_{conductive}$ the average of the upper and lower boundary temperatures (at which coefficients are taken in the Ra number) is a function of the layer's thickness. The volumetric thermal expansion coefficient was taken as $2 * 10^{-3}\ K^{-1}$ (Scott 1976).

The maximum thickness of a seasonal N_2 layer on Triton is about 10 m. On Pluto it can be even more, if we extrapolate the current condensation rates on these bodies over their winter seasons. Results of our computations for seasonal N_2 layers are shown in Fig. 2. They demonstrate N_2 grain diameters sufficiently small for thermal convection to start versus the thickness of a seasonal N_2 layer (the curve marked by filled circles). The second curve, marked by open triangles, shows nitrogen grain diameters sufficiently small for the Rayleigh number to be 5 times that of the critical Rayleigh number for the free-rigid boundary case ($Ra_{critical} = 1100.65$). Solely radiogenic heating is assumed and the average internal heat flow of $4.6 * 10^{-3} W/m^2$ is used for Pluto. This corresponds to the average thermal gradient of 0.023 K/m.

Though convection in a seasonal layer with only radiogenic heating is plausible, the grain diameters sufficiently small for its onset are about an order of magnitude smaller than the upper bound of $0.3 \mu m$ (Fig. 2). This upper constraint can be lowered by using the emissivity $\epsilon = 0.8$ for the β phase of nitrogen (Stansberry *et al.* 1996) instead of the nominal value $\epsilon = 1$ originally used by Eluszkiewicz (1991). Convection in a seasonal layer starts with larger N_2 grains (grain diameters on the order of the upper bound), provided we calculate the temperature difference between the upper and the lower boundaries considering the solid-state greenhouse effect. If N_2 ice on Pluto and Triton were not so close to the melting temperature, a stagnant layer would form on top, possibly preventing seasonal transient convection.

COUPLING THE SOLID-STATE GREENHOUSE EFFECT AND CONVECTION IN N_2 I

Since it is likely that nitrogen initially forms a transparent layer (Duxbury *et al.* 1997) on top of a dark substrate, a "super" solid-state greenhouse effect can occur (Brown *et al.* 1990). Note that the solid-state greenhouse effect does not require continuous sunlight and thus can occur in Pluto's southern hemisphere, where the seasonal N_2 layer is currently growing. Pluto's subsolar point crossed the equator in 1986 moving north at a rate of about 2 deg/earth year, hence the regions from the south pole down to about 70 S are in continuous darkness. (We again use the angular momentum vector to define Pluto's North Pole). The condition for the daily averaged insolation, sufficient for the greenhouse effect to work, can be found in the Appendix of the article by Matson and Brown (1989).

In our computations we have coupled the solid-state greenhouse effect and convection. Results in Fig. 3 illustrate the grain sizes sufficiently small for convection to start in a seasonal layer with the solid-state greenhouse effect (the curve marked by filled circles). The curve marked by open triangles shows N_2 grain diameters sufficiently small to obtain $Ra = 5 * Ra_{critical}$. The "super" solid-state greenhouse effect is assumed with a dark underlayer having an albedo of 5%, thus giving a conductive gradient of 4 K/m (Brown *et al.* 1990). This is about 174 times more than the average thermal gradient of 0.023 K/m calculated using only radiogenic heating (Fig. 2).

The plots in Fig. 4 represent an intermediate case of nitrogen grain diameters sufficiently small for thermal convection to start in a seasonal layer with the solid-state greenhouse effect (the curve marked by filled circles). The "super" solid-state greenhouse effect is assumed with an intermediate value of 1 K/m for the conductive gradient (the dark underlayer having an albedo > 5%). The curve with open triangles shows N_2 grain diameters sufficient to obtain $Ra = 5 * Ra_{critical}$.

METHODS TO ESTIMATE N_2 GRAIN DIAMETER AND N_2 ICE THICKNESS

Solid-state convection occurs on Pluto if the solid nitrogen average grain size is small enough and the N_2 ice layer is sufficiently thick. The grain diameter in *perennial* nitrogen ice can be assessed using the semiquantitative Zener theory (Kirk, personal communications; A letter by R. Kirk to N. S. Duxbury dated 31 March 1995; Duxbury and Brown 1997). Dust grains are inhibitors for the growth of the ice grains, though, as experiments with metals showed, the cessation of the grain growth may occur even in pure substance (Smith 1948). The dust flux on Triton was estimated by Pollack *et al.* (1990) from the optical atmospheric properties measured during the Voyager 2 flyby in August 1989. The dust flux is not known for Pluto. The rate of cometary impacts for the Pluto-Charon binary was estimated by

Weissmann and Stern (1994). Due to a higher flux of comets from the Kuiper belt and from the inner Oort cloud, the dust (brought by these impactors) is probably more abundant on Pluto than on Triton. Hence, the estimate for the maximum nitrogen grain size of ≈ 1 cm, which we obtained for Triton (Duxbury and Brown 1997) can be applied or even reduced for Pluto. This makes solid-state subsurface convection in perennial N_2 deposits more probable on Pluto than on Triton, assuming the same thickness of the perennial N_2 ice.

The other parameter important for calculating the Rayleigh number is the total thickness of the nitrogen layer. In this connection we propose here a new method of determining this thickness during the future Pluto flyby mission. We have dubbed it the "crater" method. By analizing the state of relaxation of the ejecta we will be able to determine whether the ejected material is near its melting point. At Pluto's surface temperature of about 40 K, N_2 ice will flow readily. If a crater's depth is great enough to extract H_2O ice, this ice (being very far from its melting temperature) forms rampart craters. It will be possible to determine a crater's depth using stereo images. (The resolution of the proposed Pluto flyby camera is planned to be better than Voyager's best resolution of 1 km/pixel). Then by comparing the relaxation of the ejecta for different craters, and thus for different depths, we can estimate the depth of the perennial N_2 layer at different locations. A second method of determining the depth of a crater is photoclinometry, but its application on Pluto will be hampered by large surface albedo contrasts. Ground-based infrared spectroscopic observations also allow to estimate the ratio of $^{15}N_2$

to the regular isotope $^{14}N_2$. If this ratio is high, then a significant portion of the regular nitrogen isotope has escaped and it is likely that the perennial nitrogen ice on Pluto is relatively thin.

DISCUSSION: NITROGEN GEYSERS ON PLUTO?

It was estimated theoretically (under the assumption that all dark streaks on the surface of Triton's south polar cap are extinct plumes) that the lifetime of Tritonian geyser-like plumes is 1 - 5 Earth years (Smith *et al.* 1989). This is consistent with our conclusion that the plumes can form in a *seasonal* N_2 layer. We suggest a concept of a cluster of geysers in order to reconcile the fact that usually the aspect ratios of convective cells are on the order of unity, the thickness of a seasonal layer is on the order of a meter, and the upper limit on the radii of geysers observed on Triton is 1 km.

The initially condensed grains grow through the formation of a neck between two grains (pressureless sintering). The process is driven by surface tension and differences in grain curvatures. When the average grain size exceeds the critical value, which is coupled with the thickness of the growing layer via the Rayleigh number, convection ceases. The probability of geysers driven by internal heat flow is somewhat lower on Pluto than on Triton due to Pluto's smaller size and consequently slightly smaller internal heat flow at the surface (this heat flow is proportional to the body's radius). Secondly, smaller gravitational acceleration results in a smaller *Ra* (the Rayleigh number is proportional to gravity). Thirdly, the N_2 escape rate on Pluto is estimated to be higher than that on Triton due to heating of Pluto's upper atmosphere (Trafton *et al.* 1996). This suggests that Pluto has a smaller amount of nitrogen currently available than Triton does. The extrapolation of the presently high escape rate over the age of the Solar System, however, may not be appropriate, because there would be little or no volatiles currently on Pluto. Since ground-based observations by Owen *et al.* (1993) showed the presence of nitrogen, methane and carbon monoxide on Pluto's surface, it is likely that either a lower escape rate or replenishment of volatiles by outgassing has occurred on Pluto.

Continuous sunlight is not needed for the solid-state greenhouse effect to be active. The formula for the temperature difference between the subsurface and the surface value uses the insolation averaged over the diurnal cycle (Matson and Brown 1989). Physically, it means that the solar energy acquired during the day may be enough to drive the plumes at night. Whether solar heating is sufficient is determined by the solar constant at the body and by the season. Nevertheless, only internal heat can drive the plumes in at least two cases. These are the existence of the plumes during a continuous seasonal night and for an opaque surface layer. The N_2 layer is probably darker on Pluto than on Triton, due to the higher abundance of CH_4 and the associated, assumed photochemical darkening. If plumes exist on Pluto, they are more likely to be internally powered, because the solar constant at 39.48 AU (Pluto's mean distance from the Sun) is less than that at 30 AU (Triton's distance from the Sun).

An observational test for the solid-state greenhouse involves moderation of the surface temperatures and a delay in the maximum diurnal surface temperature (maximum is reached later than at the local noon). An observational test for the internal origin of the plumes includes a detection of a geyser in a region of continuous darkness. We recommend conducting high-resolution IR observations of Pluto's south polar region at about 20 μm. This polar region will be in polar night down to about 40 S in 2011 A.D., the planned Pluto flyby. Another observational test for convection involves morphological evidence, e.g., cantaloupe terrain and volcanic depressions on Triton (Kargel and Strom 1990). Estimates of $^{15}N/^{14}N$ could put additional observational constraints on N_2 thickness on Pluto and Triton. Locally higher internal heat flow is suggested by the three volcanic landforms in Triton's equatorial region, which were detected in the Voyager 2 images by the two groups of investigators (Kirk and Brown 1991; Helfenstein et al. 1991, 1992).

Since convection in a seasonal layer is possible, it is interesting to consider in future how high a "warm" solid N_2 parcel will rise from the bottom of a seasonal layer before the average grain size will become large enough for convection to cease and/or before the seasonal layer will sublimate to a thickness less than the critical thickness (whichever comes first). An estimate for the rate of N_2 grain growth can be taken from Eluszkiewicz (1991). In our case the convective velocity will diminish gradually, since the Ra number decreases with an increase of the average grain size.

SUMMARY

In our previous work (Duxbury *et al.* 1997) we estimated the initial grain size at which N_2 currently condenses on Pluto and Triton to be $< 0.3\mu$m. Theoretically an N_2 ice layer at Pluto's temperatures can begin to convect having an arbitrary small thickness d if N_2 crystals are small enough, i.e.: $Ra \propto d^3/d_{grain}^3 \geq const(Ra_{critical})$. In this inequality the 3rd power of the grain diameter is used instead of the 2nd (Nabarro-Herring diffusion), since, as we have shown above, in a freshly condensed nitrogen Coble diffusion creep dominates Nabarro-Herring diffusion. This allows larger grains for the same Rayleigh number. Because the upper boundary temperature is greater than $0.6 * T_{melting}$, a stagnant layer is unlikely to form on top of convecting N_2 ice on Pluto and Triton, making transient thermal convection possible in a seasonal layer.

The mechanism of eruptions in Plutonian and Tritonian N_2 layers differs from the mechanism of terrestrial volcanism because to double the N_2 vapor pressure (this pressure difference is sufficient to drive Tritonian plumes to the observed height of about 8 km) at those cryogenic temperatures of about 40 K, a temperature difference of ONLY 1 K is sufficient. This is the difference between the N_2 surface temperature and the temperature at depth. The closer this vertical temperature difference is reached to the surface, the more probable is the geyser activity, since a crack to the shallower subsurface (geyser's vent) is more probable and more stable. The closest approach of the $T_{surface} + 1K$ isotherm to the surface occurs in the region of an upwelling subsurface plume. Our numerical results for thick perennial layers showed that $Ra/Ra_{critical} = 5$ is sufficient to bring the $T_{surface}+1K$ isotherm much closer to the surface in case of conduction plus convection ($\approx$ 16 m depth on the ascending side of the convective cell with a depth of 1 km) compared to a pure conductive case. The corresponding cross-section of isotherms and the 2D velocity field can be found in Duxbury and Brown (1997). Since ΔT=1 K is enough to drive condensing N_2 geysers on Pluto and Triton, geyser activity in N_2 ice can occur on these bodies under much lower $Ra/Ra_{critical}$ than is sufficient for volcanic activity on Earth.

A geyser's vent (provided by the change in volume due to the α-β crystalline phase transition) does not have to be directly above an upwelling plume because there can be a lateral N_2 vapor transport. It occurs in horizontal fissures due to the pressure difference, since P(vent) is slightly lower than that away from the vent due to the lower temperature at the vent. The T(vent) is lower because sublimation at the vent absorbs the latent heat.

In conclusion, we would like to underscore that solid nitrogen is a unique material in the sense that on Pluto and Triton it probably convects all the way up to the surface without forming an upper stagnant layer because it is a weakly bonded solid near its melting temperature. This behavior can be generalized for other Van-der-Waals solids (CO_2, NH_3, CH_4, CO) near their melting points. For example, our conclusions can be extended to solid methane on the Saturnian satellite Titan. The melting temperature of methane is about 90.67 K, which is very close to the estimated average surface temperature on Titan. Creep in solid methane occurs at temperatures $\geq 54.402\ K = 0.6 * T_{melting\ methane}$. This temperature would be considered the temperature at the base of the upper stagnant layer, if one exists.

ACKNOWLEDGEMENT

We would like to thank E. Ivins (JPL), M. Delitsky (JPL) and R. Kirk (USGS)

for useful discussions.

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FIGURE CAPTIONS

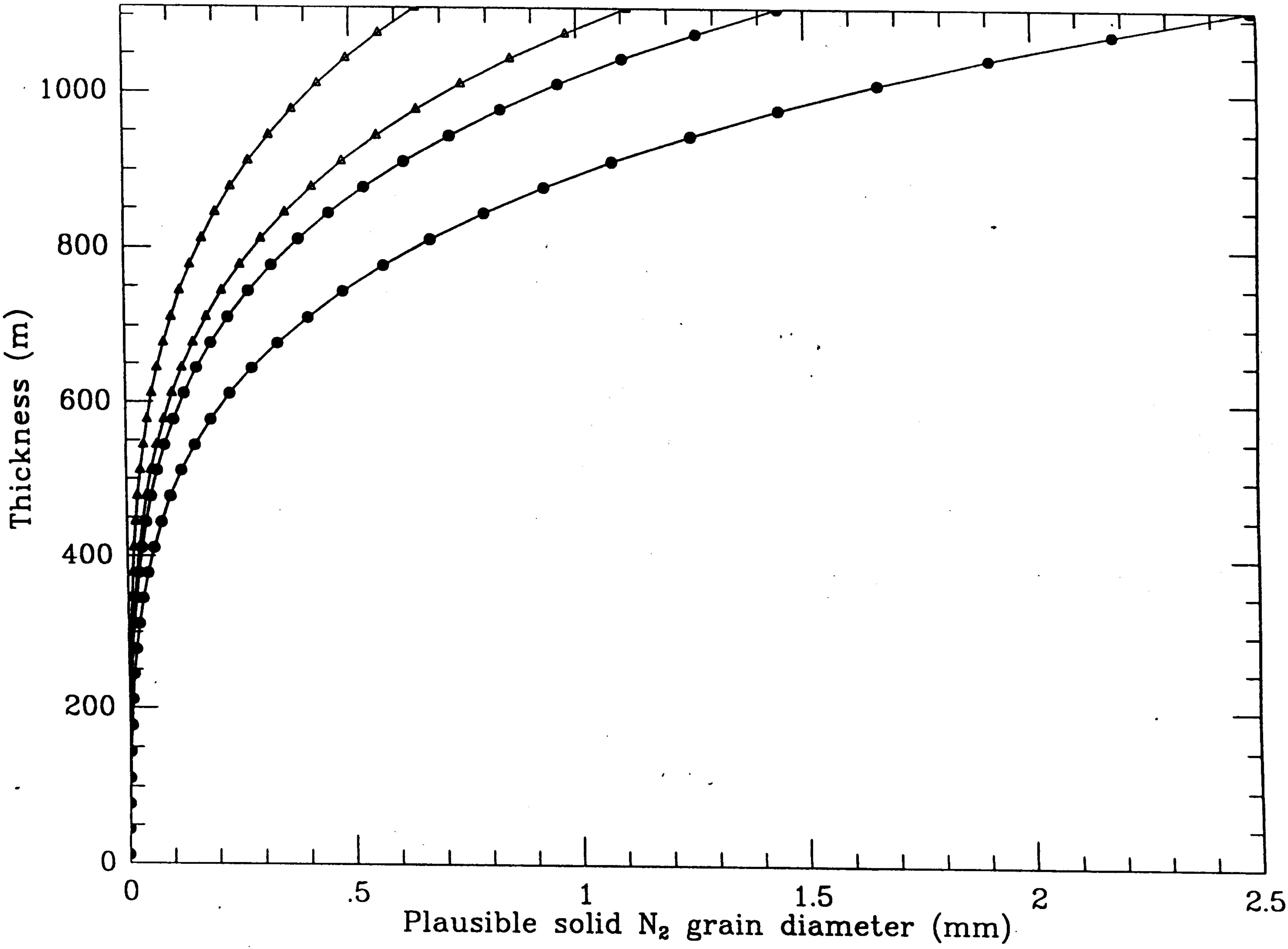
Fig. 1. Thickness of perennial nitrogen layers versus nitrogen grain diameter. These layers are thick enough to start thermal convection ($Ra = Ra_{critical}$ for the curves marked by filled circles) and to achieve $Ra = 5 * Ra_{critical}$ (the curves marked by open triangles). For the free-rigid boundary case $Ra_{critical} = 1100.65$. A pure conductive thermal gradient of 0.0225 K/m is assumed (no solid-state greenhouse effect). For the grain diameters corresponding to 800 - 1000-m-thick layers on these curves and for Pluto's temperatures, Nabarro-Herring volume diffusion dominates (Duxbury and Brown 1997). For the higher pair of curves the volume self-diffusion coefficient of nitrogen ice is assumed to be equal to the average estimate from the measurements of Esteve and Sullivan (1981). For the lower pair the self-diffusion coefficient is taken at the upper limit from the same experimental measurements.

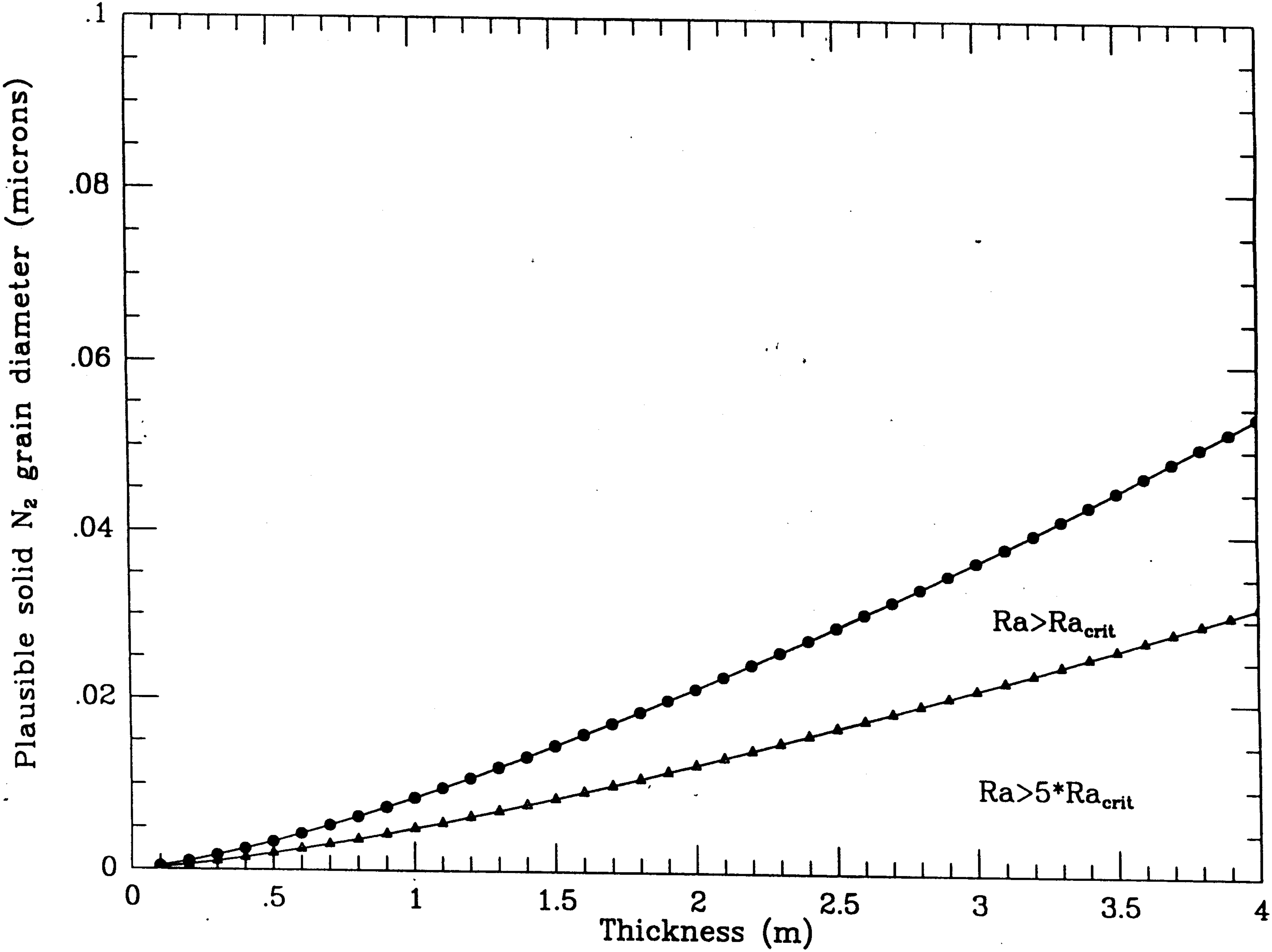
Fig. 2. Nitrogen grain diameters, assuming spherical grains, sufficiently small for thermal convection to start ($Ra = Ra_{critical} = 1100.65$) as a function of the thickness of a seasonal N_2 layer (the curve marked by filled circles). The second curve, marked by open triangles, shows nitrogen grain diameters sufficiently small for the Rayleigh number to be 5 times the critical value. Solely radiogenic heating is assumed. The average internal heat flow of $4.6 * 10^{-3} W/m^2$ is used for Pluto. This corresponds to an average thermal gradient of 0.023 K/m.

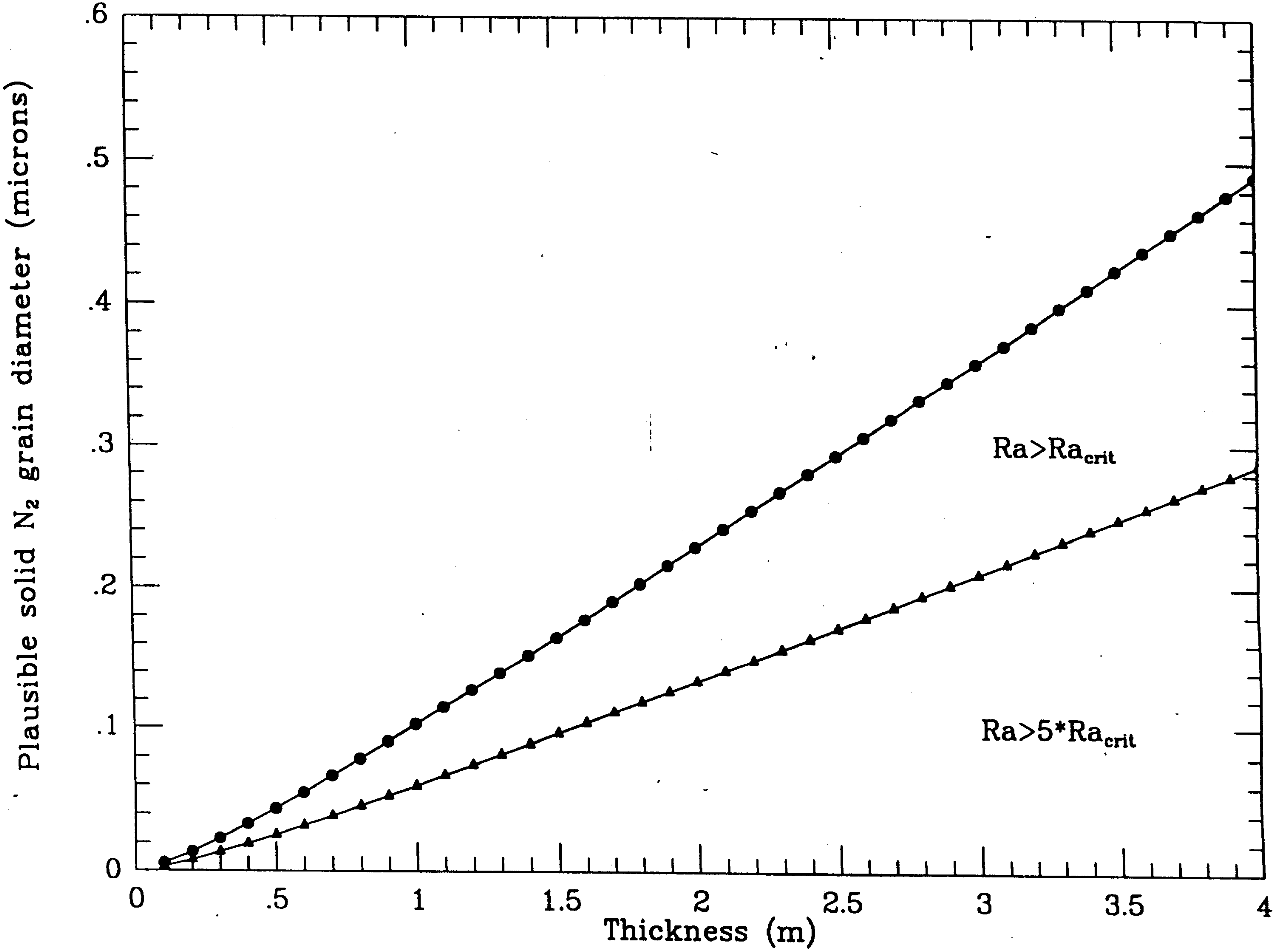
Fig. 3. N_2 grain diameters sufficiently small for thermal convection to start in a seasonal layer with the solid-state greenhouse effect (the curve marked by filled circles). The curve marked by open triangles shows N_2 grain diameters sufficient

to obtain $Ra = 5 * Ra_{critical}$. The "super" solid-state greenhouse effect is assumed with a dark underlayer having an albedo of 5%, thus giving the conductive gradient of 4 K/m. This is about 174 times more than the average thermal gradient of 0.023 K/m calculated using only radiogenic heating (Fig. 2). At those small grain sizes and Pluto's temperatures the Coble diffusion creep is dominating. Thus, we used in our calculations the dynamic viscosity proportional to the 3rd power of the grain size instead of the 2nd power as for the volume diffusion (Nabarro-Herring creep).

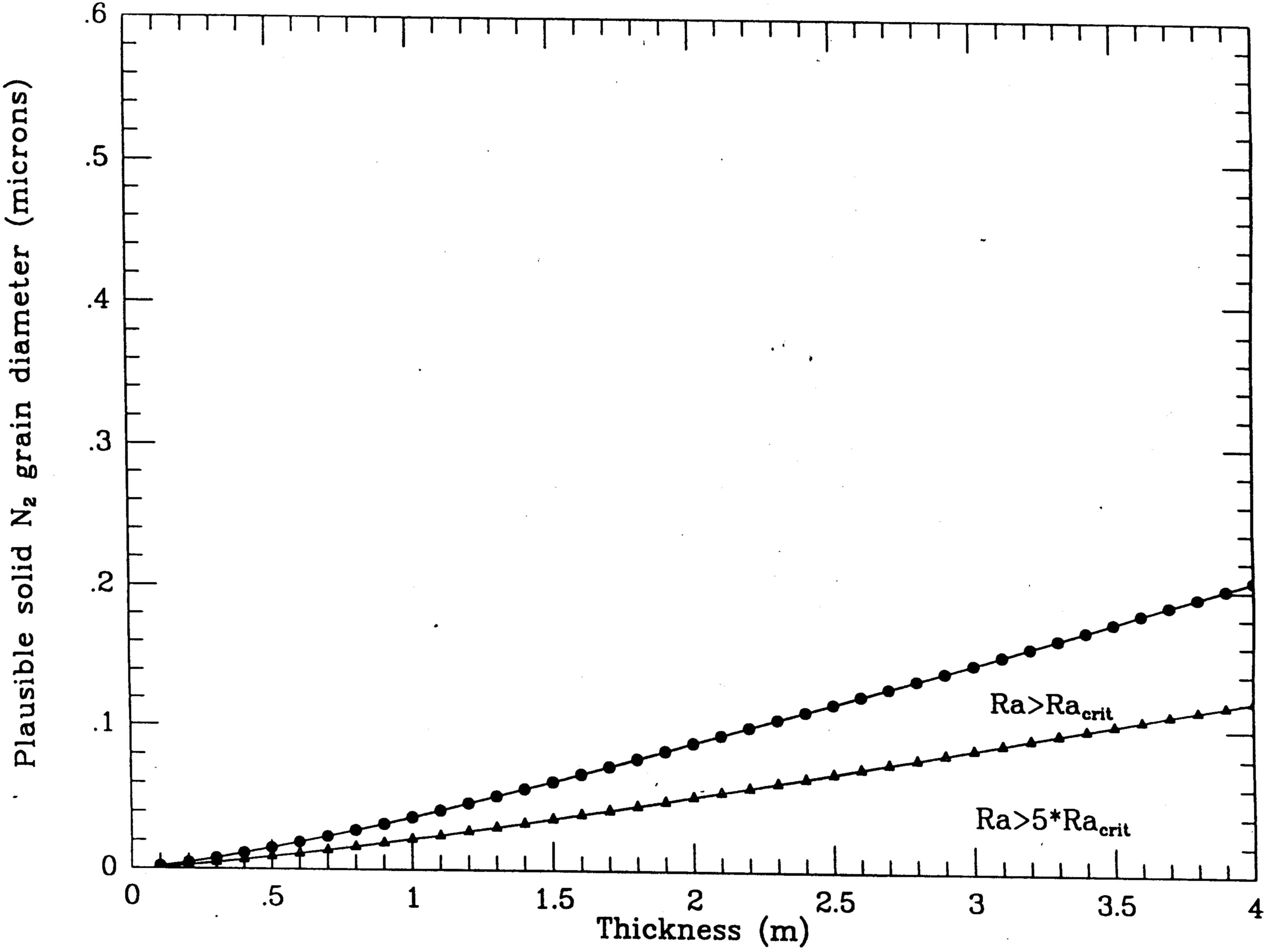
Fig. 4. Nitrogen grain diameters sufficiently small for thermal convection to start (the curve marked by filled circles) in a seasonal layer with the solid-state greenhouse effect. The "super" solid-state greenhouse effect is assumed with an intermediate value of 1 K/m for the conductive gradient (the dark underlayer having an albedo > 5%). The curve marked by open triangles shows N_2 grain diameters sufficient to obtain $Ra = 5 * Ra_{critical}$.


1000
800
600
400
200
0
Thickness (m)
0
.5
1
1.5
2
2.5
Plausible solid N₂ grain diameter (mm)


Plausible solid N_2 grain diameter (microns)
Thickness (m)
0
.02
.04
.06
.08
.1
0
.5
1
1.5
2
2.5
3
3.5
4
Ra>Ra$_{crit}$
Ra>5*Ra$_{crit}$



Duxbury et al. Fig 2


Plausible solid N_2 grain diameter (microns)
.6
.5
.4
.3
.2
.1
0
0
.5
1
1.5
2
2.5
3
3.5
4
Thickness (m)
$Ra>Ra_{crit}$
$Ra>5*Ra_{crit}$