TEMPERATURES AND TIME EVOLUTION OF HYPERVELOCITY IMPACT GENERATED TRACKS IN AEROGEL.
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Introduction: Aerogel collectors have been used to capture cometary, interplanetary, and interstellar dust grains by NASA's Stardust Mission, highlighting their importance as a scientific instrument. Due to the fragile and heterogeneous nature of cometary dust grains, their fragments are found along the walls of tracks that are formed during the capture process. These fragments appear to experience a wide range of thermal alteration [1] and the causes of this variation is not well understood at a theoretical level as physical models of track formation are not well developed. Here, I develop a general model of track formation that allows for the existence of partially and completely vaporized aerogel material in tracks. I show that under certain conditions, this general track model reduces to the kinetic "snowplow" model that has previously been proposed [2]. I show, based on energetic considerations, that track formation is dominated by an expansion that is snowplow-like in the later stages of track formation. The equation of motion for this snowplow-like stage can be solved analytically, thus placing constraints on the amount of heating experienced by cometary dust fragments embedded in track walls. I find that the heating of fragments, for a given impact velocity, is expected to be greater for those embedded in larger tracks. Given the expected future use of metal-oxide based solids for sample return missions, the results presented here also have clear implications for the choice and design of these collectors.

Energy Loss in Aerogel: The energy required for the formation of track in aerogel is provided by the energy loss of the captured projectile. To a good approximation, at high velocities v, this is given by:

$$\frac{dE}{dz} \simeq \frac{E(z)}{\lambda} \quad (1)$$

$$= C_d \rho_0 v^2 A \quad (2)$$

where ρ_0 is the aerogel density (~ 20 kg m^{-3} for Stardust aerogel), C_d is the drag coefficient of the projectile, and v is the instantaneous velocity of the projectile. and A is the cross sectional area. Near the surface of aerogel, C_d is expected to be ~ 1.

General Model of Track Formation: To derive this general model, one can consider the possibility that variable fractions of the projectile energy loss per unit length $\left(\frac{dE}{dz}\right)$ is transferred to the aerogel in the form of kinetic energy $\left(f_K \frac{dE}{dz}\right)$ and thermal energy $\left(f_Q \frac{dE}{dz}\right)$ and that some fraction (f_v) within the track volume is vaporized.

Kinetic and Thermal Energy Density: At any time in the track's evolution, the kinetic energy density $\left(f_K \frac{dE}{dz}\right)$ is given by:

$$f_K(t)\frac{dE}{dz} = \frac{1}{2}(1 - f_v)\frac{dm}{dz}v(t)_w^2 \quad (3)$$

where v_w^2 is the magnitude of the track wall velocity and $\frac{dm}{dz}$ is the total mass density of the track and f_v is the fraction of the total mass that exists in the vapor phase.

The thermal component of track energy density, $f_Q(t)\frac{dE}{dz}$, will be found in both the heat content of the track walls and any vapor found within the track (Here we consider no vapor production from the projectile's material). Accounting for all of these terms, one finds that:

$$f_Q(t)\frac{dE}{dz} = \overline{C_p}\Delta T(1 - f_v(t))\frac{dm}{dz} + \overline{C_p}\Delta T f_v(t)\frac{dm}{dz} + H_v f_v(t)\frac{dm}{dz} + \frac{f_v}{(\gamma - 1)}\frac{dm}{dz}\left(\frac{1}{\overline{m}_v}\right)k_b T_v(t) \quad (4)$$

Here $\overline{C_p}$ represents the average heat capacity of SiO_2 over the temperature range $\left(\Delta T = T_w^f - T_w^i\right)$ and H_v is the heat of vaporization of SiO_2. One should note that, ignoring energy loss due to radiative cooling or the leakage of vapor from the track walls, $f_Q(t)+f_K(t)=1$.

Energetics Constrains Allowed Values of f_v: Conservation of energy requires that the energy loss per unit length of the projectile, $\frac{dE}{dz}$, be balanced by the energy content of the track. At any given time, the total mass found within a track of radius r_T per unit length, $\frac{dm}{dz}$, is given by:

$$\frac{dm}{dz} = \rho_0 \pi r_T^2 \qquad (5)$$

where r_T is the track radius at that instant in time. This expression, together with the exponential expression for $\frac{dE}{dz}$ given by Equation (1), can be substituted into Equation to yield:

$$f_Q(t) C_d v_g(z)^2 r_g^2 = \left[\overline{C_p} \Delta T (1 - f_v(t)) + \overline{C_p} \Delta T f_v(t) + H_v f_v(t) \right] r_T(t)^2 \qquad (6)$$

If we assume that the track walls and SiO_2 vapor are in temperature equilibrium, then $\Delta T \simeq T_v$ in Equation and the temperature of the track walls and vapor is given by:

$$T_v(t) = \frac{\left[f_Q(t) C_d v_g^2 \left(\frac{r_g}{r_T(t)} \right)^2 - H_v f_v(t) \right]}{\left[\overline{C_p} + \left(\frac{f_v}{\gamma - 1} \right) \frac{1}{m_v} k_b \right]} \qquad (7)$$

By letting f_Q vary from 0-1 and $f_K = 1 - f_Q$, we can place tight constraints on the maximum values of f_v. When the temperature (T_v) of a track falls below the condensation temperature of a the aerogel material (SiO_2 in the case of Stardust), f_v=0. A plot of the temperatures as a function of r_T shows that a track has grown to about ~ 3 times the size of the projectile (v_g =6 km/s), $f_v \rightarrow 0$. The track expansion dynamics at this point should be governed by the dynamics predicted by the "snowplow" model of track formation (See Figure 1).

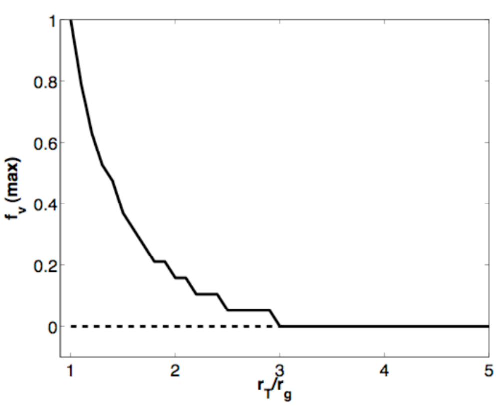

Figure 1 Maximum fraction of total track mass in vapor phase vs. normalized track radius.

Time Evolution of Track Size and Temperatures: Without knowing the detailed evolution of $f_Q(t)$, $f_K(t)$, and $f_v(t)$, it is still possible to constrain the duration and magnitude of track temperatures.

In the limit where the amount of thermal energy is maximized ($f_Q(t)$=1) and the amount of aerogel vaporized is minimized ($f_v \rightarrow 0$) , the maximum temperature of tracks can be obtained and the duration of this phase may be estimated. The results of this analysis are shown in the Figure below. A detailed analysis of these results are provided in [3].

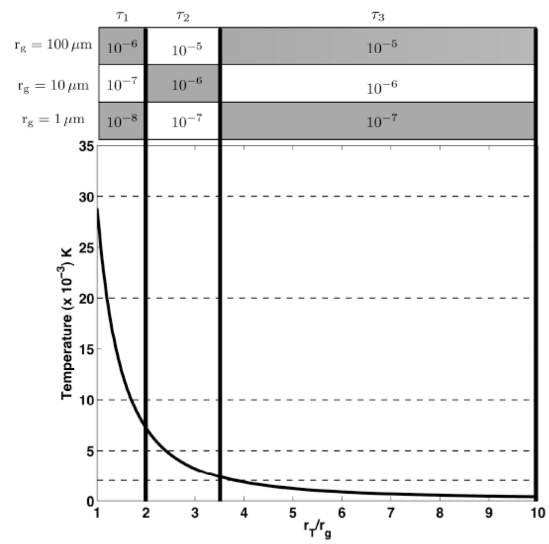

Figure 2. Maximum duration and temperatures of tracks in aerogel (v_g=6 km/s) as a function of normalized radius and time for projectiles of various sizes.

Temperature Gradients along the track:

Conclusions: The analysis of hypervelocity track presented shows that: 1) Vapor dominated track formation in aerogel is not possible due to energetic constraints and 2) A general model of track formation can be used to place quantitative predictions for track temperatures as functions of projectile velocity, track size, and time. These results should be of great interest to the Stardust community since they show at a quantitative level that the heating environment and potential for thermal alteration of captured fragments, as suggested by of [4] is heavily influenced by the location of fragments within a track.

References: 1.Zolensky, M.E., et al., Science, 2006, **314**(5806) 2.Dominguez, G., et al., Icarus, 2004, **172**3.Dominguez, G., Meteoritics & Planetary Science (submitted), 2009, 4.Roskosz, M., H. Leroux, and H.C. Watson, Earth and Planetary Science Letters, 2008, **273**(1-2)