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ATMOSPHERIC ENTRY HEATING OF COSMIC DUST

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Final Report

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ABSTRACT

A computer simulation of the atmospheric entry deceleration and heating for micrometeorites into a planetary atmosphere was developed. The results of this model were compared to an earlier model developed by Whipple and extended by Fraundorf. The major difference between the extent of heating experienced in the two models results from an underestimation of the atmospheric density at altitudes above 130 km in the earlier model. Thus the Whipple/Fraundorf model systematically overestimates the peak temperature reached on atmospheric entry. The discrepancies are small for near vertical entry and/or high density particles, where little deceleration is experienced at high altitudes. For particles entering at grazing incidence and/or of low density the discrepancies are more pronounced.

Gravitational enhancement, which is a function of geocentric velocity at the collection opportunity, was found to bias near earth cosmic dust collections in favor of low velocity particles. The effect is to increase the proportion of low velocity dust, predominately from asteroids, in the stratospheric cosmic dust collections and on earth orbiting spacecraft impact surfaces over its proportion in the interplanetary dust cloud. These collections, thus, do not represent an unbiased sample of the interplanetary dust. If, however, the velocity distribution of each particle type can be established the interplanetary abundances could be calculated knowing the near earth gravitational enhancement.

INTRODUCTION

Cosmic dust particles are micrometeorites which are sufficiently small (less than 100 micrometers in diameter) to enter the earth's atmosphere without melting. After deceleration by atmospheric drag, the particles descend into the stratosphere where they are concentrated because of their low settling rate in this region. They are collected from the stratosphere on small impact collection plates carried on U-2 and RB-57 aircraft in the NASA Cosmic Dust Sampling Program at the Johnson Space Center.

One catagory of collected dust is called "chondritic" because of the similarity of the major element abundances in these particles to those in the carbonaceous chondrite meteorites. Members of the chondritic class of cosmic dust have been shown to be extraterrestrial because of the presence of solar wind noble gases and solar flare radiation damage "tracks" in the particles. Although the major element abundances are generally similar to the primitive CI carbonaceous chondrites, enrichments in volatile elements above CI levels (van der Stap et.al., 1986) suggest the particles formed in a different region or at a different time in solar system evolution than the parent bodies of the CI meteorites. The chondritic particles, when examined on the microscale in the Transmission Electron Microscope (TEM), are seen to be aggregates of submicron or micron sized crystals (dominantly olivines, pyroxenes, or layer-lattice silicates) in an even finer grained carbon rich matrix. Examination of crystals within a given particle shows them to be hetrogeneous, non-equilibrium mixtures of minerals (Fraundorf, 1981). This suggests the particles are less metamorphosed than even the most primitive CI meteorites, and thus better sample the primitive solar nebula. It has even been suggested, principally on the basis of large Deuterium/Hydrogen fractionation, that the chondritic cosmic dust particles contain better preserved remnant interstellar grains than the most primitive meteorites (Clayton, 1986).

Larger samples of the same material would be valuable to constrain the process of solar system evolution. Thus one key objective in studying the cosmic dust is to determine its source or sources. The particles contain evidence of their exposure to the solar wind, which penetrates only a few hundred Angstroms into the surface, indicating they existed in space as small particles not much different from their size and shape as recovered from the stratosphere. These particles could not, however, have existed as small objects in space for the entire 4.5 billion years since the formation of the solar system. Poynting-Robertson drag, an interaction between the particles and solar radiation, causes particles in this cosmic dust size range to spiral into the sun in times of 10^4 to 10^5 years. Thus sources, active in the recent past, are required to provide the cosmic dust now being collected.

These sources, because of the primitive material which they contain, would be suitable targets for sample return missions. However the sources have not yet been identified. One of the major objectives of the Cosmic Dust Collection Facility, proposed for the Space Station, is to determine the velocity vector of each cosmic dust sample collected, and thus allow particles to be traced back to their individual sources. Prior to the launch of the Space Station, cosmic dust sources can only be inferred from the properties of the particles collected from the stratosphere.

In principle, almost every solar system object is able to contribute to the cosmic dust enviornment through outgassing, ejection due to cratering events, collisional fragmentation, tidal disruption, or volcanic activity. However the Infrared Astronomy Satellite (IRAS) has detected two major sources of dust in the solar system: the main asteroid belt and comets.

Particles from these sources can only be collected at earth when their orbits intersect the orbit of the earth. Generally the source orbits are not earth crossing. The orbit of the particle must then evolve from that of the parent body to an orbit which is earth intersecting. The dominant force causing this orbital evolution is Poynting-Robertson (PR) drag. Flynn (1986, 1987) has shown that, under the influence of PR drag particles arriving at earth from asteroidal and cometary sources differ significantly enough in their earth encounter geometry that they can be distinguished on the basis of the magnitude of their encounter velocity (though the full velocity vector, as will be measured on the Space Station Cosmic Dust Collection Facility, will be necessary to distinguish individual sources within the general catagories).

The major effect of PR drag is to decrease the aphelion of an initially elliptical orbit with little change in the perihelion until the orbit is near circular. Once the orbit is nearly circular the particle spirals into the sun. This effect is illustrated in Figure 1 for a particle released into the orbit of Comet Encke.

Particles originating in the main asteroid belt are initially in near circular orbits of relatively low inclination to the the plane of the earth's orbit. Under PR drag they spiral in towards the sun. The earth collection opportunity occurs when the particle orbit has a radius of about 1 AU. Thus collection is from a near circular orbit of low inclination, and the particle has a very low geocentric velocity at the collection opportunity.

Particles derived from comets divide naturally into two catagories. Those from comets with perihelia significantly larger than 1 AU have evolved to near circular orbits before the perihelion has decreased to 1 AU. Thus collection again occurs from a near circular orbit, giving a low geocentric velocity. However comet orbits are generally more highly inclined to the earth's orbital plane than are main belt asteroidal orbits. Thus collection occurs from an inclined orbit, resulting in a higher geocentric velocity at collection than for the main belt asteroidal case.

Particles from comets with smaller perihelia are collected from orbits which are still elliptical at the collection opportunity, thus giving rise to an even higher geocentric velocity at the collection opportunity. If the initial comet orbit is retrograde, as is the case for Comet Halley, the geocentric velocity at collection is still higher. The results, for main belt asteroids and a variety of comets, are given in Table I.

Since the heating experienced by each particle depends on its atmospheric entry velocity, particles from these three groups should experience different degrees of entry heating. Thus atmospheric entry heating may provide a suitable criteria to distinguish asterioidal from cometary sources.

Atmospheric Entry Heating

The first detailed model of atmospheric entry heating for micrometeorites was developed by Whipple (1950; 1951). He demonstrated that the peak temperature reached on atmospheric entry depends on the particle velocity, the angle between the normal to the earth's surface and the velocity vector at entry (with particles making more grazing entries being substantially less heated), as well as properties of the atmosphere and the particle itself. Fraundorf (1980), expanding on the Whipple model, derived a closed form solution for the probability that a particle would be heated above an arbitrary temperature T on entry given an entry velocity and assuming a random distribution of entry angles. Using the Fraundorf solution to the Whipple entry heating model Flynn (1987) showed that the entry temperature range from 500°C to 800°C is critical in distinguishing asteroidal from cometary materials. This is a temperature range in which pulse heating simulations of atmospheric entry heating confirm that many particle alterations occur. Among them are the loss of solar flare tracks through annealing, alteration to the structure of minerals (particularly layer-lattice silicates), and loss of volatile elements. These internal thermometers suggest that a large fraction of the chondritic particles recovered from the stratosphere derive from asteroidal sources. If true, this indicates a population of main belt asteroids significantly more primitive than sampled by the known meteorites. Indeed, the porous structure of the chondritic particles strongly indicates that larger meteors composed of this material would most likely fragment on entry, thus precluding recovery of larger samples among the meteorites.

If main belt asteroids are the sources of these primitive cosmic dust particles, than the asteroids may be as suitable as targets for primitive material sample return missions as the comets. However the distinction between asteroidal and large perihelion cometary sources rests on only a 100 to 200°C difference in the peak temperature reached on atmospheric entry. The purpose of this study was to review the Whipple/Fraundorf entry heating model, assess the uncertainties in its peak temperature predictions, and, where possible, improve upon the earlier model.

Entry Heating Model

The process of atmospheric deceleration and heating of micrometeorites was simply modeled by Whipple (1950). In this model the incoming dust particle (moving at somewhere in the range from 11 km/s, a lower limit imposed by gravitational infall acceleration, to 70 km/s, the upper limit for confinment in the solar system) is thought of as participating in single particle colisions with the air molecules. A dust particle moving at a velocity v and having a cross sectional area A will sweep out a volume of air V in a time interval dt which is given by:

$$V = A \cdot v \cdot dt \qquad \text{(Equation 1)}$$

If the air density at a particular height, h, is given by a function p(h), then the total mass of air encountered in the time interval dt is given by:

$$M = p(h) \cdot V = p(h) \cdot A \cdot v \cdot dt \qquad \text{(Equation 2)}$$

Although the individual air molecules are moving, on the average their velocity and momentum are zero. Interaction with the incoming particle alters the net momentum of the air molecules. At one extreme, a totally inelastic collision, the air is hit by the dust particle, sticks, and moves along with the particle, undergoing a net momentum change of M·v. At the other extreme, an elastic collision, the air molecule, initially approaching the dust particle with a velocity v in the rest frame of the particle, bounces off with a velocity v in the opposite direction. In this case the net change of momentum of the air molecule is

$2 \cdot M \cdot v$. Thus the air molecules gain (or the dust particle loses) an amount of momentum dP in the interval dt given by:

$$dP = L \cdot M \cdot v = L \cdot [p(h) \cdot A \cdot v \cdot dt] \cdot v \quad \text{(Equation 3)}$$

where L varies from 1 to 2 as the collision ranges from perfectly inelastic to elastic.

Since the particle must undergo a momentum loss of the same magnitude, the particle slows by an amount dv, given by:

$$dv = dP/m = L \cdot [p(h) \cdot A \cdot v \cdot dt] \cdot v \quad \text{(Equation 4)}$$

where m is the mass of the dust particle. Equation 4 gives the deceleration of the particle (dv/dt) for any height and velocity provided the variation of air density with height is known. With this deceleration the variation of the velocity with height can be calculated.

During the deceleration the dust particle will heat up if the collision process is not elastic. In an inelastic collision the excess kinetic energy is transformed into heat, which can be used to warm the particle or can be radiated away. The amount of heat lost, H, in the time interval dt, which depends on the particle temperature T, the surface area S, the emissivity e, and the Stefan-Boltzman constant b, is given by:

$$H = b \cdot e \cdot S \cdot T^4 \quad \text{(Equation 5)}$$

In that same time interval, if the particle has warmed or cooled from T_o at the start of the interval to T at the end of the interval an amount of heat, Q, must have been added or taken from the particle. If the particle has a specific heat C, the Q is given by:

$$Q = m \cdot C \cdot (T - T_o) \quad \text{(Equation 6)}$$

The energy gained by the particle, E, in the time interval dt is some fraction, K, of the total kinetic energy of the air molecules. K must, then, vary from 0 for the elastic case to 1 for the totally inelastic case. Since the kinetic energy of the air molecules is given by $0.5 \cdot M \cdot v^2$, the energy gained by the particle is

$$E = 0.5 \cdot K \cdot M \cdot v^2 \quad \text{(Equation 7)}$$

The temperature required for the dynamic equilibrium in which energy is radiated away as fast as it is added in the time interval is then obtained by equating the energy input E to the sum of the radiation loss H and the heat energy Q. This gives:

$$0.5 \cdot K \cdot M \cdot v^2 = b \cdot e \cdot S \cdot T^4 + m \cdot C \cdot (T - T_o) \qquad \text{(Equation 8)}$$

Since M is a function of height, as given by Equation 2, and v can be obtained as a function of height from the deceleration derived in Equation 4, Equation 8 can be solved to give the particle temperature as a function of height (or time). However, since M involves the atmospheric density p(h), Whipple found that Equation 8 could easily be solved in closed form with two assumptions:

1) the specific heat term is negligible, and can be ignored, and,

2) the atmosphere is isothermal, and of constant composition, so that p(h) varies exponentially with height.

Fraundorf followed these assumptions of Whipple to derive the probability that any given particle arriving at earth with a random orientation but specified velocity would be heated above a temperature T.

In order to apply the Whipple model values of the drag parameter, L, the accomodation coefficient, K, and the emissivity, e, had to be assumed. Following the earlier work, these were all taken to be 1. In order to assess the validity of the model each of these assumptions was considered separately.

Drag Parameter

Whipple argued that the collisions were likely to be very close to pure inelastic collisions since the energy of each air molecule in the dust particle's reference frame is tens to hundreds of eV. Thus air molecules will penetrate several atomic layers into the particle before stopping. Although these air molecules may eventually boil off as the particle heats up, the collision process is essentially inelastic.

An alternative way to look at the interaction of the dust particle with the air is in the context of normal aerodynamic drag. In this context, the drag force, F, is given in terms of the drag coefficient, D, of the particle by:

$$F = 0.5 \cdot D \cdot A \cdot p(h) \cdot v^2 \qquad \text{(Equation 9)}$$

Since the drag force can be rewritten as the time rate of change of the momentum (dP/dt), the momentum loss dP in the time interval dt is given by:

$$dP = 0.5 \cdot D \cdot A \cdot p(h) \cdot v^2 \cdot dt \qquad \text{(Equation 10)}$$

Equation 10 is identical to Equation 3 when the drag parameter L is identified as 0.5 times the drag coefficient.

Although drag coefficients have not been measured for objects in the cosmic dust size range in air densities comparable to the upper atmosphere, they have been derived for orbiting satellites on the basis of the rate of their orbital decay. King-Hele (1964) argues that for satellites of a variety of shapes, ranging from spheres to tumbling cylinders, the drag coefficient can be taken to be equal to 2.2 ± 5%. This implies a value of the drag parameter L equal to 1.1, a 10% increase from the assumed value of 1. The effect of increasing the drag parameter by 10% is to decrease the maximum temperature on entry by 2.5%, an insubstantial correction. Thus the value of 1 assumed by Fraundorf seems not to be in serious error.

Accomodation Coefficient

If the value of the drag parameter is taken as near 1, then the accomodation coefficient cannot dramatically differ from 1. The two are related in that if the air molecules stick to the particle surface then they must transfer all their kinetic energy to the particle.

Emissivity

For the emissivity a value of 1, indicating a perfect black body, was adopted by Whipple and Fraundorf. Optical microscope observation of the cosmic dust recovered from the stratosphere indicates a black color for many particles, consistent with a high absorptivity (and thus emissivity) in the visible region of the spectrum. In the infrared, absorption spectra indicate a substantial fraction of the incident light is absorbed at all wavelengths. While the results have not been quantified by the investigators in the IR absorption experiments, the results are consistent with high IR absorption even on particles crushed and spread out in order to reduce their thickness. The peak of the black body emission curve for objects in the 1000 K to 1500 K varies from 2 to 3 micrometers, substantially smaller than the typical particle dimensions of 10 to 25 micrometers. While there is not a direct measurement of the emissivity of these particles in the IR region, the available data is consistent with an emissivity not substantially below 1. Reducing the emissivity to 0.8 would increase the peak temperature on entry by 5.7%, again a negligible effect.

Atmospheric Density

Whipple assumed an exponential decrease of mass with height, consistent with an isothermal atmosphere of constant composition, in the absence of good experimental determinations. Fraundorf followed this approach because it permits a closed form solution to the entry heating equations. However, since Whipple's 1950 model, a substantial body of data on the density of the upper atmosphere has become available. A comparison of the U.S. Standard Atmospheres (1962) density with the exponential approximation (Figure 2) shows reasonable agreement up to about 130 km. Above that the U.S. Standard Atmosphere is significantly more dense, and thus has more stopping effect, than the exponential model.

To assess the magnitude of this effect a computer simulation of the entry heating was performed. In this simulation the entry heating dynamics proceed as described for the Whipple/Fraundorf model, except that at every height the atmospheric density is read from the U.S. Standard Atmospheres data table rather than using the exponential approximation. During the time when the particle is experiencing significant heating a 2/100 sec time intrerval was employed in the simulation.

Under the effect of gravitational infall, the velocity profile of a particle starting from 2×10^8 meters with a velocity of 10 km/s was calculated in the absence of an atmosphere. The same velocity profile was then calculated for a spherical dust particle of 20 micrometer diameter and density 1 gm/cm^3 encountering the U.S. Standard Atmospheres density profile. The results, shown in Figure 3, show that the dust particle reaches its maximum velocity at 176 km above the surface, indicating that it is already experiencing significant deceleration at that height. At that time the atmospheric density is an order of magnitude higher in the U.S. Standard Atmospheres table than in the exponential approximation. This indicates the exponential approximation may be a source of significant overestimation of the peak temperature reached on entry.

A direct comparison of the peak temperatures reached on normal incidence entry gives 1185 K in the Whipple/Fraundorf model versus 1159 K in this model. The effect appears to be small, however it difference between the two approaches would be expected to increase for grazing entry conditions, when the particles spend a longer time in the outer regions of the atmosphere.

To provide a direct comparison, the computer simulation was modified to allow the impact parameter (the distance of the incoming particle from a line through the center of the earth and parallel to the particle trajectory), d, of the incoming dust particle to be varied. Varying the impact parameter is the equivalent of assuming a random distribution of velocity vector orientations with respect to the top of the atmosphere. The impact parameter was varied in uniform 0.5×10^5 meter steps from zero until earth collection was no longer possible. (This maximum impact parameter varies with the velocity of the incoming particle as will be described in the section on Gravitational Focusing).

The fraction of particles not heated above a temperature T was calculated using both the computer simulation and the Fraundorf equations. The results, shown in Table II, indicate that the most serious discrepancies between the two models are at grazing incidence (which corresponds to low peak temperatures). The computer simulation gives an increase by a factor of 20, from 0.1% to 2%, in the fraction not heated above 236°C for example. Similar large differences are seen between the models for particles of very low density, since these particles experience considerable deceleration in the outer regions of the atmosphere, where the air density is significantly underestimated by the exponential model.

The peak temperature versus impact parameter is shown in Figure 4 for a 20 micrometer diameter, density 1 gm/cm^3 particle. esults are shown for three different starting velocities 1 km/s, 10 km/s, and 20 km/s. If 1200 K is taken as the melting temperature for the lowest temperature minerals in the particles, then virtually all particles with a geocentric velocity (before gravitational infall acceleration) of 20 km/s would be expected to show signs of melting. The temperature for solar flare track annealing is reported as 800 to 900 K (Fraundorf et.al., 1982), indicating that virtually all particles of this size and density with a geocentric velocity of 10 km/s would lose their solar flare tracks on entry. The presence of solar flare tracks in a large fraction of the stratospheric cosmic dust particles thus indicates a rather low geocentric velocity (no more than a few km/s) at collection. This is consistent with an asteroidal source for the majority of the particles collected at earth.

Gravitational Focusing

Perhaps the most striking feature of Figure 4 is the dramatic increase in the maximum impact parameter from which earth collection is possible as the geocentric velocity decreases. The earth effectively presents a bigger target for low velocity particles than for particles of higher velocity. Opik (1951) pointed out that the cross-section for collection of a small particle by a larger body varies with the relative velocity, v, between the two particles and the escape velocity, v_e, from the large object. This cross-section is given by:

$$CR = 3.14 \cdot R^2(1 + v_e^2/v^2) \quad \text{(Equation 11)}$$

where R is the radius of the larger object. For the case of cosmic dust being collected at or near earth from the asteroidal and cometary sources previously discussed, the effective cross-sections are given in Table I. The gravitational enhancements, that is the ratios of the effective cross-sections to the geometrical cross section, range from 126 for 1 km/s asteroidal dust to 1 for the highest velocity cometary dust from Halley.

This near earth gravitational enhancement indicates that if any particles with low geocentric velocities exist among the interplanetary dust, the proportions of those particles will be substantially enhanced relative to higher geocentric velocity particles in any near earth collection process. Thus the near earth collectors (stratospheric or satellite) do not provide an unbiased sample of the interplanetary dust cloud. Near earth collection is heavily biased towards the low geocentric velocity fraction of the interplanetary dust.

The actual distribution of velocities for particles in the cosmic dust size range has never been measured. These particles are not sufficiently heated on entry to produce luminous or ionized trails, which are the basis for detection of visual or radar meteors. The radar meteors, which are the smallest size meteors routinely detected, begin at about 100 micrometer diameter and range upwards in size. These meteors have a mean geocentric velocity (before gravitational infall) of 9 km/sec (Southworth and Sekanina, 1973). However there is reason to believe that particles smaller than 100 micrometers in diameter may differ in source, and thus in velocity distribution, from the larger micrometeorites (Flynn, 1987; Zook and McKay, 1986). If so, the radar meteor data for larger micrometeorites would not be indicative of the distribution for particles in the cosmic dust size range.

The observation of microcraters, in the size range produced by cosmic dust particles, on exposed lunar rock surfaces indicates that a large majority of the incoming particles in this size range have sufficient velocity to produce craters. However simulations indicate that a dust velocity of 3 km/s is sufficient to produce glass lined microcraters (Ashworth, 1978). This is not significantly higher than the earth-moon system escape velocity from the lunar surface, thus it does not significantly constrain the in space velocity of the cosmic dust particles.

The degree of near earth enhancement of the micrometeorite flux may provide the most significant constraint on the abundance of low geocentric velocity dust in the interplanetary dust cloud. Micrometeorite penetration detectors of similar design were flown on two earth orbiting satellites, Explorer XVI and Explorer XXIII, and on the five Lunar Orbiters. Each satellite carried pressurized-cell penetration detectors with 25 micrometer thick walls, thus measuring particles in the cosmic dust size range. The penetration rates, corrected for satellite and earth shielding, were 0.445 events/m^2·day and 0.526 events/m^2·day respectively (Naumann, 1966). The corresponding shielding corrected penetration rate for the five Lunar Orbiters was 0.19 events/m^2·day (Grew and Gurtler, 1971). These penetration rates imply a near earth enhancement over the lunar flux of 2.3 to 2.8. When corrected for the small enhancement at the moon, due to its own gravitational field, the earth enhancement over the interplanetary flux at 1 AU would be from 2.5 to 3.0.

There is considerable uncertainty in the near earth enhancement factor because of the small number of penetration events (only 22 for the five Lunar Orbiters) detected over the operational lifetimes of the satellites. In addition, the reported lunar flux may be too high due to secondary debris from lunar surface impacts striking the Lunar Orbiter spacecraft. However, taking 2.8 as the current best estimate of the near earth enhancement does apply some constraints to the velocity distribution, and thus the possible sources, of the cosmic dust.

This observed near earth enhancement clearly excludes a micrometeorite population composed solely of particles from cometary sources with samll perihelia. As seen in Table I, these sources all supply particles with enhancement factors below 2. This enhancement also appears to exclude a completely asteroidal population, since a minimum enhancement of 6 would be expected in that case. However, recent results by Gufstafson and Misconi (1986) suggest that earth scattering of asteroidal particles before the collection opportunity may increase the inclinations and ellipticities of their orbits substantially above those calculated by PR drag alone. Thus the geocentric velocities of the asteroidal particles at the collection opportunity are presently somewhat uncertain. This should improve as the process of earth scattering is better simulated.

A single source model is unrealistic in any case, since the IRAS measurements demonstrate that both comets and main belt asteroids make significant contributions to the interplanetary dust. We can place some limits on the proportions of dust from low and high velocity sources by requiring that the overall gravitational enhancement equal the observed value of 2.8. If we consider the dust to be composed of two components, one with a relatively high geocentric velocity, and the second with lower geocentric velocity, we can calculate the proportions of dust which would be observed on near earth collectors for any given interplanetary mixture. For the high velocity component I have taken dust with an enhancement factor of 1.2, the value appropriate for dust from Comet Encke.

If the interplanetary dust cloud were to consist of 99% material from this source and 1% material from a low velocity source, then an enhancement factor of 160 would be required for the low velocity component in order to produce the observed overall enhancement of 2.8. If the low velocity source had a single velocity, a velocity of 0.9 km/s would be required to produce this enhancement. In this case, although the space proportions were taken as 99% high velocity dust and 1% low velocity dust, near earth collectors would see a flux of 57% low velocity and 43% high velocity dust because of the dramatic near earth enhancement of the low velocity component. The results for a variety of other interplanetary mixtures are given in Table III.

The extent of the near earth collection bias is clearly seen in Table III. If the high velocity component has an enhancement of only 1.2, then to produce the observed overall enhancement of 2.8 results in a near earth collection dominated by low velocity dust for any interplanetary mixture of the two components. If the high velocity component is assumed to have a higher enhancement, such as the 1.7 for d'Arrest, the required low velocity enhancement is decreased. However the fraction of low velocity material collected near earth is still dramatically enhanced over the interplanetary proportions.

Near earth cosmic dust collections are dramatically biased towards the collection of the low velocity component of the interplanetary dust cloud. Detailed measurements on the velocity distribution of the near earth flux will allow the extent of the bias to be evaluated.

Conclusions

The atmospheric entry heating model developed by Whipple and extended by Fraundorf accurately assesses the entry heating of cosmic dust particles of moderate or higher density and for incidence angles near the normal. As the particle density decreases or the entry angle approaches a grazing condition the Whipple/Fraundorf model systematically overestimates the peak temperature reached on entry since there is then substantial deceleration in the upper region of the atmosphere, a region where their use of an exponentially decreasing atmospheric density underestimates the deceleration. For particles of density 1 gm/cm^3 the differences between this simulation and the closed form solution of Whipple and Fraundorf are not significant enough to alter the conclusion in Flynn (1987) that, based on the heating experienced on atmospheric entry, the majority of the chondritic cosmic dust collected from the stratosphere encountered the earth with a low geocentric velocity. This is consistent with an asteroidal origin for the chondritic cosmic dust, and distinctly different from what would be expected for dust derived from comets with small perihelia (such as Eecke) and evolving into earth intersecting orbits under the Poynting-Robertson drag force.

Gravitational enhancement of the flux of low velocity dust produces a bias in near earth collections. The effect is to enhance the proportions of asteroidal dust, and to a lesser extent dust from large perihelion comets, relative to that of dust from the large perihelion comet population in interplanetary dust cloud. Thus, if main belt asteroids contribute at all to the the interplanetary dust cloud, the expected low geocentric velocity of dust from this source would produce substantial enrichment of this material in the stratospheric and satellite collectors. The cosmic dust collected from the stratosphere or on impact surfaces of earth orbiting spacecraft does not represent an unbiased sample of the material making up the interplanetary dust cloud. The true proportions of the interplanetary cloud material can be inferred from the near earth collections if the velocity distribution, and thus the gravitational enhancement, of each particle type is established.

Table I

Relative Velocity at Earth Collection and Earth Enhancement For Dust From Asteroidal and Cometary Sources

(Particle: Density 1 gm/cm^3, Diameter 20 micrometers)

Parent Object Orbit	Geocentric Velocity* (km/s)	Near-Earth Enhancement**
Main Belt Asteroid		
Circular, 0° Inclination	1	126
Circular, 6° Inclination	3	15
Circular, 10° Inclination	5	6
Comets (perihelia > 1.2 AU)		
Giacobini-Zinner	19	1.3
d'Arrest	13	1.7
Halley	64	1.0
Swift-Tuttle	51	1.0
Comets (perihelia < 1.2 AU)		
Kopff	6	4.4
Temple I	8	2.9
Temple II	9	2.5

* Gravitational infall velocity not included.

** Ratio of earth collection cross-section to geometric cross-section.

Table II

Fraction of Particles Not Heated Above Temperature T

(Particle: Density 1 gm/cm^3, Diameter 20 micrometers, Velocity 20 km/s)

Temperature (°C)	Fraundorf (1980)	This Model
236	0.1%	2%
406	1%	4%
471	2%	6%
545	5%	10%
615	10%	16%
680	17%	26%
781	39%	50%
841	57%	75%
870	75%	90%

Table III

NEAR EARTH ENHANCEMENT

High Velocity Fraction*	.99	.90	.75	.50	.25	.10	.01
Low Velocity Fraction	.01	.10	.25	.50	.75	.90	.99
Near-Earth L/H**	57/43	61/39	68/32	79/21	90/10	96/4	99/1
Low Velocity Enhancement	160	17	7.6	4.4	3.3	3.0	2.8
Charactaristic Velocity (km/s)	0.9	2.8	4.4	6.1	7.3	8.0	8.3

* The High Velocity fraction has an assumed enchancement factor of 1.2, corresponding to Encke dust.

** Collected Proportions of Low Velocity/High Velocity Dust

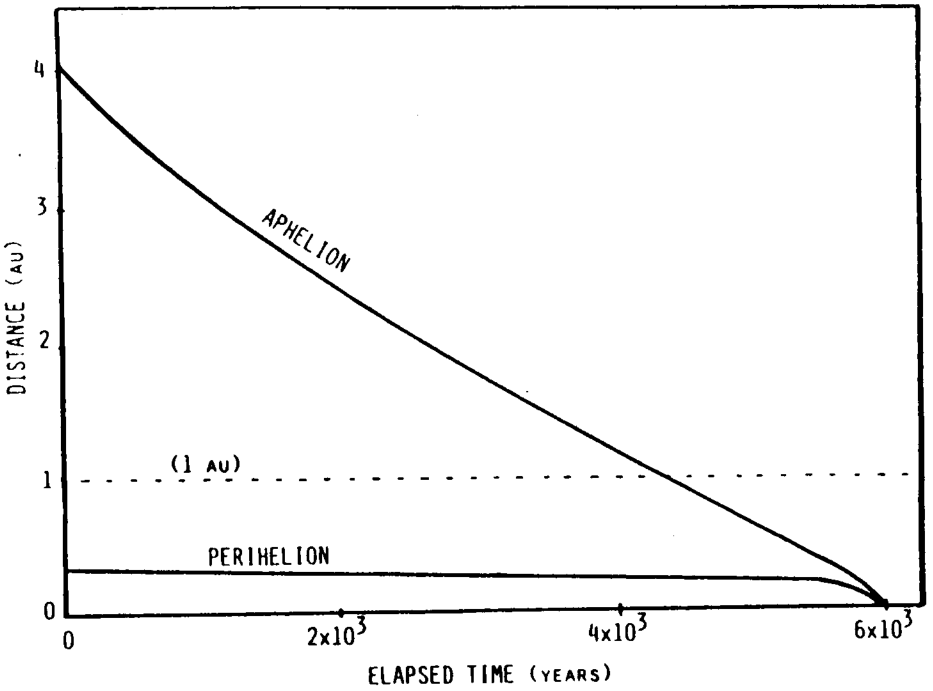

FIGURE 1. Orbital evolution for a 20 μm diameter, density 1 gm/cm^3 dust particle released into the orbit of Comet Encke under the influence of Poynting-Robertson drag.

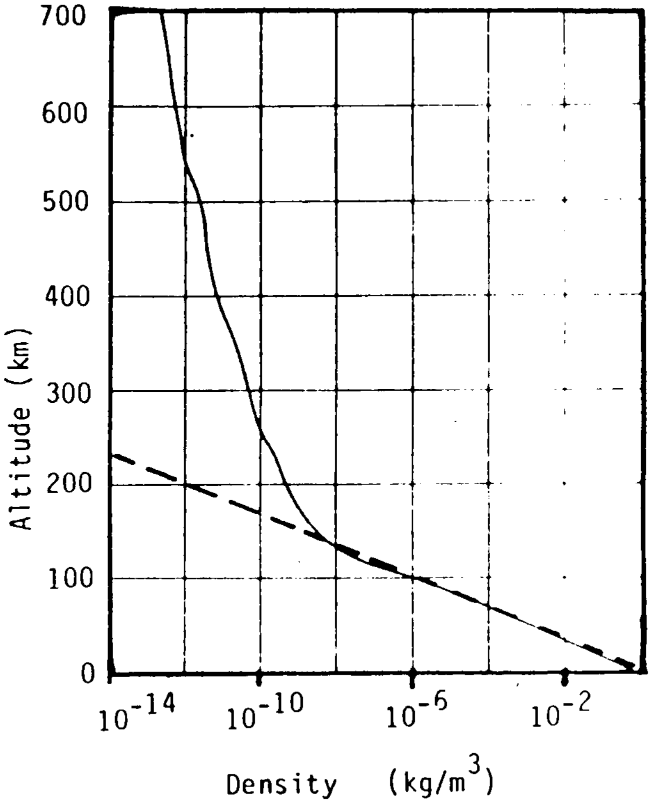

Figure 2. Comparison of the atmospheric density variation with altitude for the U.S. Standard Atmosphere (1962) (solid line) and the exponential approximation (dashed line).

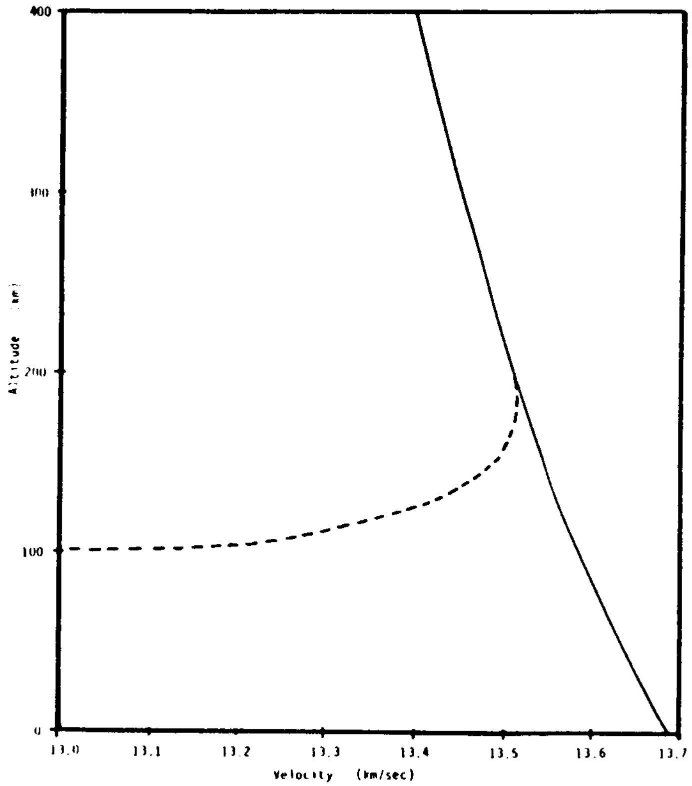

Figure 3. Velocity versus altitude for a particle released from infinity with a velocity of 10 km/s towards earth (solid line) and for the same particle encountering the U.S. Standard Atmosphere(1962) atmosphere. Particle: diameter 20 µm, density 1 gm/cm^3.

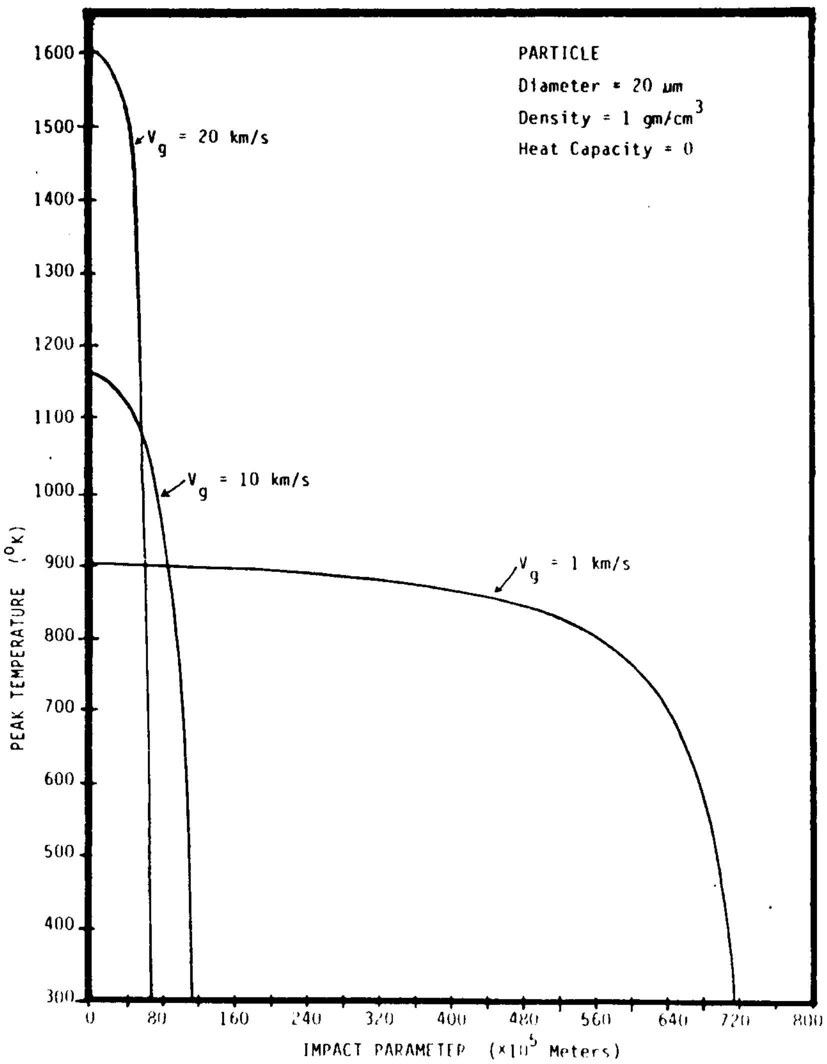

Figure 4. Peak temperature as a function of impact parameter for particles having velocities of 20 km/s, 10 km/s, and 1 km/s towards earth at 6 x 10^8 meters from earth.

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