The entry heating and abundances of basaltic micrometeorites

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Abstract—Basaltic micrometeorites (MMs) derived from HED-like parent bodies have been found among particles collected from the Antarctic and from Arctic glaciers and are to date the only achondritic particles reported among cosmic dust. The majority of Antarctic basaltic particles are completely melted cosmic spherules with only one unmelted particle recognized from the region. This paper investigates the entry heating of basaltic MMs in order to predict the relative abundances of unmelted to melted basaltic particles and to evaluate how mineralogical differences in precursor materials influence the final products of atmospheric entry collected on the Earth’s surface. Thermodynamic modeling is used to simulate the melting behavior of particles with compositions corresponding to eucrites, diogenites, and ordinary chondrites in order to evaluate degree of partial melting and to make a comparison between the behavior of chondritic particles that dominate the terrestrial dust flux and basaltic micrometeoroids. The results of 120,000 simulations were compiled to predict relative abundances and indicate that the phase relations of precursor materials are crucial in determining the relative abundances of particle types. Diogenite and ordinary chondrite materials exhibit similar behavior, although diogenite precursors are more likely to form cosmic spherules under similar entry parameters. Eucrite particles, however, are much more likely to melt due to their lower liquidus temperatures and small temperature interval of partial melting. Eucrite MMs, therefore, usually form completely molten cosmic spherules except at particle diameters \( < 100 \, \mu m \). The low abundance of unmelted basaltic MMs compared with spherules, if statistically valid, is also shown to be inconsistent with a low velocity population (12 km s\(^{-1}\)) and is more compatible with higher velocities which may suggest a near-Earth asteroid source dominates the current dust production of basaltic MMs.

INTRODUCTION

Micrometeorites (MMs) are extraterrestrial dust particles <2 mm in size that are recovered from the Earth’s surface (Genge et al. 2008) and provide valuable samples of solar system small bodies that include parent bodies not sampled by asteroids. Micrometeorites have been collected from Antarctic blue ice and snow, Antarctic traps, and aeolian deposits (Maurette et al. 1991; Taylor et al. 2000; Duprat et al. 2007; Rochette et al. 2008) and from deep sea sediments (Brownlee 1985). The most pristine collections of cosmic dust, least affected by terrestrial weathering, are from Antarctica.

The majority of MMs are thought to represent samples of primitive asteroids similar to the parent bodies of the carbonaceous and ordinary chondrite meteorites (Kurat et al. 1994; Genge et al. 1997, 2008; Cordier et al. 2011a). These particles often represent fragments of individual components of these meteorites such as CAIs, chondrules, and fine-grained matrix (Genge et al. 2005). Nonchondritic MMs are...
exceedingly rare and to date comprise only basaltic particles with compositional affinities to the HED meteorites (Taylor et al. 2007; Gounelle et al. 2009; Cordier et al. 2011b, 2012; Cordier and Folco 2014).

Micrometeorites experience heating during their atmospheric entry that can obscure their primary mineralogical and textural characteristics. Many particles experience partial melting to produce vesicular scoriaceous MMs, while a significant proportion almost entirely melt to produce cosmic spherules (Genge et al. 2008). While a significant proportion of small chondritic MMs survive atmospheric entry without significant melting, unmelted basaltic MMs are rare. Only a single unequivocal unmelted basaltic particle, supported by oxygen isotope analyses, is reported among several thousand particles from the Cap Prudhomme collection (Gounelle et al. 2009). Four unmelted basaltic particles, however, were also reported from Novaya Zemlya glacial deposits (Badjukov et al. 2010). Unmelted basaltic MMs are a class of coarse-grained MM that have grain sizes of similar order of magnitude to particle size. Extraterrestrial basaltic particles have also been found within the impact layer associated with the 4 Ma Eltanin impact (Kyte and Brownlee 1985), illustrating that particles from larger meteoroids can be locally present complicating the interpretation of the micrometeorite flux.

Cordier et al. (2012) reports that basaltic cosmic spherules have glassy textures and attributes this characteristic to the lower melting temperatures of iron-bearing silicates found in these basaltic materials. However, given that peak temperature is a function of entry velocity, entry angle, and particle size (Love and Brownlee 1991), the observation that basaltic MMs have largely glassy textures could also imply they are derived from a dust source with higher geocentric velocity than the average for chondritic particles.

The effect of solidus and liquidus temperatures on the relative abundance of MM types has not yet been investigated and yet might significantly affect the relative abundance of types among unmelted particles. Understanding the magnitude of such effects is important if the relative abundance of particles recovered from the Earth’s surface is to be related to that of their parent bodies. If, for example, basaltic MMs are less likely to survive atmospheric entry heating without melting than chondritic particles, their abundance among unmelted MMs will be underestimated, while among melted particles, their abundance will be enhanced. Basaltic micrometeorites have a relatively simple mineralogical variation from orthopyroxene-dominated diogenites, to plagioclase and clinopyroxene-dominated eucrites, allowing the effect of precursor mineralogy on survivability of atmospheric entry to be investigated. Particularly important in the nature of the final recovered particle is the partial melting behavior of such materials. To date, no atmospheric entry heating model has considered the effect of partial melting on the abundances of MMs.

In this paper, a numerical model of the atmospheric entry of basaltic and chondritic igneous objects is presented that specifically considers partial melting behavior and precursor mineralogy of MMs. The results allow the effect of entry heating on relative abundance of chondritic and basaltic MMs to be assessed and the proportions of basaltic unmelted, partially melted scoriaceous, and melted cosmic spherules to be predicted.

### METHODS

#### General Numerical Model

The numerical treatment of atmospheric entry heating used in this paper is based on the model of Love and Brownlee (1991). The equation of motion of a micrometeoroid entering the Earth’s atmosphere are described, for a spherical particle, by Equation 1. Symbols used in equations in this paper are summarized in Table 1. The deceleration term is calculated from the momentum loss of the particle due to collision with a mass of atmospheric gas molecules equivalent to a cylinder of length equal to the speed of the particle and of a diameter equal to that of the particle. This term is a function of atmospheric density, particle density, particle radius, and velocity. This formulation of deceleration is based on the assumption that gas flow is within the free molecular flow regime where no development of a bow shock occurs by interaction of backscattered with incident molecules. This is valid, given the mean free path of atmospheric molecules, for particle sizes less than ~1 mm.

| Symbol | Value |
|---|---|
| $m$ | Mass |
| $t$ | Time |
| $v$ | Velocity |
| $\rho_a$ | Density of atmosphere |
| $\rho_m$ | Density of particle |
| $c$ | Specific heat capacity |
| $\sigma$ | Stefan-Boltzmann constant |
| $\varepsilon$ | Thermal emissivity |
| $T$ | Temperature |
| $L_v$ | Latent heat of vaporization |
| $m_{mol}$ | Mean molecular mass of evaporated species |
| $A, B$ | Dimensionless Langmuir constants |
\[
\frac{\partial r}{\partial t} = \frac{1}{4\pi \rho_m r^2} \frac{\partial m}{\partial t}
\] (1)

Solution of the equations of motion depend on the calculation of atmospheric density, which varies with altitude, and particle radius, which changes due to evaporation of the particle during heating. Atmospheric density was calculated by linear interpolation of the 1976 U.S. Standard Atmosphere Model for the stratosphere and requires calculation of altitude of the particle.

The calculation of altitude depends on the trajectory of the particle, which was calculated by independent solution of equations of motion of the particle on orthogonal axes. Particles with low entry angles can pass directly through the atmosphere, performing a grazing incidence encounter, and their altitude thus increases in the final half of their trajectory. Deceleration during such aerobraking maneuvers results in a subsequent re-entry if the exit velocity is less than escape velocity. The re-entry velocity of the particle is considered equal to the exit velocity in these simulations. The cooling of particles outside the atmosphere was calculated assuming heat loss by thermal radiation with no solar insulation using an analytical expression for flight time derived from an elliptical orbit defined by the exit velocity and angle. A minimum entry angle of 10° from horizontal was used for simulations to minimize the number of computationally expensive grazing incidence encounters that needed to be considered. The maximum affect on the proportion of unmelted particles introduced by this limit is 3%.

The rate of change of radius of particles can be expressed in terms of mass loss by evaporation by:

\[
\frac{\partial r}{\partial t} = \frac{1}{4\pi \rho_m r^2} \frac{\partial m}{\partial t}
\] (2)

Surface temperature of the particle can be calculated by consideration of heat flux due to collision of air molecules with the particle, and heat losses by evaporation and thermal radiation. This treatment of energy flux specifically assumes the particle is thermally homogeneous, an assumption shown to be generally true by Love and Brownlee (1991) and only not appropriate where decomposition of volatile-bearing phases acts as an energy sink (Genge 2006). Energy lost by evaporation can be calculated from the evaporation rate and the latent heat of evaporation \( L_v \). The present model does not consider melting to be a significant heat sink since the latent heat of fusion is two orders of magnitude smaller than that of evaporation. The heat flux of an evaporating micrometeoroid during atmospheric entry can be described by:

\[
\frac{\partial q}{\partial t} = \frac{\pi r^2 \rho_a v^3}{2} - L_v \frac{\partial m}{\partial t} - 4\pi r^2 \sigma c T^4
\] (3)

An expression for surface temperature can then be generated by consideration of the specific heat capacity of the particle since:

\[
\frac{\partial q}{\partial T} = mc
\] (4)

\[
\frac{\partial T}{\partial t} = \frac{\partial q}{\partial t} \frac{\partial T}{\partial q}
\] (5)

These equations give an expression for temperature change.

\[
\frac{\partial T}{\partial t} = \frac{1}{rc \rho_m} \left( \frac{3\pi r^2 v^3}{8} - 3c L_v e^{A - B/T} \sqrt{m_{mol}/T - \sigma c T^4} \right)
\] (6)

The Langmuir formula is used to calculate mass loss by evaporation using values of \( A = 9.6, B = 26,700 \) and a mean molecular mass \( m_{mol} \) of 45 following the treatment of Love and Brownlee (1991). The latent heat of vaporization is taken as \( 6.05 \times 10^6 \text{ J Kg}^{-1} \). Although this treatment of evaporation is not as rigorous as those that consider separate vapor pressures for each volatizing species (e.g., Vondrak et al. 2008) it is an acceptable simplification for calculations requiring large numbers of simulations.

With a system of simultaneous partial differential equations describing the velocity components, altitude, radius, and temperature a solution can be approximated by numerical simulation. In this study, the Runge-Kutta 4th order method was used to numerically integrate the expressions. A time step was chosen such that temperature changes by less than 5% in a single timestep. Typical timesteps varied between 0.1 to 0.005 s and simulations were achieved in 500 to 5000 timesteps. Repeat simulations with different timesteps indicate variation of peak temperature by less than 2%.

**Simulation of Melting**

An important consideration in evaluating the proportions of unmelted, partially melted, and completely melted particles is the nature of the melting process. In previous models, melting is treated as a single phase transition occurring at a set constant temperature (Love and Brownlee 1991). However, basaltic MMs and some chondritic particles are a coarse-grained, multiphase mixture of anhydrous silicates (Genge 2008; Genge et al. 2008; Gounelle et al. 2009; Badjukov et al. 2010) that will initially experience partial melting at the eutectic of the system, with crystals surviving over a range of temperature until the
liquidus temperature is reached. The range of temperatures over which melting occurs defines the opportunity for partially melted MMs and delimits the abundance of basaltic spherules.

The melting behavior of basaltic, and coarse-grained chondritic MMs, also influences their dynamic behavior due to density, and thus volume, changes on melting. The density of particles will decrease smoothly from the onset of melting to the liquidus. Density decreases and expansion will lead to an increase in deceleration and heating rate that will act to minimize the proportion of partially melted MMs.

To rigorously treat the melting process requires knowledge of the phase relations for the bulk composition of the system. Although heating in the atmosphere is rapid, occurring on timescales of seconds, melting is a kinetically rapid processes compared with crystallization and no increase in melting temperatures is usually observed at high heating rates (e.g., Ubbelohde 1978). With the bulk composition of particles the phase relations can be used to predict the proportions of each phase present in the particle at any temperature. Equations of state for these phases can then be used to determine the particle’s bulk density.

In this study, the density-temperature path of particles was determined through thermodynamic calculations to predict the compositions and abundances of the stable equilibrium phase assemblage. These calculations were performed using the MELTS code (Ghiorso and Sack 1995; Asimow and Ghiorso 1998) at a pressure of 1 atm and fO2 fixed at the iron-wustite buffer. The choice of a fixed fO2 is somewhat arbitrary given that previous studies have demonstrated higher values are obtained during atmospheric entry (e.g., Toppani and Libourel 2003), however, calculations with different oxygen fugacities showed relatively little variation in the resulting mineralogy. The phase abundances and compositions were calculated over a range of temperatures from the eutectic to the liquidus. Since chemical equilibrium is explicit in these calculations their predictions are likely to differ slightly from reality since the compositions of solid relict phases in particular are unlikely to fully equilibrate during entry heating. However, the method provides a means of modeling the melting behavior of particles to a much higher degree of accuracy than previous treatments that have assumed a constant single phase temperature (Love and Brownlee 1991). The densities of silicate partial melt, olivine, plagioclase, clinopyroxene, orthopyroxene, and magnetite over the temperature range of melting were predicted using the DENSICAL code based on experimentally determined equations of state for these phases (Niu and Batiza 1991).

Table 2. Showing compositions used for simulation particles derived from Cordier et al. (2011b) with the addition of 0.40 wt% Na2O.

|                  | Ordinary Chondrite | Eucrite | Diogenite |
|------------------|--------------------|---------|-----------|
| SiO2             | 39.53              | 48.48   | 45.64     |
| TiO2             | 0.13               | 1.93    | 0.14      |
| Cr2O3            | 0.50               | 0.09    | 0.69      |
| Al2O3            | 2.73               | 12.20   | 3.54      |
| FeO              | 26.38              | 17.48   | 30.52     |
| MnO              | 0.32               | 0.56    | 0.84      |
| MgO              | 27.98              | 7.88    | 15.52     |
| CaO              | 2.04               | 10.98   | 2.73      |
| Na2O             | 0.40               | 0.40    | 0.40      |
| Totals           | 100.0              | 100.0   | 100.0     |

In simulating the melting of coarse-grained MMs, including both basaltic and chondritic compositions, the choice of bulk composition is problematic. Genge et al. (2008) noted that the large grain size of these particles compared to their particle size leads to mineral abundances, and thus bulk compositions, that are not necessarily representative of their parent bodies. Cordier et al. (2012) demonstrated this is the case for basaltic cosmic spherules, which they modeled through mixing relationships between phases with compositions derived from HED meteorites, and demonstrated that eucrite and diogenite-dominated howardite materials were present among their particles. To enable a realistic assessment of the behavior of basaltic MMs compositions of the eucrite and diogenite (dominated howardite) cosmic spherules from Cordier et al. (2012) were used to simulate particle melting composition.

To provide a meaningful comparison to basaltic MMs a chondritic coarse-grained MM composition is used. These are predominantly samples of chondrule fragments from chondritic parent bodies. Genge (2008) has demonstrated that a significant proportion of unmelted cgMMs are derived from ordinary chondrite parent bodies. Cordier et al. (2011a) also showed that Ni-contents of olivines within chondritic cosmic spherules allow particles with an affinity to ordinary chondrite materials to be identified. The difficulty in determining a bulk composition for coarse-grained MMs due to their large grain size can be overcome using the composition of OC-related cosmic spherules from Cordier et al. (2011a) that are their melted equivalents.

The bulk compositions adopted in the present study are shown in Table 2 and represent the eucrite (type 1) and diogenite (type 3) basaltic cosmic spherules of Cordier et al. (2012) and the ordinary chondrite related spherules of Cordier et al. (2011a). The main limitation of these compositions is the loss of Na during
atmospheric entry compared with the precursor particle. To correct for Na loss, 0.4 wt% Na$_2$O has been added to the compositions and is broadly consistent with average eucrite compositions (Mittlefehldt et al. 1998).

**Melting Relations and Density Change**

Thermodynamic calculations indicate that basaltic particles have lower melting temperatures and a narrow temperature range of partial melting than chondritic particles. Liquidus temperatures for eucrite particles are 1190 °C with a eutectic temperature of 945 °C compared with 1427 °C and 1141 °C, respectively, for chondritic particles. The diogenite particles have intermediate values of 1360 °C and 1111 °C, respectively.

The equilibrium phase assemblage predicted for the three particles also differs. In the eucrite particle the disappearance of phases during melting occurs in the order olivine, spinel, plagioclase, and finally clinopyroxene. In the diogenite particle, the order of melting is plagioclase, spinel, olivine, and then orthopyroxene. These equilibrium mineral assemblages are consistent with the interpretation of the precursor mineralogy of Cordier et al. (2012) from mixing relations and suggest these particles had broadly equilibrated mineral assemblages. In the chondritic particle plagioclase and then clinopyroxene disappear rapidly with increasing temperature, while spinel and olivine survive to higher temperatures. The predicted equilibrium mineral assemblages are shown in Fig. 1.

The density-temperature profiles of eucrite, diogenite, and ordinary chondrite particles are shown in Fig. 2. Density decreases on melting since melt density is less than the precursor crystalline materials. The basaltic particles show a rapid decrease in density with temperature due to their more limited temperature range of partial melting. The density-temperature profile of the chondritic particle, however, shows a marked rapid decrease at higher temperatures due to the rapid melting of olivine due to the curvature of the olivine solidus. The predicted densities of the eucrite and diogenite particles at their liquidi are broadly similar to those of the chondritic particle at 3.05, 2.98, and 3.08 g cm$^{-3}$, respectively.

**RESULTS**

**Peak Temperatures at Selected Entry Parameters**

Simulation results indicate that density change on melting has a relatively minor effect on the peak temperature attained during entry heating. A typical temperature-time profile is shown in Fig. 3. For 100 μm
diameter particles with an entry velocity of 12 km s\(^{-1}\) and entry angle 90° the peak temperature of chondritic, diogenite, and eucrite particles are 1494 °C, 1481 °C, and 1469 °C, respectively, and thus show less than 2% variation due to differing bulk density, and density change on melting. All the particles entirely melt at these entry parameters. A similarly small effect is noted on the final diameters of the particles, after evaporation, at 62.28, 63.50, and 65.62 µm, respectively. The difference in peak temperature, however, increases at lower entry angle with eucrite and diogenite particles showing peak temperatures of 1406.6 °C and 1421.1 °C at an entry angle of 45° and entry velocity of 12 km s\(^{-1}\). Density differences between mineralogically distinct silicate materials will, therefore, only have a relatively minor effect on the conditions experienced by particles during entry heating. Differences in melting temperature due to composition, however, are more significant.

Degree of Melting

The fraction of melt generated in eucrite, diogenite, and ordinary chondrite particles over a range of entry velocities, angles and sizes are shown in Fig. 4. The results of the ordinary chondrite S-type particle are broadly similar to those of Love and Brownlee (1991) with particles larger than 150 µm completely melting at entry angles larger than 10° at entry velocities of 12 km s\(^{-1}\). However, since the solidus and liquidus temperatures of the ordinary chondrite particles fall either side of the melting temperature assumed by Love and Brownlee (1991), and small differences in density have only a small influence on peak melt temperature, the similarity is not surprising. The diogenite simulations predict only slightly greater degrees of melting than for ordinary chondrite particles. Eucrite particles, however, show a much more limited range of partial melting due to their compositions that are closer to the eutectic of the system. The model results suggest that at entry angles greater than 10° and entry velocities of 12 km s\(^{-1}\) all particles larger than 150 µm will completely melt. Larger unmelted particles at these size must have experienced very low entry angles and probably have experienced grazing incidence encounters. These low angle particles were not considered in the current paper due to the higher computational expense of their longer simulations, however, they represent ~3% of the incoming basaltic dust flux.

Relative Abundance of Basaltic MMs

The relative abundance of melted, partially melted, and unmelted basaltic MMs requires an evaluation of the size distribution of particles since mass loss by evaporation of larger particles causes decreases in particle radius increasing the abundance of smaller MMs. Within any particular size range, therefore, the abundance of melted particles is enhanced by evaporation of larger particles. To account for changes
in particle size by evaporation, a model for the size distribution of micrometeoroids is required. This paper uses the prediction of Ceplecha et al. (1998), which is derived from meteor observations and is broadly compatible with the measurements of micrometeoroid flux using LDEF microcraters (Love and Brownlee 1993). The relative abundance of particles in 10 \( \mu \)m size bins was calculated for single velocity populations allowed to enter the atmosphere over a range of entry angles (10–90°) and scaled by entry angle probability and the initial size distribution.

To investigate the statistical validity of small scale perturbations in the size distribution due to counting effects, repeat simulations with higher size and angle resolution were performed. The results for size steps at 5 \( \mu \)m, 2 \( \mu \)m, and 1 \( \mu \)m and 5, 2, and 1° entry angle, respectively, are shown in Fig. 5 for diogenite particles with an entry velocity of 12 km s\(^{-1}\). The calculations at 1 \( \mu \)m and 1° involved simulation of the atmospheric entry of 40,000 particles. The relative distribution changes with simulation resolution but becomes relatively constant at resolutions <2 \( \mu \)m and <2° with perturbations being minimized.

The predicted relative abundance of completely melted, partially melted, and unmelted particles at any final size increases from ordinary chondrite to diogenite to eucrite particles and is shown in Fig. 6. Diogenite particles show broadly similar abundances to ordinary chondrite particles with around 50% completely melted particles at 100 \( \mu \)m diameter for the low 12 km s\(^{-1}\) entry velocity populations, ~45% partially melted, and ~5% unmelted particles. Eucrite particles show smaller abundances of unmelted particles at 0.4%, and in particular partially melted particles at ~10% and much higher abundances of melted particles at ~90% for 100 \( \mu \)m diameter particles at 12 km s\(^{-1}\).

There are two apparently anomalous features in these data. The abundance of melted and partially melted particles increases sharply with increasing size followed by a plateau in the abundance of completely melted particles, followed by another sharp increase at larger sizes. The shape of this plateau is related to the shift of partly evaporated particles from larger sizes combined with the decrease in abundance of larger particles. Evaporative mass loss and size decrease of intensely heating particles, therefore, results in a peak in the size distribution at smaller sizes. The second apparently anomalous feature is that the abundance of completely melted particles at radii of ~50 \( \mu \)m is larger for the low velocity population than the high velocity population. Again this is a consequence of the evaporation of particles since the peak formed by size reduction of evaporated particles with entry velocities of 12 km s\(^{-1}\) is located at ~50 \( \mu \)m radius while at 16 km s\(^{-1}\) the peak shifts to smaller radii due to more intense evaporation.

What constitutes completely melted and partially melted particles, however, must be carefully considered. Completely melted supraliquidus particles are likely to cool to form barred, cryptocrystalline, or glassy spherules; however, partially melted particles may still form cosmic spherules as opposed to coarse-grained MMs with a degree of partial melting. A fraction of melt of 50% has been observed as a threshold for

Fig. 4. Showing the melt fractions for ordinary chondrite, eucrite, and diogenite particles at an entry velocity of 12 km s\(^{-1}\) and different entry angles.
spherule formation by Toppani and Libourel (2003). We can, therefore, determine the relative abundance of spherules to partially melted and unmelted particles as shown in Fig. 7. The most significant feature of the data is that for ordinary chondrite particles the spherule percentage is ~60% in the size range 100–200 μm, very similar to that observed within Antarctic collections (e.g., Genge et al. 2008).

**DISCUSSION**

**The Relative Abundances of Basaltic MM Types**

The results of the simulations indicate that the relative abundances of unmelted, partially melted, and completely melted basaltic MMs vary considerably with initial particle size and with entry velocity. The maximum abundance of unmelted particles is observed for the low entry velocity population (12 km s\(^{-1}\)) and provides values of 4% for 100 μm diameter particles and ~5 and ~11% for 60 μm particles for eucrite and diogenite materials, respectively. At entry, velocities of 16 km s\(^{-1}\) values of 3 and 6% are obtained for 50 μm eucrite and diogenite particles and no unmelted particles survive at 100 μm diameter, albeit with the caveat that some very low angle, grazing incident particles will be present. At small sizes, therefore the abundance of unmelted diogenite MMs would be expected to be enhanced compared to that of eucrites by around a factor of 2. The abundance of unmelted ordinary chondrite-like material at 60 μm for an entry velocity of 12 km s\(^{-1}\) is 14%, higher than either diogenites or eucrites. The relative abundance of unmelted ordinary chondrite materials compared to eucrites will, therefore, be enhanced by a factor of almost 3 compared with the pre-atmospheric abundance.

The results also allow an evaluation of MM types expected from eucrite and diogenite particles among melted particles. Particles with between <50 vol% partial melting typically form scoriaceous MMs and contain vesicles within a melted mesostasis with some relict unmelted phases (Toppani and Libourel 2003; Genge et al. 2008). Observations of the fusion crusts of diogenites and eucrites indicate the presence of vesicles due to incipient volatile contents (Genge and Grady 1999). Particles with >50 vol% melting form cosmic spherules. Those that are incompletely melted probably form porphyritic spherules since they retain numerous crystallization nuclei, while those which completely melt form barred olivine, cryptocrystalline, or glassy spherules depending largely on the survival of heterogeneous crystal nuclei and their composition. The survival of crystal nuclei for a particular precursor material decreases with temperature and thus glassy spherules are likely to be form at the highest peak temperatures and barred olivine and cryptocrystalline at lower peak temperatures.
The effect of composition on crystallization is also important. Olivine normative melts such as those formed by melting of ordinary chondrite materials have olivine as a liquidus phase and are likely to form porphyritic or barred olivine spherules on cooling depending on peak temperature. Eucrite and diogenite

Fig. 6. Showing relative size distributions of unmelted (black), partially melted (0–100 vol%; gray), and entirely melted (white) particles formed from ordinary chondrite, diogenite, and eucrite compositions. Data for entry velocities of 12 and 16 km s\(^{-1}\) are shown.
melts, however, are pyroxene normative and since the crystallization of pyroxene is kinetically impeded compared to olivine (Taylor and Brownlee 1991) are likely to fail to crystallize and be preserved as glassy spherules. In contrast, the final textures of pyroxene normative spherules that have not completely melted

**Fig. 7.** Showing the abundances of unmelted (black), scoriaceous (0–50 vol%; gray), and cosmic spherules (>50% melted; white) formed from ordinary chondrite, diogenite, and eucrite compositions. Data for entry velocities of 12 and 16 km s\(^{-1}\) are shown.
are likely to be cryptocrystalline, since surviving relict crystals will act as nucleation sites for growth of pyroxene dendrites.

The simulation results shown in Figs. 6 and 7 allow the relative abundance of spherule types for basaltic MMs and a comparison made to the spherules types formed from OC materials, given the assumptions on spherule textures outlined above. The results suggest that eucrite MMs will have small abundances of cryptocrystalline spherules, corresponding to 50–100 vol% melting, and comprising only 6% of spherules at 100 μm. Diogenite particles, however, have a much larger fraction of cryptocrystalline spherules compared to glassy spherules at 19% at 100 μm. Ordinary chondrite particles are predicted to have 19% porphyritic spherules at 100 μm broadly similar to the overall abundance of this spherule type in the 50–100 μm size range (Genge et al. 2008).

The large differences in spherule type abundances with material composition is a consequence of differences in melting behavior. The melt fraction for diogenite particles increases rapidly over a small temperature range at low suprasolidus temperatures leading to a larger fraction of cryptocrystalline compared to glassy spherules than eucrite compositions. The abundance of porphyritic spherules in ordinary chondrite particles is a consequence of the olivine normative melt composition due to the rapid increase in melt fraction generated by melting only olivine at just below the liquidus.

The results also allow the abundance of partially melted scoriaceous particles to be predicted. For ordinary chondrite scoriaceous MMs comprise 29% of particles for the 12 km s⁻¹ population, while eucrite and diogenite particles both have low abundances of such particles at 5 and 6%, respectively, similar to the abundance of unmelted particles. Among these coarse-grained materials partial melting up to 50 vol% produces particles that might still be identified on the basis of their precursor mineralogy.

Grain size may be a factor in the relative abundances of basaltic MMs since large grain size within their precursor materials may lead to MMs consisting of a single mineral grain. Small particles are much more likely to be single crystal MMs, which could make them difficult to identify.

The Orbits of Basaltic MMs

Studies of basaltic MMs within Antarctic collections indicate the majority of particles are cosmic spherules with a fraction of 0.5 ± 0.4% of the South Pole Water Well collection (Taylor et al. 2007) and 1.6% of the Transantarctic Mountains collection (Cordier et al. 2012). Only a single unmelted MM has been recovered from Antarctic ice (Gounelle et al. 2009). Five unmelted basaltic particles have, however, been reported from Novaya Zemlya glacier ice in the Arctic circle (Badjukov et al. 2010) and comprise 0.2–0.5% of the collection.

Given that among 60 μm particles unmelted basaltic MMs represent 5–10% of total basaltic materials, and that partially melted basaltic particles, which can be recognized on the basis of their mineralogy, will be present in nearly the same abundance, the available Antarctic data suggest that unmelted basaltic MMs are under-represented if they represent a population with a 12 km s⁻¹ entry velocity. Basaltic MMs larger than 200 μm are relatively common (1.6%; Cordier et al. 2012); only a single unmelted basaltic particle has been identified in the smaller size range, despite thousands of characterized particles. This could be the result of difficulties in identifying unmelted basaltic MMs, which are similar to terrestrial samples, or it could be that basaltic MMs are less abundant at small sizes than the values determined for large spherules by Taylor et al. (2007) and Cordier et al. (2012). The low abundance of unmelted basaltic MMs compared with basaltic spherules would most readily be explained if the population has a higher average entry velocity. Figure 8 shows the entry velocities of dust particles with different orbital parameters and includes acceleration to the top of the atmosphere by the Earth’s gravity. Low entry velocities of 12 km s⁻¹ mainly require low eccentricities of <0.1 and semimajor axes of close to 1 AU while those of 16 km s⁻¹ require eccentricities of >0.35.

Orbital parameters are, however, not an absolute indicator of source due to the affect of P-R light drag, which leads to circularization of orbits and thus low eccentricities (Dohnanyi 1976), while planetary
perturbations can also lead to changes in eccentricity. As a result dust from mature Main Belt sources, and from some comets has low entry velocities <12 km s^{-1}. Appropriate sources of basaltic dust with eccentricities >0.35 could be found among near-Earth objects if produced relatively recently so their orbital eccentricities have not been circularized. One possible explanation for the low apparent abundance of unmelted basaltic MMs in Antarctic collections, therefore, could be if they represent the product of a collisional disruption of a basaltic asteroid among the near-Earth asteroid population. Numerous object with V-type reflectance spectra exist within the near-Earth asteroid and have been shown to have surface mineralogies similar to HED meteorites (Burbine et al. 2009).

The discovery of four unmelted particles within Novaya Zemlya glacial deposits suggests an anomalously high abundance of unmelted basaltic MMs. According to the simulations presented here, four eucrite-like particles >100 μm in diameter would be accompanied by >1000 basaltic spherules even at a low entry velocity of 12 km s^{-1} and thus should comprise almost the entire Novaya Zemlya collection, contrary to observation. It is possible that the abundance observed is not statistically significant, for example, these could represent particles that had grazing incidence encounters, or it could be explained if the collection is biased toward the survival of unmelted basaltic particles. Alternatively, like Eltanin particles (Kyte and Brownlee 1985), these could have originated through the fragmentation of a basaltic achondrite meteoroid in the atmosphere and thus not strictly represent micrometeorites but meteorite ablation debris.

Near-Earth object sources for basaltic MMs is not consistent with measurements of the abundance of basaltic spherules which are comparable to that of HEDs (Cordier et al. 2012). Oxygen isotope data on recovered basaltic MMs, however, might support a non-Vesta source for these particles since they are different from those of the HEDs (Gounelle et al. 2009; Cordier et al. 2012). Further data on the variation of basaltic MM abundance, in particular to melted to unmelted ratio, will be needed to evaluate their source.

**Implications**

The simulations of basaltic MMs indicate that solidus and liquidus temperature, partial melting temperature interval, and the shape of the solidus all influence the relative abundances of different particle types. Similar processes are likely to affect the relative abundances of chondritic particles that dominate the micrometeorite flux. Taylor et al. (2012) suggests that fine-grained particles with affinities to CI and CM chondrites dominated the precursors of cosmic spherules from the South Pole Water Well, while Sauvet et al. (2010) and Cordier and Folco (2014) suggests on the basis of oxygen isotopes that both ordinary chondrite and carbonaceous chondrite-like materials are the precursors of many spherules. Cordier et al. (2011a) likewise suggested ordinary chondrite precursors were present among cosmic spherules from the Ni-abundances of their olivines. The precursors of cosmic spherules are thus mineralogically diverse and likely to exhibit different melting behaviors that will affect their relative abundances.

Unmelted micrometeorites demonstrate a wide range of mineralogies. Fine-grained MMs are dominated by CM-like particles, with lesser CI-like materials, that are dominated by phyllosilicates and are volatile-rich (Kurat et al. 1994; Genge et al. 1997; Taylor et al. 2012). Coarse-grained MMs mostly have mineralogies similar to chondrules and are dominated by olivine, pyroxene, and glass with minor metal and sulfide and are relatively volatile poor (Genge 2006, 2008). Chondrule-derived MMs, are likely, therefore, to have significantly higher solidus and liquidus temperatures than fine-grained MMs and thus to be over-represented among unmelted MMs compared to the pre-atmospheric dust population. Conversely among completely melted particles fine-grained precursors are likely to be over-represented. Even within particle classes melting temperatures may have a significant effect. Among coarse-grained MMs, for example, two main groups of particle are observed: (1) type I reduced particles dominated by Mg-rich silicates and metal/sulfide, and (2) type II oxidized particles dominated by Fe-rich silicates and iron oxides (Genge 2008). Type I particles are likely to have higher solidus and liquidus temperatures, particularly during nonequilibrium melting, than type II particles and thus will be more abundant among unmelted particles compared to the pre-atmospheric dust population. Interpretation of the relative abundances of types in terms of the contribution to their terrestrial dust flux must, therefore, consider the melting behavior of particles.

**CONCLUSIONS**

Numerical simulations of basaltic and ordinary chondrite MMs incorporating their partial melting behavior allow the abundance of unmelted, partially melted, and completely melted spherules to be predicted, as well as the relative abundance of spherule types to be evaluated. The results of this study indicate that there is a significant difference between the behavior of diogenite and eucrite particles, with eucrite particles more likely to melt to form cosmic spherules.
than either diogenite or ordinary chondrite materials. The abundance of unmelted basaltic MMNs are shown to
be around 5–10% of total basaltic MMNs for 60 μm particles if basaltic particles predominantly have low
entry velocities. However, to date very few unmelted
basaltic MMNs have been identified despite the 0.5–1.6%
basaltic spherules discovered perhaps suggesting higher
entry velocities predominant and implying a source in
the near-Earth object population.

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