Tomography of Metal Beads in Micrometeorites. S. Taylor[1], G.F. Herzog[2], and K.W. Jones[3]. [1]CRREL, 72 Lyme Road, Hanover, NH 03755, [2] Rutgers University, Piscataway, NJ,.08854 [3] Brookhaven National Laboratory, Upton, New York 11973-5000

Introduction: As a group, micrometeorites have elemental compositions that are most similar to CI and CM chondrites [1,2]. The CI and CM chondrites, however, are oxidized and contain no metal [3] while melted micrometeorites (cosmic spherules) often contain well-defined FeNi beads. Metal beads in cosmic spherules could form if C or organic-rich phases reduced FeNi oxides during atmospheric entry heating [4,5]. Alternatively metal beads could form if Ni bearing sulfides lose their sulfur during entry heating [6].

In an effort to better understand the formation of metal beads we tried to capture a series of images representing bead formation. Using previously sectioned micrometeorites (MM) we measured the diameters of beads and well-defined sulfur-rich regions. Classical sectioning, however, reveals only a small fraction of the volume of any micrometeorite whereas x-ray tomography allows one to study the occurrence of these phases in whole MMs. To this end we mapped the internal structure of stony MMs using the technique of synchrotron computed microtomography (CMT) and measured the shapes and size distribution of the beads relative to their host MMs.

Methods: All of these MMs studied were collected from the South Pole water well [7]. We examined 926 sectioned micrometeorites from 15 mounts containing a random sample of MM collected in 1995. All the MMs in these mounts had been previously imaged. We measured the apparent diameter of the MM and its associated bead from the images.

We also imaged 4 samples (1a, 1b, 2a, and 2b) containing 96 cosmic spherules using the CMT technique at beam line X2B, Brookhaven National Laboratory. CMT has several advantages. It is non-destructive so that the rare spherules are preserved for further experiments. The apparatus on X2B has high spatial resolution, 4 µm voxel size and the X-ray attenuation coefficients for silicate, sulfide and metal, differ sufficiently to allow tomographic identification. Finally, simultaneous measurements can be made on volumes that include many spherules.

For the CMT scans the MMs were placed in a Tygon tube having a 1-mm internal diameter. Each sample had 20 to 30 MMs and filled 2 to 3 mm of the tube. We added a Cu sphere at each end of the tube to serve as a reference metal and plugged the ends with epoxy. For these samples we have both radiographs and images of 4 µm slices taken perpendicular to the length of the tube, 800 images per sample or about 25 slices for a 100µm MM.

We noted the external appearance of each of the MMs placed in the tubes. For our first sample we selected micrometeorites with visible surface beads to confirm that we could see the beads with CMT.

Results: Sectioned MM mounts show that: unmelted and scoriaceous micrometeorites have sulfides disseminated throughout their matrices; relict-bearing cosmic spherules have discrete sulfide-rich regions; and barred olivine and glass spherules contain well defined FeNi beads (Fig. 1). Of the 926 MMs examined from sectioned mounts 140 (15%) contained metal or sulfides and 78 (7%) contained well defined-beads (Table 1).

Table 1. Number of MM and beads studied.

MM Optical				
Diameter µm	**<100**	**100-250**		**>250**
# MM	175	417		334
# beads	16	31		20
CMT Samples	**1a**	**1b**	**2a**	**2b**
# MM in sample	26	26	27	25
# Imaged by CMT	26	25	23	22
# beads by CMT	22	9	13	12

The CMT radiographs show clear differences between the metal-rich phases and the silicates (Fig. 2). Vesicles in glass spherules and scoriaceous micrometeorites are also easy to see (Fig. 2). As the images of the spherules are superimposed on the radiographs it is sometimes difficult to match a particular bead with its host spherule. We, therefore, used the CMT slices to count the number of MMs and the the number of beads, and to measure their respective diameters. The CMT slices also clearly show disseminated sulfides and vesicles in MMs (Fig. 3). Of the 96 spherules imaged, 56 had beads (Table 1). Discounting sample 1a, where MM with visible beads were selected, 68% of the MM contain beads- much higher than the 7% found by optical microscopy in sectioned mounts.

Fig. 4 shows the ratio of bead to MM diameter plotted versus the MM diameter. The diameter of the beads relative to their host MMs varied from 0.02 to 0.80 with one peak at ~0.09 and a second at ~0.22. As expected the beads measured in the sectioned mounts (squares) are smaller than those measured by CMT since the widest part of the bead would generally not be intersected.

Discussion: Taylor and Lever [8] described a framework for classifying micrometeorites that can also be regarded as a temporal series of formation stages in which most MM begin as fine grained CI- or CM-like material and undergo varying degrees of atmospheric heating over a total period lasting only seconds. As the matrix of the MM melts on entering the Earth's atmosphere, the dispersed sulfides begin to aggregate (Fig. 1a,b, scoriaceous and porphyritic MM, and scoriaceous MMs in Fig.3). As the MM decelerates, buoyancy differences between the sulfide and silicate phases then move the sulfide to the leading edge of the MM (Fig. 1c, glassy MM) where the sulfur is rapidly decomposed followed by evaporation of Fe and or S or oxidation of S to SO_2(g) or SO_3(g)). We think that FeNi beads in cosmic spherules are the end result of this process (Fig. 1d). Generally one bead forms but if the micrometeoroid was spinning two or, rarely, three or four beads form and produce spindle or tetrahedral shaped 'spherules'.

In this picture, micrometeoroids that contain sulfides should always give rise to metal beads. Further, because fine-grained chondritic precursors often have sulfides and are thought to be a source for MMs, metal beads should be common. Our CMT data show that over 50% of the cosmic spherules examined contained metal or sulfide beads. This percentage does not account for an estimated 1 to 5% of the spherules that may have already lost a bead. Furthermore the FeNi beads are almost always found at the surface and are smaller and more spherical than the sulfide-rich beads consistent with loss of sulfur. Finally the negative correlation of relative bead size with MM diameter (Fig. 4) shows that larger, more highly heated MMs have proportionally and absolutely smaller beads.

Conclusions: Decomposition of sulfides contributes importantly to the formation of metal beads in cosmic spherules. The detailed mechanism is not clear and may involve reduction by carbon-rich material. The absence of many small metal and/or sulfide beads in wholly melted spherules indicates that once reduced, metal coalesces rapidly. Smaller beads in larger (>300 µm) micrometeorites are consistent with large, ~50%, losses of iron from these objects.

Tomography is a good method for observing the formation of metal beads in stony micrometeorites. The beads are easy to see and their true diameters can be measured relative to the diameters of their host MM. In addition vesicles in scoriaceous and glass micrometeorites show up clearly in the tomographic sections making it possible to calculate MM porosity from vesicle volumes.

Figure. 1. Sulfides and FeNi bead in MMs.

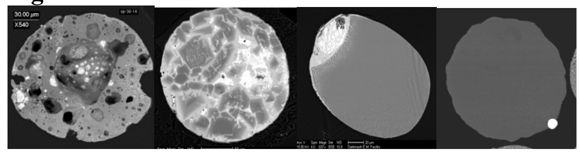


Figure 2. Radiographs for samples 1a & b.

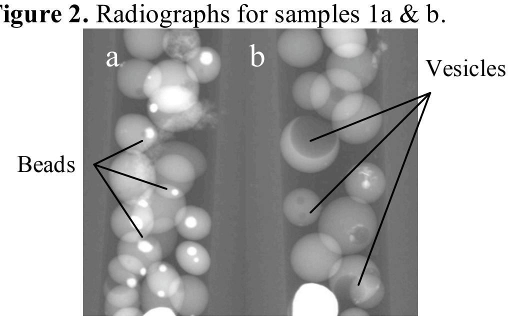


Fig 3. CMT slices showing a bubbly glass, a waning barred olivine spherule and two scoriaceous micrometeorites. The slices are 20µm apart.

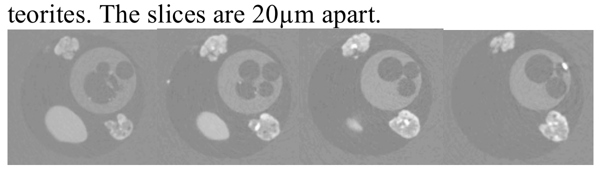
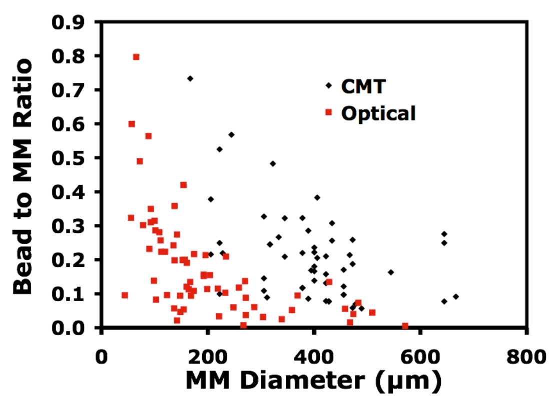


Fig. 4. Bead to MM diameter ratio plotted versus MM diameter for whole and sectioned MMs.



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