The Meteoritical Society

Meteoritics & Planetary Science 53, Nr 2, 326–332 (2018)
doi: 10.1111/maps.13013

Comment

Comment on "Unmelted cosmic metal particles in the Indian Ocean" by Prasad et al.

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(Received 29 June 2017; revision accepted 23 October 2017)

INTRODUCTION

Iron-nickel metal is common within chondritic and achondritic meteorites and is one of the fundamental mineralogical components of our solar system. The discovery of unmelted iron-nickel particles from deep-sea sediments in the Indian Ocean reported by Prasad et al. (2017) is, therefore, very interesting since it is the first unequivocal discovery of well-characterized unmelted metal grains within sediments. The discovery of abundant unmelted metal grains, suggested by the authors to be micrometeorites (MMs), however, is also very surprising since none have yet been found within Antarctic collections, despite their low degree of alteration and characterization of many thousands of particles, nor have they been recovered from previous deep-sea sediment collections (Brownlee 1985). Rare unmelted metal grains have, however, been reported from Greenland cryoconite but have not been thoroughly studied (Maurette et al. 1987).

The occurrence of abundant metal in meteorites indicates that metallic particles undoubtedly exist among interplanetary dust and are accreted by the Earth. Some of these grains are certain to survive atmospheric entry to be preserved on the Earth's surface as MMs. The principle evidence that such grains exist is the occurrence of I-type cosmic spherules dominated by magnetite and wüstite, with many (40%) also containing an FeNi metal bead (Brownlee 1985; Herzog et al. 1999; Rudraswami et al. 2014; Genge et al. 2017). Oxygen isotope analyses of these spherules reveal that their oxygen is terrestrial (Engrand et al. 2005; Pack et al. 2017), thus these were metal grains that melted and were oxidized during atmospheric entry. Within Antarctic collections, I-types comprise ~1% of grains; however, within deep-sea sediments, they have higher abundances of >5% (Prasad et al. 2013) owing to removal of the more common silicate-dominated particles by alteration. The absence of silicates within I-types suggests that many metal grains are liberated from their parent bodies as metal-dominated grains (Herzog et al. 1999).

Atmospheric entry heating represents a significant barrier to the survival of unmelted metal. Numerical simulations of the atmospheric entry of metallic interplanetary dust particles indicate that the high density of FeNi metal results in significant heating with the result that most melt to form spherules except at small sizes (Genge 2016). In this critical comment, the identity of the metal grains reported by Prasad et al. (2017) as unmelted metal MMs is queried and a possible alternative explanation, that these are meteoroid ablation debris, is proposed.

ENTRY HEATING OF METALLIC MICROMETEORITES AND ABUNDANCES

Prasad et al. (2017) suggest that the discovered unmelted particles represent that fraction of the metallic interplanetary dust flux that enters the atmosphere at a sufficiently low angle to undergo minimal heating. Low-angle atmospheric entry is certainly one mechanism by which objects can decelerate in the atmosphere without heating to high temperature and melting, with those

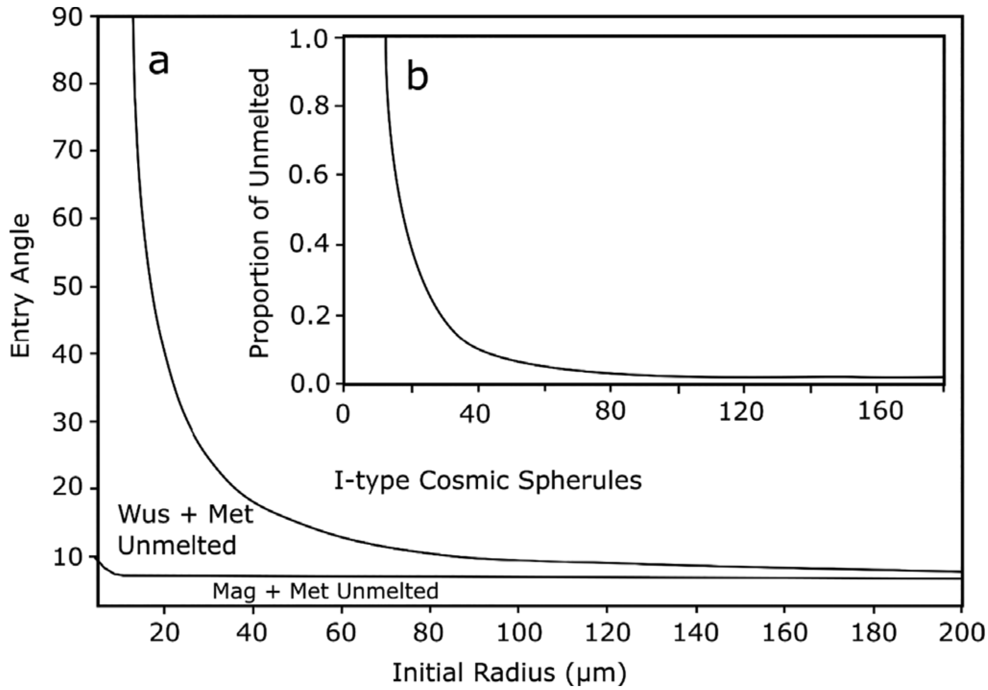

Fig. 1. The abundance of unmelted metal micrometeorites derived from numerical simulations at an entry velocity of 12 km s^{-1}. a) The final products of entry heating of FeNi metal for particles of different initial size and entry angle. Most particles melt to form cosmic spherules except at small sizes and low entry angles. Unmelted particles that experience peak temperatures >550 °C will develop oxide rims of wüstite on unmelted FeNi metal grains (Wus + Met). Particles heated to lower temperatures only have rims of magnetite on unmelted FeNi metal grains (Mag + Met). b) The relative abundance of unmelted metal micrometeorites against initial radius. Final particle radii are likely to be smaller owing to evaporation leading to lower abundances of unmelted grains at small sizes.

particles that undergo grazing incidence encounters, in particular, having the lowest peak temperatures (Love and Brownlee 1991). Genge (2016) presented a numerical model of atmospheric entry heating including a treatment of oxidation and the formation of an iron oxide mantle. Figure 1a shows the results of simulations of the atmospheric entry of metallic unmelted MMs at entry velocities of 12 km s^{-1} following Genge (2016). The results show that only at diameters <25 μm do all metal grains survive melting without melting to form I-type cosmic spherules. The abundance of unmelted metallic grains is shown in Fig. 1b and is calculated from the collision probability with the Earth at a particular entry angle; this does not, therefore, include the decrease in size of I-type spherules owing to evaporation that will increase spherule abundances and decrease unmelted metal grain abundances at small sizes. The results suggest that the maximum proportion of metal grains surviving atmospheric entry at diameters of 100 and 150 μm is 10% and 2%, respectively.

Prasad et al. (2017) report the discovery of 129 FeNi metal particles out of a collection described as >800 particles comprising 50% I-type and G-type cosmic spherules. Eighty particles were irregular metal grains, and a further 50 were metal-dominated beads; both were suggested to have survived atmospheric entry without melting. If we assume that there are ~800 iron-dominated particles, then the proportion of unmelted to melted metallic particles is ~33%, depending on the abundance of G-type spherules. Of the 80 irregular unmelted particles, 70% are larger than 100 μm in maximum dimension and 25% larger than 150 μm with two greater than 300 μm (maximum 373 μm). The sizes of only half of FeNi metal beads were reported, of which ~20% are larger than 100 μm with a maximum of 266 μm. The abundance of unmelted grains, therefore, would appear to be significantly larger than would be expected for low entry angle particles; however, a complete size distribution of I-type spherules as well as unmelted grains would be necessary to assess the degree of disparity.

Prasad et al. (2017) recognized that the large abundance of unmelted particles is not consistent with the entry heating of metal micrometeoroids. To reconcile the abundances, they suggested that metal grains could be liberated by fragmentation of larger dust particles at the top of the atmosphere causing deceleration and a decrease in heating. Fragmentation,

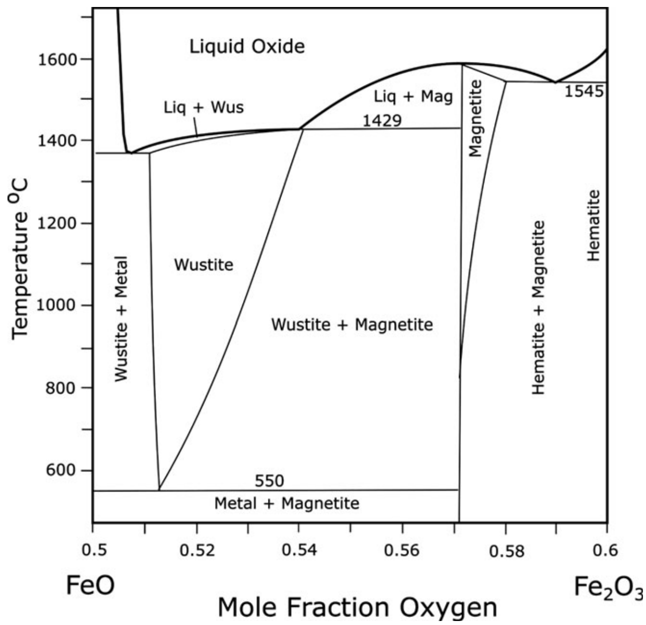

Fig. 2. A portion of the Fe-O phase diagram showing the stability of wüstite and magnetite. The phase diagram was calculated using the thermodynamic package, FactSage.

however, only occurs once the ram pressure exceeds the mechanical strength of the material and thus typically occurs at low altitudes, by which time these particles are likely to have already melted.

The abundance of I-type cosmic spherules within the reported collection of ~50% also appears to be anomalous. Previous studies of Indian Ocean cosmic dust by Prasad et al. (2013) suggested abundances of ~5%; larger than that of Antarctic collections of 1% (Taylor et al. 2007). The enhanced abundance of I-types within deep-sea sediment collections has previously been attributed to the removal of S-type (silicate) spherules by weathering in the marine environment (Taylor et al. 2007). The significant enhancement in I-types in the reported collection, therefore, would require the removal of 99% of S-types but the survival of unmelted metal grains. An alternative explanation would be the addition of metallic particles from a separate source such as a single large bolide event.

TEXTURAL AND MINERALOGICAL EVIDENCE FOR AN UNMELTED ORIGIN

The evidence presented by Prasad et al. (2017) for an unmelted origin is compelling for irregular metal grains. The majority of the grains have external rims of iron oxide consisting of wüstite adjacent to the FeNi metal and an external layer of magnetite. Prasad et al. (2017) suggest that the presence of wüstite indicates heating at 550 °C under low oxygen fugacity; however, the Fe-O phase relations indicate that wüstite will form by oxidation of metal at temperatures between 550 and 1375 °C under a wide range of oxygen fugacities, with magnetite forming at lower temperatures on cooling (Fig. 2). Indeed wüstite is also metastable at <550 °C; however, its decomposition to magnetite and metal alloy is kinetically impeded, as shown by its presence in 2.7 Ga I-type cosmic spherules (Tomkins et al. 2016).

Prasad et al. (2017) suggest that oxide rims form by surface melting and rapid oxidation of the metallic liquid during atmospheric entry heating in a similar way to igneous rims formed on silicate MMs (Genge 2006). Thermal gradients in small particles during atmospheric entry, however, are minimal (Love and Brownlee 1991) owing to the rapid nature of thermal conduction compared with the 1–5 s of high-temperature flight and preclude such surface melting. Igneous rims formed on silicate MMs form as a result of heat losses by endothermic decomposition of phyllosilicates (Genge 2006) and thus do not apply to metal grains. Melting is, in any case, not necessary to form oxide rims since solid-state oxidation is observed during the high-temperature corrosion of steels in atmosphere (Chen and Yuen 2003).

Despite the issues with the mechanisms of oxide rim formation, the presence of rims with a wüstite inner layer is excellent evidence that irregular particles were solid metal grains heating in atmosphere to temperatures of >550 °C. Numerical modeling of entry heating, however, suggests that metal micrometeoroids that enter the atmosphere at angles of <7° will undergo one or more grazing incidence encounters (Love and Brownlee 1991) that greatly reduce peak temperature to <550 °C (Fig. 1). These particles will not form wüstite rims and should have only thin rims of magnetite. The relative abundance of such particles increases with size and should be more abundant than wüstite-bearing particles at diameters >150 μm (Fig. 1a). No such particles were reported by Prasad et al. (2017).

The textural evidence that the reported FeNi metal beads represent unmelted metal MMs is considerably less compelling. Most beads are described as having no or minor wüstite rims in contrast to most I-type cosmic spherules that have well-developed oxide mantles of wüstite and magnetite. However, the authors do concede that these particles could represent the metallic cores of I-type spherules that have lost their oxide mantles, although they seem to conclude that an origin as unmelted particles is more likely.

CHEMICAL EVIDENCE FOR FORMATION AS METAL MICROMETEORITES

A key characteristic of MMs is their derivation as interplanetary dust from diverse parent bodies through

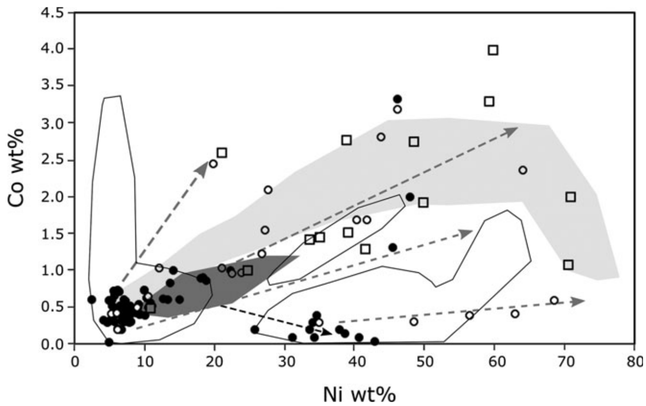

Fig. 3. Compositions of metal grains. The composition of unmelted metal grains (solid circles) and FeNi metal beads (open circles) from Prasad et al. (2017) has been renormalized to account for low totals. The metallic cores of I-type cosmic spherules from Larkman Nunatak, Antarctica are shown as open squares. The range of metal grains from Henbury, Wabar, and Monturaqui impactites is shown in light gray (Gibbons et al. 1976) and those from Kamil crater, Egypt in dark gray (Folco et al. 2015). The range of compositions of metal from meteorites is outlined in black and is derived from Prasad et al. (2017) with the addition of the cores of taenites from iron meteorites (Goldstein et al. 2014). Gray arrows represent constant Co/Ni ratios, while the black arrow represents diffusion within taenite in iron meteorites.

collisional processing of asteroids or sublimation of cometary nuclei (Genge et al. 1997, 2008; Genge 2008; Taylor et al. 2011; Van Ginneken et al. 2017). Metallic MMs are most likely to be derived from asteroids and thus probably are related to meteoritic metal phases. Prasad et al. (2017) show that the Co/Ni ratios of irregular metal grains fall into the following two groups (1) a high Co/Ni group with compositions suggested to be consistent with kamacite and plessite, and (2) a low Co/Ni group with compositions consistent with taenite. This evidence is compelling, although particles are identified as kamacite, plessite, and taenite on compositional rather than structural constraints and those identified as plessite also have compositions compatible with the cores of taenite crystals from iron meteorites (Goldstein et al. 2014).

The evidence that the particles are metal MMs derived from numerous parent bodies, rather than metallic debris from a single source, such as a disrupted large iron bolide, is based on the variation in Co/Ni contents. Chemical zoning in individual iron meteorites exhibits Co contents that vary less than ~0.1 wt%, smaller than the observed value of ~0.3 wt% for the low-Ni, high-Co/Ni particles likely to be derived from kamacite (e.g., Goldstein et al. 2014). The reported compositions of the particles are shown in Fig. 3 and have been renormalized since many have low totals (>88 wt%).

Although the high Co/Ni group does exhibit a larger variation than in a single iron meteorite, it does have a much smaller range of Co/Ni ratios than observed in meteorites (e.g., fig. 6, Prasad et al. 2017) and is thus certainly not a sample of parent bodies representative of the meteorite flux. An important question, however, is whether dust-sized ablation debris released from a single object disrupted in the atmosphere could compositionally evolve to a wider range of Co/Ni ratios. Studies of metal grains within impactites associated with Kamil, Henbury, Wabar, and Monturaqui craters provide some support for compositional evolution of metal grains at least during impact disruption (Gibbons et al. 1976; Folco et al. 2015). Impactite metal suggests that an increase in Co and Ni abundance occurs with oxidation with some minor variation in Co/Ni ratio. Many of the metal particles reported by Prasad et al. (2017) have, however, experienced aqueous alteration within the marine environment. Studies of iron meteorites suggest that variations in Co and Ni content of residual metal can be affected by weathering (Oshtrakh et al. 2016). Since the low analytical totals reported by Prasad et al. (2017) are likewise probably the result of weathering, the compositions are somewhat too uncertain to entirely rule out derivation from a single source.

Some evidence was, however, presented to identify the parent body of four particles. M-shaped nickel concentration gradients were observed in irregular taenite particles allowing an estimate of cooling rate of 0.1 K Myr^{-1} (for three particles) and 100 K Myr^{-1}. These values are typical of iron meteorites rather than chondrites. Measurable nickel enrichment in metal, however, is also reported during high-temperature oxidation of steels adjacent to the oxide scale (Chen and Yuen 2003), and all four grains appear to have low-Ni oxide rims. Consequently, the profiles may have changed during atmospheric entry. Evidence that this may be the case is the preservation of an M-type profile since it would seem highly coincidental that all the grains would sample the full thickness of kamacite bands.

The FeNi metal beads reported by Prasad et al. (2017) show a much larger range of compositions than irregular grains and were suggested to form as (1) beads separated by immiscibility from chondritic objects during atmospheric entry, (2) unmelted spherical metal grains, or (3) the separated cores of metallic I-types. The compositions of the cores of Antarctic I-type spherules are shown in Fig. 3 (from Genge et al. 2017) and are very similar to the FeNi beads, as was noted by the authors in comparison to Rudraswami et al. (2014). The compositions of metal chondrules from bencubbinites (Weisberg et al. 2001)

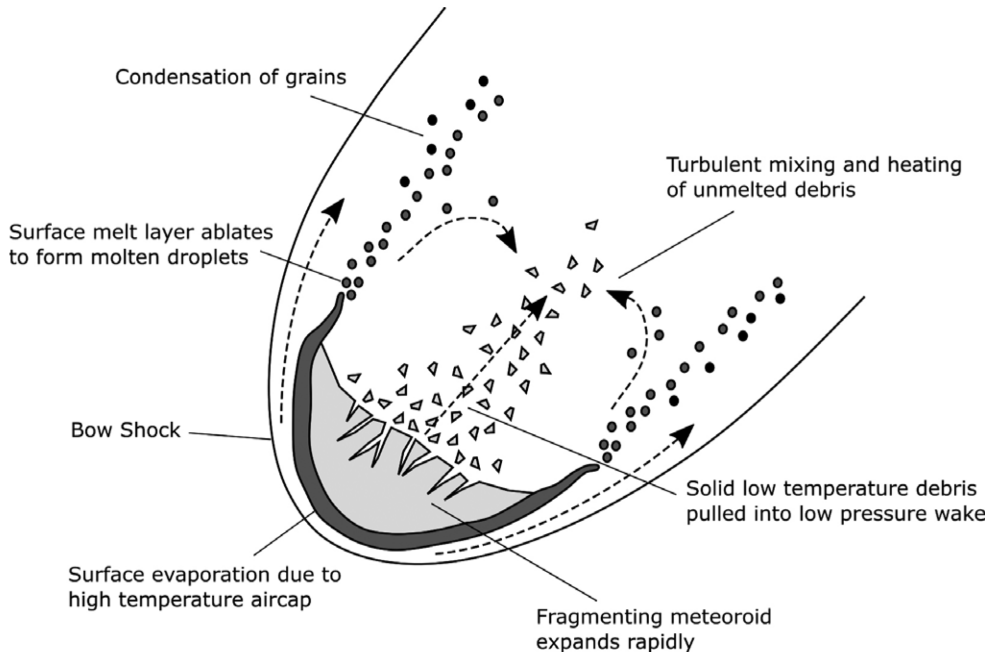

Fig. 4. Schematic diagram showing a model for the formation of unmelted heated metal grains mixed with melted spherules and vapor condensates during a fragmentation event of an iron meteoroid.

and CH chondrites (Campbell and Humayun 2004) fall within the range of meteorite metal shown in Fig. 3. The metal beads, therefore, are most likely the cores of I-type spherules and thus are not unmelted grains.

METEORITE ABLATION ORIGIN

The fact that unmelted metal particles are present in the reported Indian Ocean collection in abundances that exceed expectation and yet are absent in Antarctic collections is puzzling. The destruction of unmelted metal grains within Antarctic collections through weathering can be discounted since the degree of alteration, even within moraine hosted collections, is minor with abundant unaltered metal present (Van Ginneken et al. 2016). The localized abundance of unmelted metallic particles in the Indian Ocean collection is thus most easily explained by a local event, such as the disruption of a large iron bolide. Although meteorite ablation debris is rare compared to MMs owing to the much smaller mass of meteorites 10 t/yr compared to 1600 t/yr of MMs at the ground (Bland et al. 1996; Love and Brownlee 1993), the spatially restricted nature of terminal detonations can result in these particles being locally abundant (Genge and Grady 1999). The discovery of high abundances of meteorite ablation debris from a 480 kyr Tunguska-like event in the Transantarctic Mountains collection, in particular, demonstrates that these particles can be locally significant (Van Ginneken et al. 2010).

The very high, but unspecified, abundance of I-type spherules of up to 50% in the collection may also support the presence of abundant meteorite ablation debris. Studies of spherules associated with the fall of the Sikhote Alin meteorite closely resemble I-type cosmic spherules and include those with metal beads as well as those dominated by magnetite and wüstite, albeit with a higher abundance of magnetite-bearing particles (Badyukov and Raitala 2012). Particles similar to I-types are also found associated with Kamil crater but include those with somewhat unusual textures (Folco et al. 2015).

The nature of meteorite ablation debris is uncertain; however, ablation of numerous small bolides is likely to produce mainly molten spherules and to be less abundant than the MM flux. Fragmentation during an energetic detonation, however, can produce a mixture of melted and unmelted debris in a high local abundance. Harvey et al. (1998), for example, described that melted and unmelted silicate particles from the bit 58 layer at Allan Hills, Antarctica represent the product of the fragmentation of a large H chondrite meteoroid.

The mechanisms by which unmelted debris can survive such energetic events are uncertain; however, hydrocode simulations of fragmentation events suggest that rapid expansion of the solid meteoroid occurs once the ram pressure exceeds the characteristic strength of the material (e.g., Robertson and Mathias 2017). Unmelted dust particles are likely to be generated during rapid fragmentation through both differential pressure and comminution by fragment collisions; however, intense radiative heating at the leading face of the expanding debris cloud is likely to cause melting and evaporation. Survival of unmelted grains is thus most likely on the trailing face of the meteoroid, with dust-sized fragments removed into the low-pressure wake. Whether these particles survive is likely to depend on the optical opacity of the debris cloud, since this provides shielding from thermal radiation, and the extent of turbulent mixing in the meteoroid trail, which mixes higher temperature debris and gas into the trail. This hypothetical model of the formation of unmelted grains is shown in Fig. 4.

There would seem, therefore, to be appropriate mechanisms that could explain an enhanced abundance of melted and unmelted metallic particles over a region of the Earth's surface owing to the fragmentation of a large iron meteoroid. Whether the Indian Ocean particles are unmelted metal MMs or the product of fragmentation could perhaps be determined through a study of the exposure histories of particles owing to the likely shielding depth of particles generated by fragmentation. Whether they are the first unmelted MMs or the first iron meteoroid fragmentation products, these particles remain a clearly important discovery.

Acknowledgments—This work was funded by the Science and Technology Council (STFC) (grant number ST/J001260/1).

Editorial Handling—Dr. Donald Brownlee

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