Micrometeorites: Extraterrestrial particulate matter on the Earth

About 40,000 tons of cosmic dust rains on the earth every year – this constitutes the sub millimeter extraterrestrial material which is released into the inner solar system either by collisions between asteroidal material or by release from comets during their perihelional passage around the sun. This particulate extraterrestrial material constitutes 95% of all extraterrestrial matter that is attracted by the earth. This forms an important resource of solar system material and more importantly, it is distributed almost everywhere on earth. Either way, this material offers a unique window to understand not only early solar system processes, but also the earth crossing meteoroid complex. Cosmic dust has been collected from various domains such as deep sea sediments, beach sands, lithified sedimentary formations, Antarctica ice, from the Transantarctic Mountains, Greenland blue water lakes and from glacial sediments etc., each of which offers advantages which are unique. Perhaps the most technologically advanced and ambitious collections so far are by the Stardust Mission which captured micrograms of material from comet Wild 2. It took seven years and a space travel of 4.6 billion km to bring back unique samples. The other one is MUSES-C or the Hayabusa mission which embarked upon bringing back samples from asteroid Itokawa. These two missions offer exciting possibilities of sampling from the parent bodies directly. They are both seven year missions. While the first one delivers materials from a comet, the other from an asteroid.

Earth based collections offer the easiest access to cosmic dust. While meteorites are rare, cosmic dust is everywhere. Cosmic dust, cosmic spherules, micrometeorites are normally used interchangeably, although by definition cosmic dust is the extraterrestrial particulate material that is available in the interstellar and interplanetary medium; micrometeorites are individual particles which were earlier defined as material that has arrived on earth unmelted; and cosmic spherules are molten and solidified droplets of meteoritic material that has undergone melting during atmospheric entry. The term micrometeorite is more popular today, because it has been recognized that each such particle is a meteorite by itself, albeit much smaller in dimension (generally <1mm) than a conventional meteorite. The large collection of micrometeorites provides us an opportunity to look at a very wide spectrum of solar system materials, perhaps much wider than those represented by known types of meteorites. Therefore this becomes a very important resource of extraterrestrial matter available on Earth.

Cosmic dust collections

Deep sea

Nature facilitates micrometeorite collections in several environments: the deep sea regions in view of the prevalent low sedimentation rates would help concentrate cosmic dust. A meter thick layer of sediment could contain all the cosmic dust that fell in the spot in a million years (which would be in various stages of preservation). Deep sea was the preferred location for cosmic dust collection during the 1970s and 80s. Some of the more modern collections have been from the polar regions where the cryogenic conditions ensure better preservation of the extraterrestrial particulate matter. Several large scale collections were made from the deep sea. The ones that stand out are collections made by Millard and Finkelman, 1970; Brownlee et al., 1979; Murrell, 1980; Blanchard et al., 1980. Some of the more recent collections were carried out from the Indian Ocean and were investigated under the PLANEX project on cosmic dust. A simple magnetic panel was fixed to a deep sea dredge which was dragged along the seafloor and the material that was attracted to these panels was recovered carefully (Fig. 1) (Parashar et al., 2010; Rudraswami et al., 2011). All these methods used simple magnetic techniques. The underlying principle was that the iron in micrometeorites get magnetized during atmospheric entry so much so that a hand held magnet can perhaps extract most of the cosmic dust from any medium. These investigations, complimented by simulation studies, established some of the primary criteria for identifying the particles as cosmic. From these studies it has emerged that there are primarily three types of cosmic spherules: (1) the S-type or chondritic : these bear a direct resemblance to chondritic meteorites in terms of their compositions (Fig. 1a,b,c,d,e,f) (2) the I-type : which comprise of magnetite and wustite (a metastable mineral formed during the hypervelocity entry of the particle into earth under low oxygen fugacity conditions). The presence of wustite in a spherule was suggested as a sure shot evidence of its cosmic origin (Fig. 1G). (3) the G-type or the glassy type : comprising

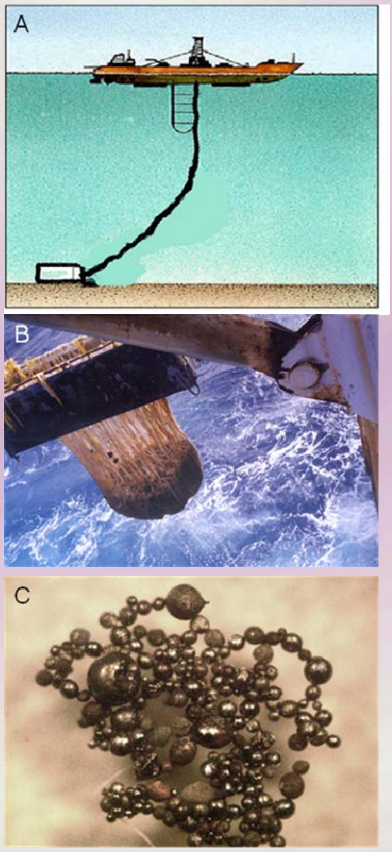

Figure 1.

A : Schematic diagram of a sledge dragged along the deep sea floor for collection of cosmic spherules

B : Image of a dredge which has a magnetic panel fixed (not seen in the picture) that has collected magnetic material from deep sea sediments of Indian Ocean

C : Photomicrograph of spherules recovered from the above operation

of a dendritic network of magnetite in an glassy matrix and the presence of an Fe-Ni bead (Fig. 2H). These types of micrometeorites were considered as intermediate between the S- and the I-types.

Space borne

Pioneering work on collection of interplanetary dust particles (IDPs) was initiated by Brownlee, such collections are now routinely carried out. During the 1970s, aircraft were flown with specially designed cosmic dust collectors mounted on them. The IDPs collected in the stratosphere (Brownlee, 1985) led to the discovery of the bunch of grapes structured 'brownlee particles' which were chondritic porous IDPs recovered in a pristine condition. In addition, several other unique particle types were recovered such as the metal mound silicate particles, and the FSN (Fe, sulfur and Nickel) particles and other micrometeorites that make up the earth – crossing meteoroid complex. These particles represent a unique group of extraterrestrial materials because they were found to contain some mineral assemblages which do not occur in any meteorite class.

Polar collections

Since the 1980s, large scale collections have been made in the polar regions – both the Arctic (Greenland) and the Antarctic. It has been recognized that the freezing conditions, and the fast rates of ice formation in the polar regions help preserve some very pristine, delicate micrometeoritic material which is not affected largely by the rigors of atmospheric entry. The polar collections therefore provide scope for collection of extraterrestrial particulate matter which can be collected on large scales. The largest among these collections are by the EUROMET (Maurette et al., 1992) where, in two different collection efforts, a massive quantity (~40,000 particles) were collected by melting several tens of tons of polar ice.

In these unique collections, in addition to unmelted micrometeorites several other hitherto unknown particles such as glass spherules, bubbly glass spherules, spherules with glass caps, and ones with sulfide coatings were also discovered. These collections also put valuable constraints on atmospheric entry heating of micrometeorites. If the time of fall of the particles could be well constrained, it was also possible to ascertain the absolute flux of particles that survive atmospheric entry. Further, Taylor et al. (2000) presented a sub-classification of the S-type spherules based on their structures which were reflective of the degree of alteration (heating and melting) experienced by each of the spherules during atmospheric entry.

PARENT BODIES OF MICROMETEORITES

While collecting material directly from the parent bodies are unique, rare and expensive, they offer the possibilities of directly looking at early solar system processes such as formation and origin of comets themselves, interstellar material, and probably the origin of life on earth. It is further seen that 87% of the meteorite flux is constituted by ordinary chondrites, whereas the parent bodies conceived from micrometeorites are reverse i.e, 70% of these are assigned carbonaceous chondrite parent bodies and only 30% are assigned an ordinary chondrite parent body. This might mean several things : since the carbonaceous chondrites are more friable they fragment much more easily during asteroidal collisions and generate more dust size particles. However, in a very recent finding it was observed that some of the glassy spherules (0.5%; which were previously assigned a chondritic parent body) actually have HED meteorites as progenitors. Further, the scoriaceous micrometeorites (Figure 2a) have compositional heterogeneities at micrometer levels which have not been observed in carbonaceous chondrites – the most preferred parent bodies of these micrometeorites. Identifying the contributing progenitors to the earth crossing meteoroid flux is still an evolving area.

Oxygen isotope investigations:

Study of oxygen isotopes (specifically $\Delta^{17}O$) in meteorites is the primary tool for classification of meteorites as it reflects the composition of the original parent body. Even upon melting and recystallization, isotopic composition shift along well defined slope half line therefore $\Delta^{17}O$ remain unchanged. Therefore study of oxygen isotope of micrometeorites can be helpful in establishing their relation to the known meteorite class. Several recent investigations have been undertaken on the oxygen isotopes of cosmic dust/micrometeorites.

Taylor et al. (2005) analysed eight Antarctic micrometeorites for oxygen isotopes. Selection of particles was carried out based on an earlier classification of silicate spherule texture by Taylor et al. (2000). The study aimed at identifying the relationship between microparticle texture and its degree of heating and also the possibility of deriving information for the identification of possible parent bodies. Yada et al. (2005) investigated chemical compositions, in addition to oxygen isotopes of 48 stony cosmic spherules, they however did not find any identifiable correlations between the particle texture and isotopic compositions. While the values derived from a majority of the spherules implied a carbonaceous chondrite parent body, however, oxygen isotopic ratios of one of the spherules showed an excess $\Delta^{17}O$ not observed before in any known extraterrestrial material.

More recent investigations using sophisticated instrumentation analyzed all the different types of spherules. These studies further suggested that these isotopic analyses would permit estimates of mass loss from cosmic spherules, which in turn would help in fine tuning the estimates of particle flux to Earth. In addition, Herzog et al. (1999) suggested that most type I spherules are atmospherically processed metal grains from carbonaceous chondrite-like bodies. Suavet et al. (2009) presented an interesting concept that 99% of the small micrometeorites (150 -250 µm) have a carbonaceous (CM/CR related) /cometary parent bodies, whereas their oxygen isotopic investigations on large micrometeorites (>500 µm) showed that ~30% of these particles are related to ordinary and R chondrites. Further, micrometeorites with similar textures could

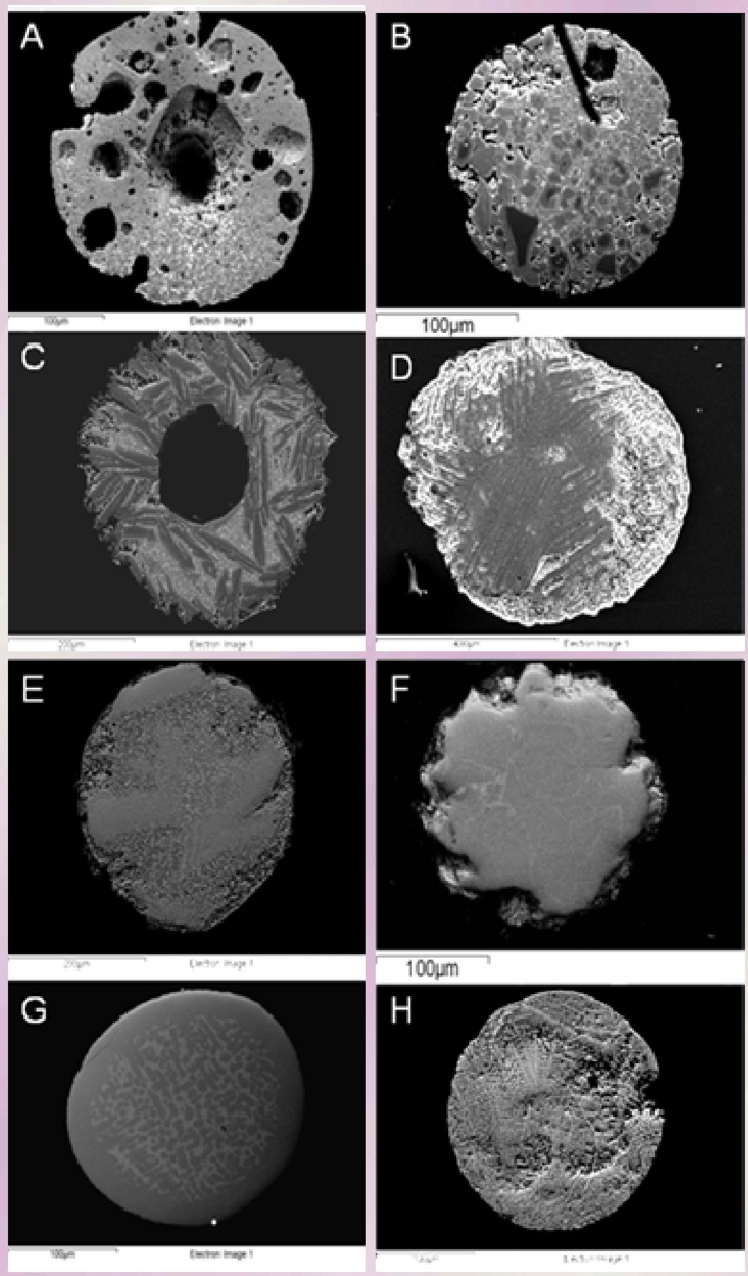

Figure 2. Polished sections of cosmic spherules from the Indian Ocean : A – F are S-type cosmic spherules in the sequence of increasing melting and evaporation as classified by Taylor et al. (2000).

A : Scoriaceous micrometeorite with void spaces which were occupied by volatiles; B : Relic grain bearing spherule. Large, dark colored grains are relic forsterite grains; C : Porphyritic micrometeorite with large olivine grains in a matrix of glass; D : Barred olivine micrometeorite where lathes of parallelly aligned olivine grains are present with interstitial glass and magnetite;. E : Cryptocrystalline micrometeorite with minute grains of olivine and magnetite; F : Glassy micrometeorite, which has experienced maximum heating during atmospheric entry where the entire spherule is smooth textured and glassy in appearance; G : I-type Micrometeorite with interlocking crystals of wustite (grey coloured) and magnetites (dark colored). A rare platinum group nugget is seen at the bottom of the spherule; H : G-type spherule with dendritic network of magnetite crystals in a glassy silicate matrix, this type of spherules also contain an Fe-Ni bead.

have been derived from different parent bodies. Another independent investigation suggested that size does matter when one looks at micrometeorites. Distinct chemical and mineralogical differences exist between IDPs, micrometeorites and meteorites and their components. Therefore, the larger micrometeorites or minimeteorites should represent transitional components between micrometeorites and the larger meteorites. In all the above investigations, a majority of the samples showed effects of mass-dependent fractionation of oxygen due to evaporation especially in the I-type spherules. This in itself would provide a window to the understanding of the effects of flash melting.

More importantly, all the above studies also indicated an exotic component not observed so far. Some of these contrasting conclusions from these investigations point towards a possibility that there are gaps in our understanding. Therein lies the challenge : is there a much larger spectrum of extraterrestrial material than that we know from our knowledge of meteorites ?

One final word : although there has been a primary division of cosmic spherules into three types, namely, the S-, G- and the I-types, Brownlee could not find a gradation from the G-type to the other S-type spherules. Further, detectable levels of ^{26}Al found in I-type spherules suggest that these are primary bodies – which contrasts the present understanding that these spherules are melt derivatives from chondritic micrometeorites during atmospheric entry. And, the micrometer scale of inhomogeneity observed in scoriaceous (S-type) spherules has not been observed in the proposed parent bodies, such as CI, CV or CM carbonaceous chondrites. Therefore, there are explanations which add to the understanding on the origins of these three types of spherules.

Investigations on micrometeorites have been ongoing since ~130 years. Brownlee (1985) estimated a million micrometeorites in the collections worldwide two and half decades ago, the number would of course, be much larger today. We seem to have just scratched the proverbial tip of the iceberg with many more exciting discoveries ahead.

Further reading :

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