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Morphological, Chemical and Mineralogical Studies of Cosmic Dust [and Discussion]

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Morphological, chemical and mineralogical studies of cosmic dust

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Significant numbers of 5 μm–1 mm particles of interplanetary dust have been collected and subjected to laboratory analysis. The extraterrestrial origin of selected samples has been established by detection of space-exposure effects such as implanted solar wind and tracks of solar cosmic rays. The collected samples should contain both cometary and asteroidal particles. The asteroidal component is probably a representative sample of typical main-belt asteroids. The elemental composition of the majority of particles is similar to CI and CM chondrites. Most particles can be grouped into one of two general classes, those that contain hydrated minerals and those that are anhydrous. Some of the hydrated particles may be samples of CI/CM matrix whereas most of the anhydrous particles are clearly unrelated to any known chondrite class. Some of the anhydrous particles are very porous aggregates that at least superficially resemble models of cometary meteors. Future studies of cosmic dust will probably lead to criteria for distinguishing between asteroidal and cometary particles.

INTRODUCTION

The submillimetre particles that permeate the interplanetary medium are commonly referred to as cosmic dust. The particles crater lunar rocks and spacecraft and they enter the atmosphere at an annual rate of 10^4 t. The flux of 10 μm dust particles near the Earth is relatively high, about 1 m^2 d^{-1} but the spatial density is less than 1 km^{-3}. Dust-impact craters found on buried lunar samples suggest that the current dust density has remained roughly constant over much of the Solar System's history. This is remarkable in light of processes that destroy interplanetary dust at a rate of 10 t s^{-1}. Dust particles are lost from the interplanetary medium on timescales of 1000–100000 years because of collisions and orbital decay caused by the drag component of sunlight pressure (Grün *et al.* 1985). Steady-state survival of the Solar System dust cloud requires continual injection of fresh particles. For most of the Solar System's history the major suppliers of new dust have been comets and asteroids. Comets are widely believed to be the major dust source but the infrared emission from asteroid dust measured by the IRAS satellite indicates that dust from asteroid collisions may also be a significant component (Zook & McKay 1986).

Recovered samples of cosmic dust particles are of major scientific interest because they are samples of bodies believed to be relic planetismals preserved since the earliest history of the Solar System. Analysis of collected dust samples is an interesting compliment to studies of conventional meteorites because there are classes of extraterrestrial material that are only collectable in the form of dust. Unlike meteorites, collectable dust samples may be rather representative samples of the asteroids and comets in the planetary system. Conventional meteorites are wonderful samples for investigating early Solar System history but they are limited because only certain types of extraterrestrial materials can become meteorites. To become a conventional meteorite an object must be relatively large (so that it can be found on the ground), it must have undergone a rare set of gravitational perturbations to reach an earthcrossing orbit and lastly it must be sufficiently strong to survive the mechanical and thermal stresses experienced by rock-sized objects entering the atmosphere at hypervelocity. Dust particles, on the other hand, have fewer orbital restrictions because they diffuse through the Solar System because of light pressure drag (the Poynting–Robertson (P–R) effect) and they do not have to be strong to survive atmospheric entry. Dust particles decelerate at altitudes where the air density is low and the maximum dynamic ram pressure is orders of magnitude lower than that experienced deeper in the atmosphere by larger meteorites travelling at hypervelocity. Thus atmospheric entry is a filter that allows weak materials to survive as dust but not as objects larger than a centimetre. This filter may be critical for cometary materials because observation of the entry of visual cometary meteors indicates that typical cometary samples are more fragile than the weakest recovered conventional meteorite specimens.

Collection

Collection of 2–50 μm particles is done routinely in the stratosphere by using impactors mounted on U2 aircraft and particles up to millimetre size have been recovered in abundance from the ocean floor and from blue ice lakes in Greenland. Some particles have been collected from orbiting spacecraft but most have been appreciably altered because the high velocity of collection. The most pristine particles are those collected in the stratosphere. They are small and hence minimally heated and they have not undergone chemical reactions with terrestrial materials. Typical stratospheric particles are heated (uniformly) to about 500 °C for a few seconds during entry. Particles entering at low velocity and at near grazing incidence angle can survive without being heated above 300 °C. Most particles larger than 100 μm are heated to their melting points and they form spheres often called 'cosmic spheres'. Because of magnetite formation most of the spheres are magnetic and they can be collected from deep sea sediments and Greenland ice lakes with simple magnets. These larger particles are too rare to collect in the atmosphere. The first deep-sea cosmic spheres were collected during the *Challenger* expeditions of the past century.

The majority of all collected particles have chondritic elemental compositions and their distinction from terrestrial contamination is usually quite straightforward (Brownlee 1985). Individual particles have been proven to be extraterrestrial on the basis of implanted solar wind, solar-flare tracks, trace-element composition and cosmogenic isotopes produced by cosmic-ray irradiation. Both the spheres and the smaller unmelted particles (micrometeorites) are important sources of information on interplanetary dust. The small particles are the best preserved but the spheres are individually more massive and they can be collected in unlimited quantities. The largest deep-sea spheres contain over 10^6 times the mass of the typical particle collected in the stratosphere.

Chemical composition of the dust progenitors

For the refractory elements, the average dust elemental compositions are best determined from the massive cosmic spheres larger than 300 μm in size. Analysis of hundreds of unweathered particles has shown that 85% of the particles have Mg, Al, Si, Ca, Ti and Mn compositions compatible with those of the CI and CM meteorites (Bates 1986). Volatile elements and many of the siderophile elements are lost from cosmic spheres during atmospheric entry. The analyses indicate that only a minor fraction of the samples could have been derived from ordinary chondrites or achondrites and it is clear that the relative abundance of meteoroid composition types in the dust differs radically from the meteorites. Only 2.5% of meteorite falls are of the CI or CM type (Wasson 1974).

If dust particles truly are a representative sampling of the Solar System's minor bodies, then the particle analyses imply that most of these bodies have unfractionated major and minor refractory element abundances similar to these very rare meteorite types. If, as expected, most of the spheres are cometary then the major dust producing comets must also have this composition. Except for special effects attributable to single mineral grain precursors there are no major subdivisions among the chondritic composition spheres.

The small unmelted particles collected in the stratosphere do not appear to have suffered loss of volatiles during entry. It is likely that the small particles are genetically related to the larger dust fragments and their volatile abundances are probably also representative of the sphere producing particles before they entered the atmosphere. Unfortunately the analysis of minor elements in the stratospheric particles is not straightforward and because of smaller sample size there is more dispersion in the data. The existing volatile measurements for C, S, Zn and Br all indicate high volatile abundances similar to CI meteorites (van der Stap *et al.* 1986) but the data are limited to a small set of particles.

Some of the collected particles are single mineral grains or are clusters of a limited number of grains and these samples do not have chondritic elemental abundances. The striking result, however, from years of work is that the bulk of all particles in the 5–1000 μm size have compositions similar to CI or CM meteorites. This rather monotonous result indicates that the particles must be fine grained and not substantially fractionated from what is believed to be solar composition. It is significant that no meteorite type including the CIs and CMs have this homogenous composition on a size scale as small as the interplanetary particles.

Mineralogical and morphological dust types

Some of the deep-sea and Greenland samples contain unmelted relict mineral grains. The grains are normally contained in a matrix that is usually either recrystallized melt or unmelted fine grained material. The general abundance of large mafic grains is higher than observed in CI meteorites. Commonly the relict grains are forsterite, enstatite and pyrrhotite. Rarer phases include FeNi metal, spinel, diopside and perovskite. The trace element content of the forsterite grains indicates a similarity to the CM meteorites (Steele *et al.* 1985).

Unfortunately the deep-sea samples that were not strongly altered by heating during atmospheric entry are altered in the ocean sediment environment and so little can really be said about their original morphology of the nature of their submicrometre mineral grains. Sea-floor weathering does not harm many of the large grains but its effect on the small ones makes direct comparison with the stratospheric particles difficult. The true nature of the larger particles cannot be studied directly.

The stratospheric particles are well preserved and mineral grains can be studied well into the submicrometre-size region. Most of the particles that do not have chondritic elemental compositions appear to be single mineral grains or grain clumps that were previously imbedded in fine grained material of chondritic composition. Most of these particles are composed of olivine, pyroxene or sulphide and they are encrusted with black chondritic material. They appear to be mere fragments from chondritic host materials. The most important materials to study are the chondritic particles where mineral chemistry and structure can be studied for coexisting grains in a given particle.

Although there may be a variety of subgroups the major subdivisions of chondritic dust particles are those that contain hydrous minerals and those that do not. These are truly distinct particle types that differ in morphology and mineralogy. The hydrated particles are largely composed of hydrated silicates with lesser amounts of sulphide, magnetite and anhydrous mafic minerals (Tomeoka & Buseck 1986).

In some cases the dominant hydrous phases are serpentines with basal spacings of 7.2 Å† and in others they are smectites with spacings of 11 Å. Although there are some exceptions, most of the hydrated particles are compact masses of platey phyllosilicate sheets and fibres. Their porosity is low and externally they often are smooth at the micrometre level. The anhydrous particles are aggregates of fairly equidimensional grains ranging in size from the submicrometres to micrometres. As viewed in the SEM some of these particles resemble porous grape clusters where the individual grapes are typically 0.3 μm in size. The most porous of these particles have densities of less than unity and they are the most porous meteoritic materials (Bradley & Brownlee 1986).

The individual grains in the anhydrous samples are of three types; single mineral grains, carbonaceous matter and 'tar balls'. The tar balls are collections of 100–1000 Å mineral grains imbedded in a yet uncharacterized carbonaceous material. The tar balls are unique to the anhydrous particle type. Individual phases in the anhydrous particles include enstatite, olivine, NiFe carbide, pyrrhotite, pentlandite, magnetite, albite and trace amounts of metal and other phases.

The hydrated particles are similar in many ways to CI and CM meteorites while the anhydrous particles are distinct from all established meteorite groups. Many of the hydrated types could come from the same parent materials that produce CI and CM meteorites although the H isotopic data (see elsewhere in this symposium) and the existence of smectites argues against a simple direct genetic relation. The porosity of the anhydrous particles is quite distinct from the chondrite classes which are all solid rocks with minimal pore space. The porosity of these samples is consistent with models for cometary grains. Unfortunately it is not known if such porous fine grained material could survive in the internal environment of asteroids that contain no ice to fill pore spaces and have extensive histories of collisional modification.

ORIGINS

A major thrust of future laboratory studies of interplanetary dust will be to determine the origins of some of the different classes of particles. This will involve synthesis of laboratory analytical data, astronomical observations and data from cometary missions. Even the general distinction of cometary and asteroidal particles might provide valuable insights into early Solar System processes. The asteroidal dust particles that have been collected are probably representative samples of the typical main-belt asteroids and are therefore presumably typical

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† 1 Å = 10^{-1} nm = 10^{-10} m.

of the materials that accreted in the Mars–Jupiter region of the solar nebula. The cometary dust samples may or may not be particles from typical comets but at least they must be samples of materials that accreted well beyond the orbit of Saturn. The relative properties of samples from these two regions should relate to differences in the temperatures, pressures, gas compositions and processes that occurred in the inner and outer regions of the solar nebula. For example, if the porous anhydrous particles were shown to be cometary and the compact hydrated particles were shown to be asteroidal, then this would give direct insight into the nature of the processes that produced water bearing silicates in the nebula. In addition to the distinction of asteroidal and cometary particles, a major goal of future activity will be to identify possible presolar components that might exist in either particle type. Because comets formed in very cold regions of the nebula it is likely that presolar grains in cometary solids might have survived Solar System processes with minimal alteration.

A key to the distinction of cometary particles from asteroidal ones is the analysis of dust on cometary missions. The recent data on the elemental composition of individual Halley particles (Kissel *et al.* 1986) combined with future elemental, isotopic and morphological analysis on proposed comet rendezvous missions may provide definitive criteria for identifying cometary particulates. The ultimate information source for this work, of course, will be direct cometary sample return, an ESA cornerstone mission. Even when there have been several comet missions, including a sample return mission, the interplanetary particles will still be of value because they are samples of a larger set of parent bodies than could be visited by spacecraft. In addition to the mission results there are other possible methods of distinguishing asteroidal and cometary particles. Sandford (1986) has discussed a technique involving the densities of solar-flare tracks in crystalline grains. Particles spiralling in from the asteroid belt by P–R drag all have exposure times and hence track densities above a minimum value while cometary particles have a broader range of exposure including some that can be very short. Another cosmic-ray exposure technique involves the concentration of ^{10}Be a cosmogenic isotope produced primarily by exposure to galactic cosmic rays. Raisbeck & Yiou (1985) found a ^{10}Be concentration in a single deep-sea sphere that was above the saturation value that occurs at 1 AU and they suggested that the particle was irradiated in the outer Solar System where the galactic cosmic ray flux was less modulated by the solar magnetic field. Other observable properties such as spectral reflectivity might also be useful for matching particle types with parent bodies.

The search for presolar components is an active area in meteorite research and in dust studies. Possible ways of connecting meteoritic materials with interstellar grains are to search for isotopic or spectral features that are unique to interstellar grains. The strongest isotopic link for the laboratory dust samples are the high D/H values for several micrometeorites measured with the ion microprobe by McKeegan *et al.* (1985). The high D/H ratios are suggestive of a link to the ISM because such strong fractionation is unknown in the Solar System but it is common in molecular clouds, where it is believed to be produced by ion–molecule reactions. Spectral links to particular particle types might be made by the analysis of well-known interstellar features in the IR, UV and visual. These include the shape of the 9.7 μm 'silicate feature', the 2175 Å bump, the diffuse bands and an assortment of IR features. High quality IR spectra for individual 10 μm particles have been reported by Sandford & Walker (1985) and Sandford (1986). These authors made an interesting comparison of the IR features in a hydrated micrometeorite with the highly reddened protosellar object W33 A. In addition to a good fit for the silicate feature at 9.7 μm there is also a good correspondence for the features at 6 and 6.8 μm. As an interesting case of scientific synergism, the 6.8 μm feature in the dust particle was shown to be due to carbonates because electron microscopy showed that carbonates were abundant in the particle, and that after acid treatment the carbonates and the 6.8 μm feature were gone. Although this does not prove that the dust in W33 A contains carbonates it suggests this and it does demonstrate that there are fascinating possibilities for linking purely astronomical observations with studies of meteoritical materials.

REFERENCES

Bates, B. 1986 Ph.D. thesis, University of Washington.
Bradley, J. B. & Brownlee, D. E. 1986 *Science, Wash.* **231**, 1542–1544.
Brownlee, D. E. 1985 *A. Rev. Earth planet. Sci.* **13**, 147–173.
Grün, E., Zook, H. A., Fechtig, H. & Giese, R. H. 1985 *Icarus* **62**, 244–272.
Kissel, J. *et al.* 1986 *Nature, Lond.* **321**, 336–337.
McKeegan, K. D., Walker, R. M. & Zinner, E. 1985 *Geochim. cosmochim. Acta.* **49**, 1971–1987.
Raisbeck, G. M. & Yiou, F. 1985 *Meteoritics* **20**, 734–735.
Sandford, S. A. 1986 *Science, Wash.* **231**, 1540–1541.
Sandford, S. A. & Walker, R. M. 1985 *Astrophys. J.* **291**, 838–851.
Steele, I. M., Smith, J. V. & Brownlee, D. E. 1985 *Nature, Lond.* **313**, 297–299.
van der Stap, C. C. A. H., Vis, R. D. & Verheul, H. 1986 *Lunar planet. Sci.* **17**, 1013–1014.
Tomeoka, K. & Buseck, P. R. 1985 *Nature, Lond.* **314**, 338–340.
Wasson, J. T. 1974 *Meteorites.* (316 pages.) New York: Springer Verlag.
Zook, H. A. & MacKay, D. S. 1986 *Lunar planet. Sci.* **17** 977–978.

Discussion

J. DARIUS (*University College, London and Science Museum, U.K.*). Because some of the submicrometre particles Professor Brownlee described have high carbon content, can he distinguish decisively between anhydrous grains of low exposure age and particles of terrestrial origin such as volcanic ash?

D. E. BROWNLEE. All of the high-carbon grains mentioned here are constituents of larger particles that have chondritic elemental abundances. To my knowledge no terrestrial particle in this size range matches chondritic composition for the elements that are routinely measured with the electron microscope (Na, Mg, Al, Si, S, Ca, Ti, Cr, Mn, Fe and Ni). Volcanic ash is collected in the stratosphere following some eruptions and it is usually straightforward to identify on the basis of composition and morphology.

M. K. WALLIS (*Department of Applied Mathematics and Astronomy, University College, Cardiff, U.K.*). May I dispute the long-standing supposition that P–R drag removes the interplanetary dust?

Firstly, lifetimes of 100 μm grains to P–R drag are so long that destructive collisions with the smaller grains measured by spacecraft are dominant (Leinert *et al.* 1983; Grün *et al.* 1985).

Secondly, the mean radiation pressure due to geometric asymmetries gives tangential forces on elongated grains (Voshchinnikov & Il'in 1983) that are much stronger than the P–R drag calculated for spherical grains, which is small through the 10^{-4} relativistic factor.

Thirdly, electromagnetic forces on the charged grains and fragments under 1 μm in size cause mean diffusion out of the Solar System, overwhelming the inwards P–R drag (Wallis 1986).

So please reorient your thinking away from the P–R transport and loss concept, which neither fits the interplanetary data nor accords with theory.

Additional references

Leinert, C., Röser, S. & Buitrago, J. 1983 *Astron. Astrophys.* **118**, 345.
Voshchinnikov, N. V. & Il'in, V. B. 1983 *Soviet Astr. Lett.* **9**, 101.
Wallis, M. K. 1986 *Nature, Lond.* **320**, 146.

D. E. Brownlee. Lifetimes of micrometre-sized dust in the interplanetary medium are limited by the effects of collisions, radiation pressure drag (the P–R effect) and radiation pressure 'blow out'. Sputtering and Lorentz effects are probably only important in the sub-micrometre region. Collisions have generally been considered to be the dominant destructive effect for particles larger than 100 μm and P–R drag the major effect for the few micrometre to 100 μm range. This is clearly shown in figures 6 and 8 in Grün *et al.* (1985). For 10 μm particles, the size most commonly collected in the stratosphere, the P–R lifetime is a factor of 100 shorter than the collisional lifetime. The P–R lifetimes for this size are consistent with particle exposure ages calculated from the measured densities of solar-flare tracks in collected micrometeorites. If 10 μm particles were only removed by collisions, their million-year exposures would result in track densities high enough to obliterate internal crystal structure. If the anisotropy effect described by Voshchinnikoav & Il'in is important for real interplanetary particles, as well and the cylinders described in their paper, then this effect could considerably effect the orbital evolution of interplanetary dust.

G. W. Wetherill (*Department of Terrestrial Magnetism, Carnegie Institute of Washington, U.S.A.*). Assuming these particles are derived from comets, what would one expect their dynamical history to be; for example the relative importance of Poynting–Robertson effect, collisional destruction and radiation pressure?

D. E. Brownlee. I do not think that we really understand the evolutionary histories of interplanetary dust. If the model of Grün *et al.* (1985) is correct then we would expect that the typical 10 μm cometary-dust particle at 1 AU would be a fragment of a millimetre-sized meteoroid. The model predicts that the meteoroids of less than 100 μm are produced by collisional fragmentation of millimetre-sized particles. The collisional destruction of the larger particles is predicted to occur on a timescale of only 10000 years. The 10 μm particles liberated by this process would have additional lifetimes of the order of 10000 years before the P–R drag causes sufficient orbital decay that they are destroyed near the Sun. During orbital decay, their orbits would become partially circularized. The major discrepancy between this model and observations, is the short lifetime of the millimetre-sized particles. The measured cosmic ray exposure times of the millimetre-sized spheres collected from the ocean floor and Greenland are a 100 times the predicted collisional lifetimes. The fragmentation laws used in the model assume that the particles fragment in a manner similar to the large pieces of basalt that have been experimentally well studied with hypervelocity impacts in the laboratory. Real meteoroids may respond quite differently. So far no shock effects have been recognized in collected samples of interplanetary dust.