8

Cosmic Dust

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Dust is a ubiquitous component of our galaxy and the solar system. Its average spatial density is less than one particle per cubic kilometer but the total number of particles is large. The particles are so prevalent that both interstellar and interplanetary dust can readily be seen with the naked eye under dark sky conditions. Zodiacal light, a glow usually seen in the east before dawn twilight and in the west following sunset, is sunlight reflected off dust particles orbiting the Sun. The dark band marking the central plane of the Milky Way is caused by absorption of background starlight by dust concentrated in the plane of our galaxy. In fact, dust is so prominent that light typically travels only a thousand years in the plane of our galaxy before it is absorbed by dust. The distance traversed in this time is only 1% of the diameter of the galaxy.

Interstellar dust is the predominant form of the condensable elements in the galaxy that are not in stars. The grains form in gas outflows from stars and they are processed, perhaps even destroyed and reformed, in the interstellar medium and molecular clouds. Interplanetary dust is debris recently liberated from comets and asteroids within the solar system. There is a strong link between interplanetary and interstellar dust. Prior to

formation of the solar nebula, most of the atoms heavier than helium that found their way into our solar system were contained in interstellar grains. Some of these grains were incorporated into comets and asteroids. Comets forming in the outer fringes of the nebula presumably contain relatively higher abundances of presolar grains. Many of the grains preserved in comets may then be older than the Sun and planets. Comets are thus vehicles potentially capable of carrying the products of interstellar chemical processes directly to planets. They are believed to contain substantial organic components produced in space by nonequilibrium reactions such as catalysis and radiation processing of condensed volatiles.

The collection and analysis of extraterrestrial dust particles is important to exobiology because it provides information about the sources of biogenically significant elements and compounds that accumulated in distant regions of the solar nebula and that were later accreted onto the planets. Both interstellar and interplanetary dust seeded the early Earth with elements and compounds that may have played important roles in the origin and development of life. Interplanetary dust particles (IDPs) that are collected in the stratosphere and analyzed in the laboratory are preserved fragments from asteroids and comets, bodies which formed in the outer regions of the solar nebula, are relatively rich in volatiles, and which are a source of abiotic organic molecules that have fallen to Earth throughout its history.

Interplanetary dust particles accreted by the Earth must first enter the atmosphere. They enter the atmosphere at velocities ranging from 11.2 km/s, the Earth's escape velocity, to a maximum of 72 km/s, the velocity of a head-on impact with a particle in a retrograde parabolic orbit. The kinetic energies corresponding to these velocities are capable of melting or vaporizing the incoming particles if the energies are converted to internal heat. In the case of conventional meteorites, the surfaces are heated to vaporization temperatures, although the short time scale of heating and the combined effects of thermal inertia and conductivity confine melting and strong heating to the outer millimeter or so of the body. The interiors of the meteorites remain essentially unheated. Dust particles in the 0.1 mm to several mm size range typically also experience melting from atmospheric drag but, because of their smaller size, they tend to have isothermal interiors and they melt completely, resulting in the loss of volatiles such as sulfur, sodium, and organic matter. Such particles form melt spheres (cosmic spherules) that have been collected in abundance from the ocean floor and polar ice deposits.

Particles smaller than 0.1 mm, however, enjoy a special advantage over conventional meteorites and larger dust particles. These grains can usually enter the atmosphere without melting. This is possible because the particles only travel at high velocity at altitudes above 90 km where the air is very tenuous. For a given velocity, the frictional power density generated on the face of a particle depends only on the local air density. At 90 km, the frictional energy is generated slowly enough that it can be thermally reradiated without the particle being heated to its melting point. Smaller particles decelerate at higher altitudes and for a given initial velocity there is a limiting size below which no melting will occur. Particles that do not melt are called micrometeorites and are genuine samples of interplanetary dust. Most particles below 50 μm in size do not melt upon atmospheric entry and the survival of solar flare cosmic ray tracks and minerals with low thermal stabilities in the particles indicate that typical 10 μm particles are not heated above 600°C.

An additional factor favoring the survival of interplanetary dust during atmospheric entry is the fact that they are not subjected to large ram pressures during atmospheric deceleration. The ram pressure experienced by dust particles is orders of magnitude smaller than must be survived by larger objects such as conventional meteorites. This allows fragile materials to enter as dust but prevents them from surviving as millimeter or larger sized objects. At a given velocity the ram pressure is proportional to the ambient air density. The maximum ram pressure experienced by a micrometeorite that decelerates near 90 km is 100,000 times smaller than that experienced by a 10-kg rock that has retained its cosmic velocity down to an altitude of 40 km. Even the most fragile conventional meteorite is a factor of 100 times stronger than the materials observed in cometary meteor showers. The altitudes and velocities where cometary meteors are observed to fragment imply typical crushing strengths of 10^5 dynes/cm^2 and in the extreme case of the Draconid meteors (the youngest meteor stream) the pressure is only 10^3 dynes/cm^2. Micrometeorites this fragile can enter the atmosphere without fragmentation whereas larger objects cannot.

Thus, typical cometary rocks cannot enter the atmosphere without being crushed. Once crushed, most fragments should either melt or vaporize because fragmentation occurs at lower altitudes where frictional heating of small hypervelocity particles is severe. If comets do not contain any strong centimeter and larger components, then dust would be the only meteoroid type that could carry cometary molecules to the Earth's surface.

Micrometeorites ranging in size from 5 to 50 μm are routinely collected in the stratosphere using high-altitude aircraft. The particles are characterized and curated for distribution to investigators worldwide. Most of the particles are easily identified as extraterrestrial on the basis of their elemental composition which is similar to that of primitive meteorites but quite different from most terrestrial particles. Typical particles are composed of Mg, Si, Fe, S, Ca, Na, Al, Ni, Mn, Cr, and Ti in ratios that match their relative abundance in the Sun. Oxygen and carbon are also major constituents but, as in meteorites, their relative abundances are less than solar. An extraterrestrial origin can be proven for any given particle by detection of He implanted by the solar wind or tracks in mineral grains produced by solar flare cosmic rays. As previously mentioned, larger particles are also recovered from deep sea sediments and from polar ice (Greenland and Antarctica). Particles larger than 0.1 mm are usually melted, but a few particles up to 1 mm survive without any melting. These rare, giant micrometeorites are presumably particles that entered at relatively low velocity and very low incident angles. In low-angle impacts the hypervelocity interaction with the atmosphere occurs at higher altitudes and results in prolonged but less severe heating.

General Properties of Interplanetary Dust

The most common IDPs collected from the stratosphere are black, fine-grained materials that have major and minor element compositions similar to those of carbonaceous chondrites, i.e., primitive meteorites. Particles with this composition are referred to as being "chondritic" even though they may have no actual relation to chondritic meteorites. Some micrometeorites do not have chondritic compositions, but many of these are large single-mineral grains that have surficial debris indicating that they were previously embedded in larger samples of fine-grained chondritic material. The "chondritic" particles are small (typically less than 20 µm in diameter) and classifying them into meaningful groups is much more difficult than with conventional kilogram-sized meteorites. The primary properties that can be readily measured are morphology, elemental composition, and mineralogical composition as determined by both electron microscopy and infrared spectroscopy. The particles can be grouped into two major classes: those dominated by hydrated (layer-lattice) silicates and those dominated by anhydrous silicates, of which pyroxene and olivine are the most common. These differences are clearly seen in infrared spectra of individual particles (fig. 8-1).

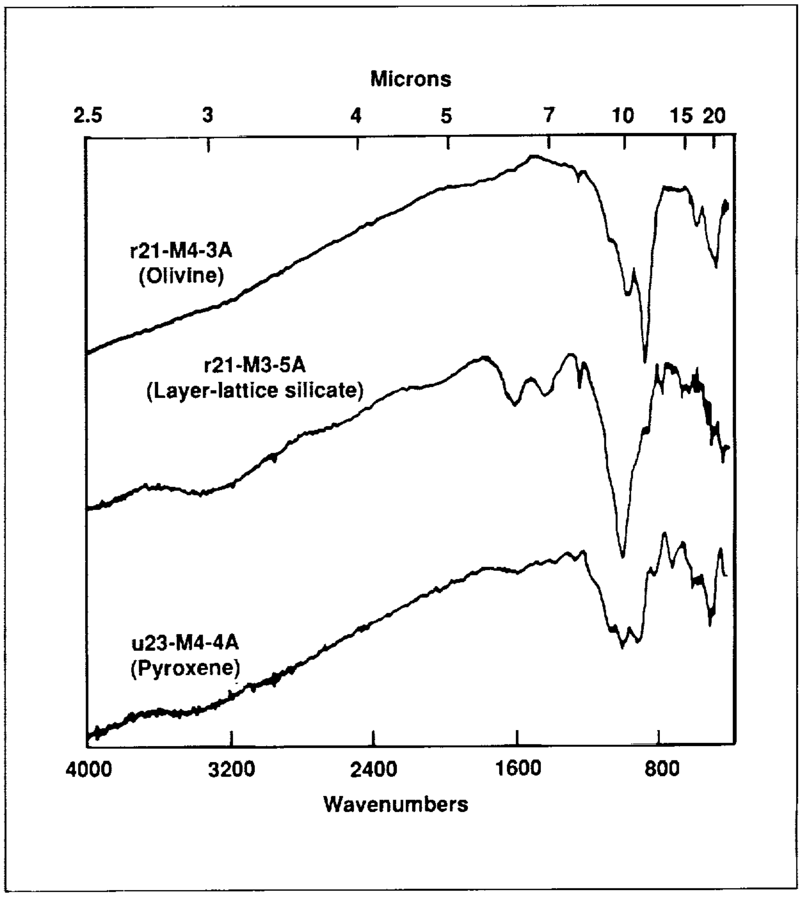

Figure 8-1. The three major infrared spectral IDP classes. From top to bottom, these spectra are representative of IDPs dominated by the minerals olivine, layer-lattice silicates, and pyroxenes, respectively. The spectra can be easily separated by the profiles of their characteristic 10 µm (1000 cm^{-1}) Si-O stretching features. The spectra also show longer wavelength features due to Si-O-Si bending vibrations in the silicates. In addition to the Si-O bands, spectra from the particles dominated by layer-lattice silicates also show bands centered near 3.0 and 6.0 µm (3330 and 1670 cm^{-1}) due to O-H stretching and H-O-H bending vibrations in adsorbed and absorbed water, and bands near 6.8 and 11.4 µm (1470 and 875 cm^{-1}) due to C-O stretching and CO_3 scissoring vibrations in carbonates. Note the minor features at 3.37, 7.94, and 12.53 µm (2970, 1260, and 798 cm^{-1}) due to silicon oil in the middle spectrum.

The hydrated particles are similar to two types of primitive meteorites known as the CI and CM carbonaceous chondrites. These meteorites are dominated by layer-lattice silicates and they are the only chondrites that have carbon abundances appreciably above 1% by weight. The bulk of hydrated IDPs is composed of tangled masses of layer-lattice silicate sheets and fibers. There are two subgroups of hydrous IDPs, one dominated by serpentine-like minerals with 7 Å basal spacings typical of CI and CM meteorites, and one dominated by a layer-lattice silicate with 10-12 Å spacings not seen in most meteorites. Like the conventional meteorites, most of the hydrated IDPs are compact objects having only minimal pore spaces (fig. 8-2). Like the CI and CM chondrites, many of these particles have properties consistent with processing by aqueous alteration on a parentbody. These include the existence of carbonates, clusters (framboids) of rounded magnetite grains, and redistribution of Ca and Mg, elements that often are components of water-soluble

Figure 8-2. A scanning electron microscope photograph of a particle dominated by hydrated (layer-lattice) silicates. These particles are generally compact and contain little void space. The white scale bar on the photograph is 10 µm long.

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minerals. The CI and CM chondrites are the most primitive meteorites known on the basis of match with the elemental composition of the Sun, but they are heavily altered rocks that have been processed in a relatively warm and wet parentbody. Their parentbodies were almost certainly asteroids as it is difficult to imagine aqueous alteration occurring on comets, small bodies which sublime when warmed above cryogenic temperature. By analogy, it is likely that many and possibly all of the hydrated IDPs are also of asteroidal origin.

The second general class of IDPs is dominated by anhydrous minerals such as olivines, pyroxenes, and iron sulfides. These particles are similar to CI and CM chondrites in bulk elemental composition, but in terms of mineralogy and structure they are unique and have no close analogs among meteorites. These IDPs should be considered a new type of carbonaceous chondrite that apparently does not survive atmospheric entry in the form of conventional, large meteorites. They are carbon-rich and composed of roughly equidimensional grains ranging in size from micrometers to less than 100 Å. They also contain amorphous materials such as glass and disordered carbon. Some of the anhydrous particles are highly porous (as in the Frontispiece) and resemble gravel aggregates or clusters of grapes. The high porosity suggests a similarity to the porous, fragile materials observed in cometary meteor streams. High porosity and weak structure are evidence against compaction processes that probably occur in asteroids due to meteoroid impact and, in some cases, self-gravitation. The submicrometer and micrometer pore spaces in IDPs are likely to be voids produced by sublimination of volatile materials such as ice or perhaps organic compounds with high vapor pressures.

The Carbonaceous Component of IDPs

Carbon is a major element in IDPs, but it is difficult to study because of fundamental analytical limitations and ever present contamination problems. Studies of the carbon in IDPs are in an early stage of development and the nature of its form and distribution in this material is not yet well established. The carbon abundance in the particles is not well determined but it appears to be in the 5-15% range by weight for most particles. In terms of atom fraction this makes carbon the second most abundant element after oxygen in IDPs. This carbon content is intermediate between that of the most carbon-rich meteorites known and that measured in dust from comet Halley by Soviet and European spacecraft.

Electron microscope studies have shown that most of the carbon in IDPs is amorphous. It occurs in micrometer and submicrometer grains, as a component of submicrometer lumps composed of 100 Å mineral grains and carbon, and as 100 Å films on mineral grains. Oxygen and nitrogen do not appear to be major constituents of the carbonaceous matter and from an electron microscopy viewpoint the material looks like elemental carbon (although the techniques used could not detect hydrogen). The H, C, N, and O containing "CHON" grains identified as abundant micrometer-sized particles in the Halley coma have not been identified in IDP samples. It is possible that the cometary CHON grains consist of relatively volatile materials and they do not survive the prolonged exposure to space and subsequent entry into the Earth's atmosphere.

Part of the problem with studying the carbonaceous material in IDPs by electron microscopy is that this technique is most sensitive to crystalline phases, while most of the carbon in IDPs is amorphous. The most common carbon-bearing crystalline phases found in IDPs include Mg- and Ca-rich carbonates, iron carbides, lonsdaleite, and trace amounts of graphite. The iron carbide is ε-iron carbide and it is found in association with elemental carbon, Fe-Ni metal, and magnetite. The carbides are believed to have been formed by catalytic reaction of CO gas on grain surfaces. This most probably occurred in the solar nebula. Graphite is easy to identify in the electron microscope because of its distinctive 3.4 Å basal spacings. Yet graphite is rarely seen in IDPs. If the anhydrous particles are cometary, it is clear that graphitic carbon is not a major constituent of comets. If preserved grains are abundant components of comets, then it would also follow that graphite is not abundant in interstellar grains either.

Additional information about the form of the carbonaceous material in IDPs can be gleaned from their infrared transmission and Raman spectra. As was shown earlier (fig. 8-1), the infrared transmission spectra of individual IDPs are dominated by their abundant silicate minerals. However, some spectra also show the presence of a weak absorption feature near 3.4 μm (2940 cm^{-1}). This spectral position is characteristic of C-H stretching vibrations and suggests the presence of hydrocarbons. Unfortunately, the stratospheric IDPs are collected on impact collectors coated with a thin layer of silicone oil, which itself produces an absorption feature near 3.4 μm. Thus, it is difficult to ascertain what fraction of the observed 3.4 μm band in the IDP spectra is due to indigenous hydrocarbons and how much is due to residual silicone oil that was incompletely removed from the particle during curation. The layer-lattice silicate in figure 8-1 provides a good example of a particle in which the majority of the observed 3.4 μm feature is probably due to silicone oil. The presence of features at 7.94 and 12.53 μm (1260 and 798 cm^{-1}) are also characteristic of silicone oil. There are particles, however, in which a 3.4 μm feature is present and unaccompanied by the corresponding silicone oil features at 7.94 and 12.53 μm. In these cases, we may be seeing evidence of indigenous carbonaceous materials, although it has not been possible up to the present time to eliminate the possibility of other forms of contamination.

If the 3.4 μm features observed in IDP spectra are due to indigenous materials, their positions and profiles indicate that aliphatic compounds are present. The overall IDP feature, when seen, is similar to that observed in spectra taken toward the galactic center and from residues produced in laboratory experiments in which simple mixed molecular ices are irradiated with ultraviolet photons or ions. All three cases represent material which has had volatile components removed. In the case of the IDPs, the more volatile components have been removed by exposure to the Sun in interplanetary space and by heating during atmospheric entry. In the case of the galactic center, the volatiles have been removed by long duration exposure to the diffuse interstellar medium. Unfortunately, our inability to rule out contamination by silicon oil or other lab materials makes uncertain any conclusions derived from the observed 3.4 μm IDP features. Further work will be needed before the infrared spectra can place any strong constraints on the composition of the carbonaceous compounds in IDPs.

Raman spectroscopy has been somewhat more successful in providing information about the state of the carbon in IDPs. As can be seen in figure 8-3, Raman spectroscopy is particularly sensitive to the CC vibrations within the aromatic molecular units in carbonaceous materials. The top five spectra, taken from laboratory standards, demonstrate how the Raman spectra of carbonaceous materials change as the material becomes less ordered and the size of the aromatic domains decreased. Graphite, a material in which the aromatic domains are very large, produces a single intense first-order band at 1581 Δcm^{-1} and a weaker second-order feature near 2700 Δcm^{-1}. As the aromatic domains decrease in size, both of these bands grow broader and new features appear near 1350 and 2950 Δcm^{-1}. The bottom two spectra were taken from individual IDPs. Comparisons of the widths and relative strengths of the features in both sets of spectra show that the carbonaceous material in IDPs contains aromatic domains which are generally smaller than 25 Å.

In addition to the vibrational features, many of the Raman spectra of IDPs also show a broad photoluminescence feature arising from electronic transitions (see, for example, the bottom spectrum in figure 8-3). The position and strength of the luminescence varies from particle to particle, but typically the short wavelength limit of the feature is around 5400 Å and the feature peaks between 5900 and 6400 Å. This red luminescence is of particular interest since it has been known for some time that small bodies in the outer solar system show a general tendency to grow darker and redder with heliocentric distance. Photoluminescence associated with carbonaceous materials similar to those in the IDPs may contribute to the observed reddening.

It is also interesting to note that, while the particles are dominated by silicate minerals (as evidenced by the infrared spectra and the electron microscope studies), the Raman spectra seldom contain bands due to these minerals. This suggests that the carbonaceous material in IDPs effectively "screens" the silicates from visible photons. This explains how the IDPs can have relatively dark appearances and yet still be dominated by silicate minerals. This observation has implications for the many observations obtained during comet Halley's recent apparition.

Many of the collected IDPs are likely to be derived from comets. Figure 8-4 shows comparison between a 5-13 μm (2000-770 cm^{-1}) spectrum of comet Halley and a composite spectrum derived from IDP data. The IDP composite spectrum consists of a mixture of roughly 65% olivine-rich, 35% pyroxene-rich, and 10% layer-lattice silicate-rich IDPs. Note that not only is the 10 μm (1000 cm^{-1}) silicate feature reasonably well fit, but the Halley spectrum also shows a feature near 6.8 μm (1470 cm^{-1}) which is consistent with the presence of

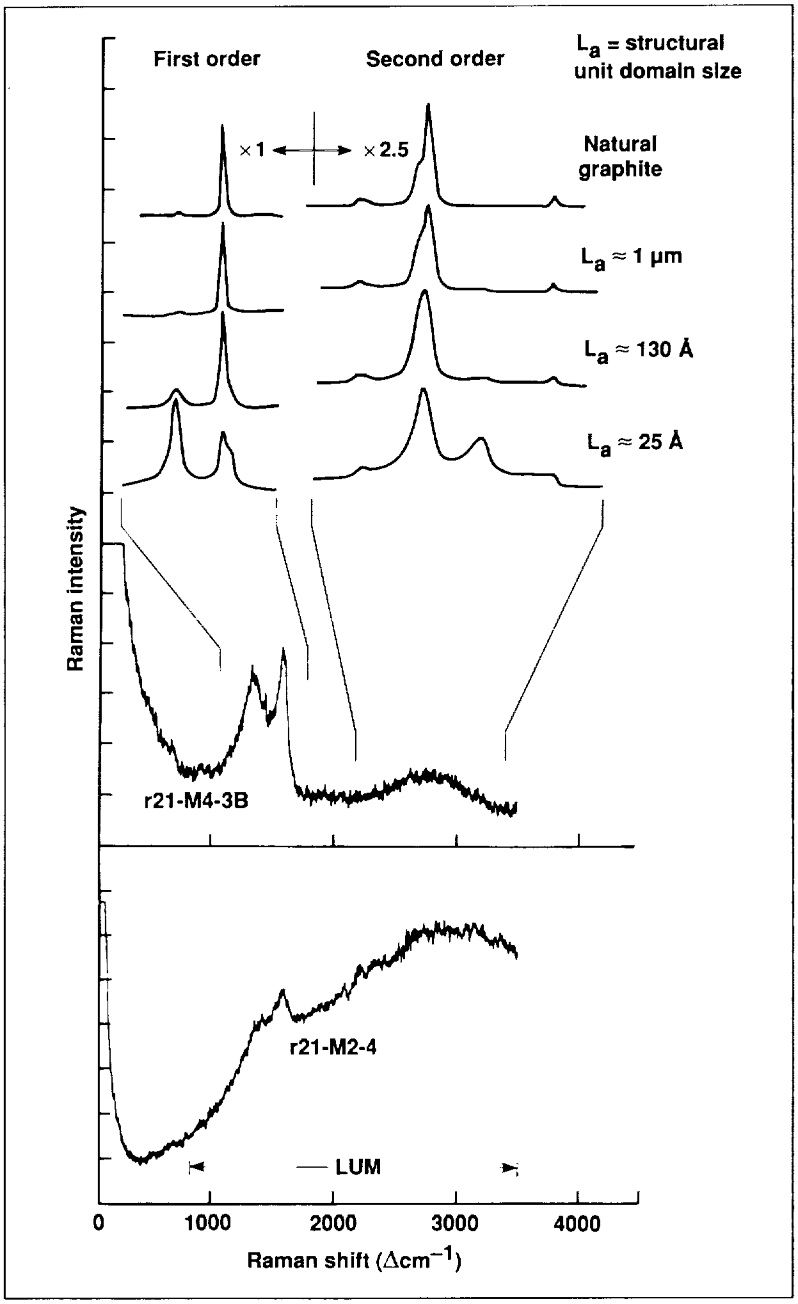


Figure 8-3. Raman spectra of several laboratory standards and IDPs. The top five spectra were taken from laboratory materials having decreasing degrees of crystalline order. The bottom two spectra were taken from individual IDPs. Comparison between the two sets of spectra show that the aromatic domains in IDPs are mostly smaller than 25 Å. Note the broad photoluminescence apparent in the lowest IDP spectrum.

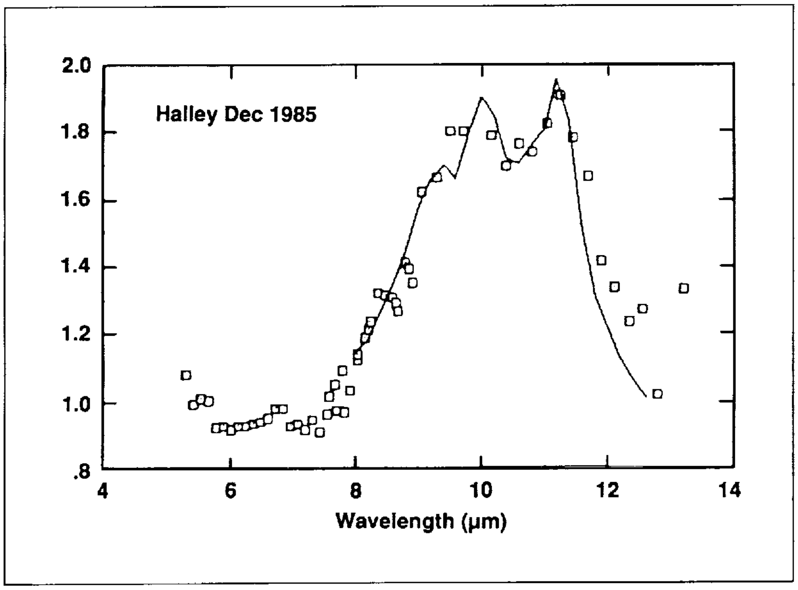


Figure 8-4. A comparison between the spectrum of comet Halley (points) and a composite spectrum of several IDPs (solid line). The IDP composite contains contributions for all three IDP infrared classes in the relative proportions of 55% olivines, 35% pyroxenes, and 10% layer-lattice silicates.

carbonates in the abundances they are normally found in the IDPs dominated by layer-lattice silicates. Similar fits to the IDP data have also been found for comets Wilson and Giocobini-Zinner. The match between the IDP spectra and the cometary spectrum and the detailed structure within the cometary 10 μm feature demonstrate that these comets contain large amounts of silicates and that these silicates are crystalline. Thus, analogous to the collected IDPs, the low observed albedo of Halley does not necessarily imply the comet is dominated by carbonaceous materials. Instead, the abundant silicates may be screened from visible photons by less abundant carbonaceous materials.

There is some indication, however, that the carbonaceous component in comets includes a component that is not present in the collected dust. Infrared spectra of comets Halley and Wilson have been shown to contain emission features near 3.4 μm (2940 cm^{-1}) that are diagnostic of C-H stretching vibrations in hydrocarbons. These features fall at shorter wavelengths than similar features observed in IDPs and toward the galactic center. As the collected dust and the dust toward the galactic center has undergone some thermal processing, this suggests that comets contain some carbonaceous materials that have relatively low volatilities. This material may remain with the dust long enough to be observed in the telescopic data but not survive long enough to be observed in the collected interplanetary dust.

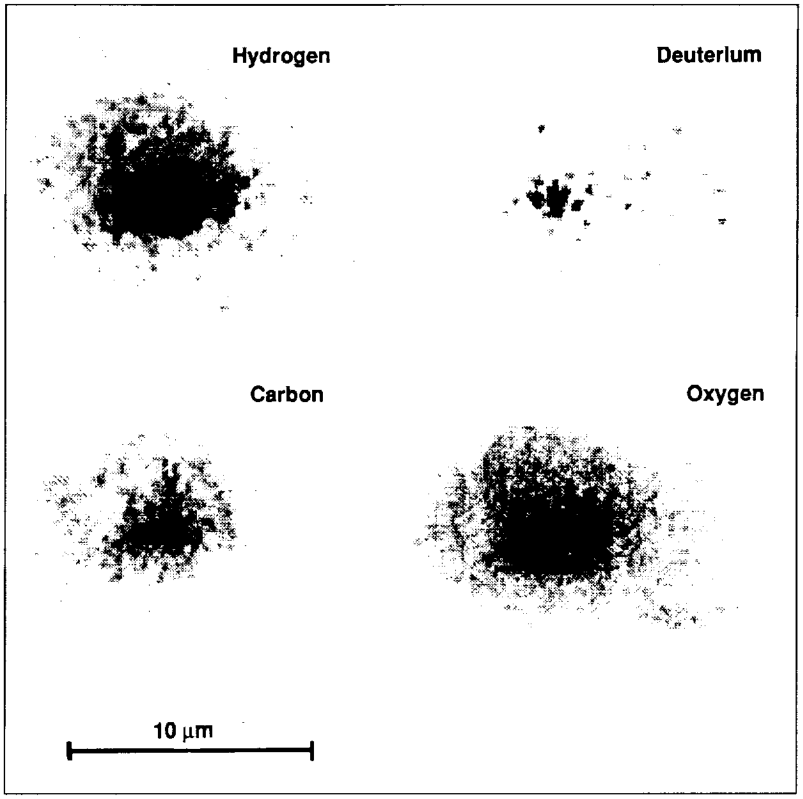
In summary, while the presently available information about the chemical state of the carbonaceous material in IDPs is quite limited, there is presently nothing inconsistent with the view that the majority of the carbonaceous material in IDPs is similar to the kerogen-like materials in carbonaceous meteorites, i.e., it consists of a network of small aromatic domains randomly interlinked by more-aliphatic bridges. This material contains minor amounts of O and N and resides in the particles both as separate clumps and as matrix material.

The Presence of an Interstellar Component

The actual formation sites of the carbonaceous material in IDPs are unknown. Certainly, some of the material must have formed in the early solar nebula. However, given that much of the dust may come from comets and that comets are likely to be relatively primitive bodies, the intriguing possibility exists that a fraction of the material has an interstellar origin. This possibility is of special interest to biogenic studies since the interstellar medium offers a rich variety of environments in which carbon chemistry can occur. In addition to normal gas phase chemistry, carbon-containing compounds can form in the interstellar medium via ion-molecule reactions, reactions between gas phase molecules catalyzed on grain surfaces, and reactions in ice mantles induced by ultraviolet photons and cosmic rays. This wide variety of chemical processes potentially provides for the production of a rich assemblage of biogenically interesting compounds. Given the diversity of chemical processes operating in the interstellar medium, it is worth asking whether there is any evidence that the carbonaceous material in IDPs contains an interstellar component. The answer, provided by isotopic studies, is yes!

Many of the collected IDPs are found to contain large deuterium enrichments which are inconsistent with an origin in the solar system. The spatial distribution of the carrier of the deuterium excess in IDPs is not uniform, but instead seems to be confined to "hot spots" whose dimensions are smaller than a micrometer (fig. 8-5). This suggests that the carrier of the deuterium consists of small "grains" which are distributed randomly within

Figure 8-5. "Pictures" of an IDP taken at different masses using an ion microprobe. Note that while the elements oxygen, carbon, and hydrogen are distributed more or less uniformly throughout the particle, the deuterium is concentrated in a localized region. The size of the observed deuterium-rich "hot spot" (approximately 1 µm in diameter) is on the order of the spatial resolution of the ion probe. As a consequence, only a lower limit to the deuterium enrichment in this spot can be obtained. The D/H ratio in the hot spot is found to be greater than a factor of 10 times the terrestrial value, making this the most deuterium-rich naturally occurring sample ever examined in the laboratory. The scale bar is 10 µm long. (Picture courtesy of R. Walker, Washington University at St. Louis).



the overall particles. Unfortunately, because of the small size of the carrier, it is not yet clear whether the deuterium-rich hot spots represent true, unaltered interstellar grains that have been incorporated into the larger IDP, or whether they represent material partially altered in the solar nebula which still has a "molecular memory" of such a grain. The deuterium enrichments seem to correlate loosely with carbon concentration, suggesting a carbonaceous carrier phase is responsible. However, the carbon isotopic system is clearly decoupled from the deuterium enrichments. The D/H ratio is not found to correlate with the $^{13}C/^{12}C$ ratio in the same particles, nor does the $^{13}C/^{12}C$ ratio show the same heterogeneity exhibited by the D-H system. This implies that, while the deuterium is carried by a carbonaceous phase, the carrier and the enrichment need not have formed in the same place, at the same time, or by the same process(es).

The chemical origin of the deuterium excess is uncertain. Deuterium enrichment via chemical reactions requires very low temperatures ($T < 100$ K), but at these temperatures the reaction rate is extremely slow. The reaction threshold is greatly reduced, however, if one of the reactants is an ion. For this reason, it is felt that ion-molecule reactions taking place in dense, cold interstellar clouds may be the source of the observed deuterium enrichments. An additional means by which the deuterium enrichment could have occurred in the interstellar medium involves selective photodissociation reactions. Interactions of ultraviolet photons with aromatic molecules in the interstellar medium should result in the photodissociation of some of the molecules' peripheral hydrogen atoms. Since the zero point energy of the C-D bond in polycyclic aromatic hydrocarbons is lower than that of the C-H bond, deuterium is less likely to be dissociated. The dissociation site is then free to capture a new atom. Over an extended period of successive photodissociation and recapture, a deuterium enrichment of the molecular aromatic population is expected. In any event, whether the observed enrichments are produced via ion-molecule reactions or selective photodissociation, their presence in IDPs clearly points to material having an interstellar origin.

It should be noted, however, that while the presence of an exotic isotopic component can prove that interstellar material is present, the lack of an exotic isotopic signature does not necessarily imply formation in the solar system. Since the solar system is presumably derived from more or less normal interstellar material, we might expect most interstellar material to have "normal," i.e., solar system-like isotopic abundances. Thus, the interstellar material evidenced by the deuterium enrichments represents a lower limit to the abundance of interstellar material present.

Summary

Collected samples of interplanetary dust are of exobiological interest since these particles contain a variety of carbon-bearing compounds and offer an efficient means of seeding planets in the early solar system with these materials. Because of their small size, IDPs can be decelerated from cosmic velocities at high altitudes in planetary atmospheres. As a result, much of the dust is captured without experiencing thermal excursions sufficient to melt or vaporize them. Any carbonaceous materials indigenous to the particles are then deposited on the surface of the planet.

While several minor carbon-bearing phases have been identified in IDPs, the majority of the carbonaceous material in IDPs seems to consist of a disordered material rich in C and H and containing minor amounts of

O and N. Spectroscopic evidence suggests that this material contains aromatic molecular units smaller than 25 Å in size and possibly aliphatic hydrocarbons as well. In so far as a comparison is possible, the majority of the carbonaceous material in IDPs appears to be similar to the kerogen-like material found in primitive carbonaceous meteorites, a material consisting of small aromatic moieties that are randomly interlinked by aliphatic structures.

The collected dust can provide reasonable matches to astronomical spectra of comets. The known extraterrestrial nature of these particles and their spectral similarity to primitive astronomical objects all argue that the collected IDPs contain "primitive" materials that may have been present during the formation of the solar system.

Isotopic studies of the IDPs demonstrate that many of them contain small (<1 micron) components that are greatly enriched in deuterium. The magnitudes of the observed enrichments are not explainable in terms of solar system processes and indicate the presence of interstellar material. It is not clear at this time whether the carriers of the isotopic anomalies represent true, unaltered interstellar dust grains, or whether they represent an altered component with a molecular "memory" of original interstellar grains. In any event, it is clear that the collected IDPs contain molecular material not only from the early solar system, but also from the interstellar medium. Since the interstellar medium contains a wide variety of environments in which many different chemical processes can occur, it would not be surprising if IDPs contain a varied assemblage of compounds of exobiological interest.

Finally, we note that there are a number of proposed spacecraft missions that could provide important new insights into the nature of interplanetary dust and comets. The most spectacular of these is the Rosetta Comet Sample Return Mission planned by the European Space Agency. This Mission will be flown in the next century and is designed to land on a short period comet, collect a core sample, and return the sample to Earth while retaining cryogenic temperatures. A nearer term mission is the Comet Rendezvous Asteroid Flyby (CRAF) Mission which is tentatively planned for a 1996 launch that will result in matching orbits with a short period comet. The spacecraft will be in close proximity to the comet for over a year and will measure the composition of the gases and dust emitted by the comet over much of its orbital cycle.

Additional Reading

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