CONSTRAINTS ON THE PARENT BODIES OF COLLECTED INTERPLANETARY DUST PARTICLES

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ABSTRACT. Samples of interplanetary dust particles (IDPs) have now been collected from the stratosphere, from the Earth's ocean beds, and from the ice caps of Greenland and Antarctica. The most likely candidates for the sources of these particles are comets and asteroids. Comparison of the infrared spectra, elemental compositions, and mineralogy of the collected dust with atmospheric entry models and data obtained from cometary probes and telescopic observations has provided important constraints on the possible sources of the various types of collected dust. These constraints lead to the following conclusions. First, most of the deep sea, Greenland, and Antarctic spherules larger than 100 µm are derived from asteroids. Second, the stratospheric IDPs dominated by hydrated layer-lattice silicate minerals are also most likely derived from asteroids. Finally, the stratospheric IDPs dominated by the anhydrous minerals olivine and pyroxene are most likely from comets. The consequences of these parent body assignments are discussed.

1. Introduction

Sites from which samples of interplanetary dust have been collected include the Earth's stratosphere and ocean beds, and the Greenland and Antarctic ice caps. The collected interplanetary dust particles (IDPs) generally have diameters less than 200 µm and survive atmospheric entry because their small masses allow them to be decelerated high in the Earth's atmosphere. The thinness of the upper atmosphere allows the particles to decelerate over large distances, and many are not heated to sufficiently high temperatures to be vaporized, although the larger particles may be melted. It is these melted particles that make up the majority of the collected deep sea spherules. The IDPs collected in the stratosphere are typically smaller than the spherules (d < 50 µm) and consequently have usually survived unmelted. Because of their more pristine nature, this paper will concentrate largely on the stratospheric IDPs. The properties of the collected IDPs will not be presented here in great detail but will only be discussed in-so-far as they provide information about their parent bodies. More detailed reviews of the properties of IDPs and the techniques used for their collection can be found in the literature (Sandford 1987; Bradley et al. 1988).

Most of the IDPs collected in the stratosphere can be placed into one of three classes defined by their characteristic infrared spectra (Sandford and Walker 1985) (Figure 1a). The IDPs in these classes are dominated by olivine, pyroxene, and layer-lattice silicate minerals, respectively. The first two categories are often referred to collectively as the 'anhydrous' IDPs and the last category is referred to as the 'hydrous' IDPs. The existence of several distinct IDP types strongly suggests that multiple sources are responsible for the

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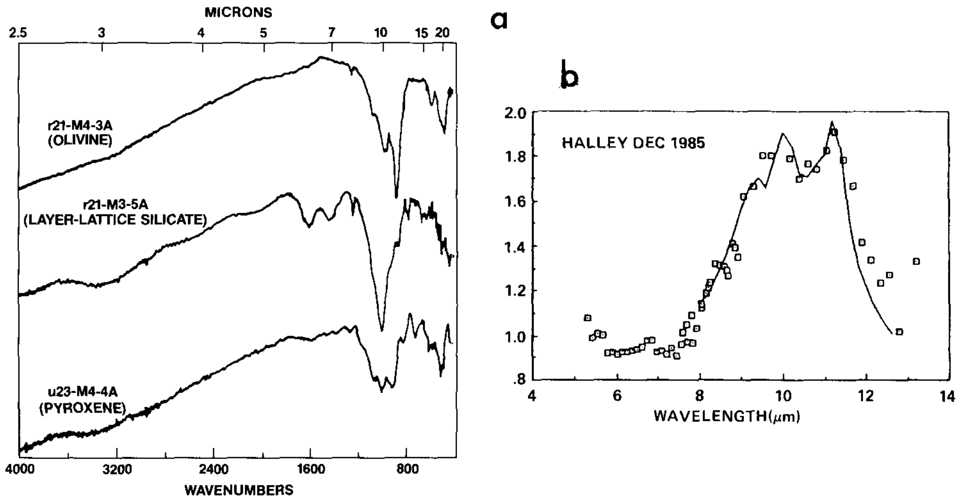

Figure 1 - (a) representative infrared spectra of the three main IDP types: pyroxene, layer-lattice silicate, and olivine, and (b) a comparison between the spectrum of Comet Halley (points) and an IDP composite (see text).

interplanetary dust complex. If the various collected dust types can be matched with sources, it then becomes possible to infer some of the sources' properties and evolution histories from the measured properties of the collected dust. Until recently, IDP-source relationships could only be suggested by comparing the collected IDPs with our preconceptions of what materials from comets and asteroids ought to look like. In the past few years, however, with the aid of good infrared cometary spectra, data returned from the Halley spaceprobes, and additional modelling of the atmospheric capture of the dust, it has become possible to constrain the possible sources of the dust more quantitatively. This paper reviews the present state of our knowledge about the sources of the collected IDPs and discusses some of the implications of the suggested IDP-source relationships.

2. Sources of the Collected Dust

The three techniques which have proven to be the most useful in constraining the sources of the collected dust take advantage of comparisons between: (i) the infrared spectra of the IDPs and comets, (ii) the elemental compositions of the IDPs and Halley dust (as measured by spacecraft), and (iii) the maximum temperatures experienced by the IDPs during atmospheric entry and those expected for different kinds of Earth-encounter orbits. Each of these three techniques will be discussed separately below. Note that the terms 'asteroid' and 'comet' will be used in a genetic sense throughout the discussion in this paper. Thus, dormant or defunct comets are still assumed to be comets, not asteroids.

2.1 CONSTRAINTS FROM INFRARED SPECTRA

As already mentioned, the majority of the stratospheric IDPs fall into one of three classes defined by their infrared spectra (Sandford and Walker 1985) (Figure 1a). The spectra from each class show distinctive silicate absorption features diagnostic of the major mineral present (olivines, pyroxenes, or layer-lattice silicates). The advent of improved telescopic infrared spectrometers now make it possible to obtain good quality, moderate resolution spectra of comets in the infrared spectral region. Thus, direct comparisons can be made between the infrared spectra of comets and the various collected IDP types.

Figure 1b shows a comparison of the spectrum of Comet Halley with a 'best fit' composite spectrum containing 55%, 35%, and 10% contributions from the olivine, pyroxene, and layer-lattice silicate IDP classes, respectively (Bregman et al. 1987). Several points are immediately apparent. The presence of substructure within the overall '10 μm' silicate feature clearly demonstrates that crystalline silicates are present, i.e. *cometary dust is not entirely amorphous*. (It will be argued later that cometary dust is probably dominated by crystalline material). Comparisons with the IDP spectra demonstrate that the presence of olivine is required to fit the strong sub-peak near 11.3 μm and that substantial amounts of pyroxene are required to match the width of the Halley feature. The fit does not suffer, however, if the 10% contribution from layer-lattice silicates is removed. Thus, there is no convincing spectral evidence that comet Halley contains layer-lattice silicates. The 11.3 μm sub-peak has since been detected in several other comets (Lynch et al.1989; Hanner et al. 1990). Comparisons of the IDP spectra with the spectra of these other comets yield matches similar to that shown in Figure 1b. Thus, the presence of crystalline olivines and pyroxenes may be a general property of comets.

In summary, comparison of the infrared spectra of comets and the collected stratospheric IDPs suggests that *comets are a viable source for the collected anhydrous IDPs dominated by the minerals olivine and pyroxene*. By process of elimination, this suggests the IDPs dominated by layer-lattice silicates may have an asteroidal origin.

2.2 CONSTRAINTS FROM DUST COMPOSITIONS

Detailed transmission electron microscope (TEM) studies demonstrate that the different IDP types exhibit distinctly different chemical and mineralogical properties. The anhydrous IDPs generally consist of a porous structure of crystalline materials that are usually not in

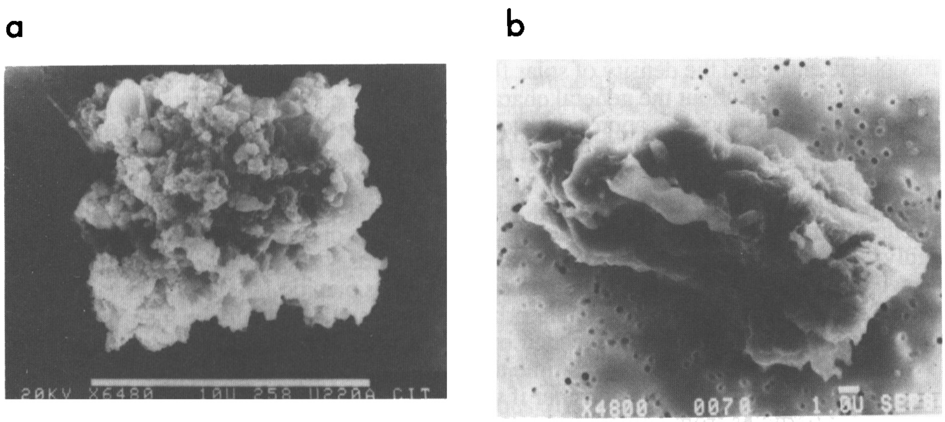

Figure 2 - TEM photographs of (a) a representative anhydrous IDP, and (b) a representative hydrous IDP (photos courtesy of J. Bradley, McCrone Associates).

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chemical or mineralogical equilibrium with each other (Bradley 1988) (Figure 2a). This suggests that the various subcomponents within the particles were formed in very different environments and subsequently mixed together. The lack of equilibration between the minerals indicates that very little alteration occurred to these particles after they were incorporated into their parent body(s). Such a composition is consistent with that expected for particles from comets if comets are true repositories of pristine, primitive materials (a common belief, but one that still has not been unequivocally demonstrated). In contrast, the IDPs dominated by layer-lattice silicates generally show much lower porosities and a much higher degree of chemical and mineralogical equilibration (Figure 2b). The minerals and their structures are characteristic of hydrothermal alteration processes similar to those thought to have occurred to several types of meteorites (although the majority of the layer-lattice silicate IDPs differ in detail from the known meteorites) (Tomeoka and Buseck 1985). These similarities suggest an asteroidal origin for the hydrous IDPs. These arguments are not particularly rigorous, however, since they depend to some extent on our preconceptions of what cometary and asteroidal grains should look like.

Lawler et al. (1989) have compiled the relative abundances of Fe, Mg, and Si from the best data sets returned by the Vega-1 and Giotto spacecraft and compared them with data from the CI meteorite Orgueil and several IDPs. They found that Halley dust spanned a large compositional range, suggesting the presence of unequilibrated phases. The compositional ranges spanned by both the CI meteorite and the IDPs dominated by layer-lattice silicates were found to be much smaller than that observed from Halley dust. The compositional scatter of an anhydrous IDP, however, was found to provide a good match to the Halley data.

Thus, the spacecraft data appear to be largely consistent with our general preconceptions, namely that *the anhydrous IDPs are more likely to be derived from cometary sources and the hydrous IDPS are more likely to come from asteroids.*

2.3 CONSTRAINTS ON THE PRE-CAPTURE ORBITS OF THE COLLECTED DUST

Determination of the pre-atmospheric orbits of collected IDPs could provide extremely useful information about the dust sources. Unfortunately, it is not possible to determine the exact orbital parameters of the collected dust since this information is lost upon atmospheric entry. However, determination of the peak temperature the IDPs experienced during atmospheric entry and the density of solar flare particle tracks in their constituent minerals provide information about the general characteristics of the particles' orbits.

Before continuing, it is appropriate to briefly review the orbital evolution of dust particles in the size range of the collected IDPs as they are influenced by Poynting-Robertson (PR) radiation drag effects (Poynting 1903; Robertson 1937). Particles evolving under the PR effect have orbits whose semi-major axes decreases with time. Aphelia distances decay much more rapidly than perihelia distances and elliptical orbits are rapidly circularized before the perihelion distance decreases appreciably. Thus, particles injected into the interplanetary medium in circular orbits outside 1 AU spiral towards the sun and arrive at 1 AU in nearly circular orbits. Particles injected into the interplanetary medium in elliptical trajectories have their orbits circularized before their perihelia distance is significantly decreased after which time they spiral sunward in relatively circular orbits.

There are several cases to consider if we are to model the Earth encounter orbits expected for particles from comets and asteroids (Sandford 1986). First, particles from the main belt asteroids should arrive at 1 AU in nearly circular, prograde orbits having low inclinations. Such particles will have low Earth encounter velocities and a narrow (mass scaled) range of non-zero exposure ages in space (about 10^4 years for a 10 μm particle). In contrast, particles from highly eccentric Earth-crossing comets will have a range of

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inclinations up to and including retrograde motion. Depending on the nodes of the orbit, the particle could be captured by the Earth immediately after injection into the interplanetary medium or as late as the time at which the aphelion distance falls below 1 AU. Thus, dust from Earth-crossing comets will have higher Earth encounter velocities and show a much larger range in space exposure ages (0-10^4 yrs for a 10 μm particle). Comets with modest inclinations and perihelia outside ~1.2 AU provide a special intermediate case. Here, the particle orbits will circularize before their perihelia fall to 1 AU. As a result, particles from these sources will reach Earth in orbits similar to those of particles from asteroids. These particles would have space exposure ages similar to those of asteroidal particles but could have slightly higher Earth encounter velocities if their inclinations were significant. While this last case covers a restricted orbital phase space, it applies to many short period comets which may be major contributors to the overall zodiacal dust complex. Thus, with the possible exception of confusion between dust from asteroids and low-inclination prograde comets with perihelia outside 1 AU, the IDPs from comets and asteroids might be separated by determining either their PR infall times or their Earth encounter velocities.

The PR infall times of the collected stratospheric IDPs, as determined by the density of solar flare tracks within their constituent minerals, could be used to constrain the sources of the different classes of dust (Sandford 1986). Solar flare particle tracks are produced within the olivine and pyroxene minerals of IDPs by the passage of solar flare iron nuclei and have been detected in many IDPs using TEM techniques (Bradley et al. 1984). Since these energetic nuclei only have a range of ~100 μm in silicates, the track density in an IDP is a measure of the time it was exposed to space as a small particle. The populations of asteroidal and cometary IDPs may then be distinguishable by their different track density distributions. Unfortunately, it has so far proven difficult to carry out such a study due to complications associated with limitations of the TEM technique and to uncertainties associated with the possibility of track annealing during atmospheric entry heating.

Better progress towards defining the source of the dust has been made by comparing expected Earth encounter velocities with those inferred from the collected IDPs. Several investigators have modelled the entry of small dust particles into the Earth's atmosphere and computed the maximum heating expected as a function of particle velocity, entry angle, mass, and density (cf. Fraundorf 1980). Recently, Sandford and Bradley (1989) derived rough 'thermometers' that could be applied to the collected IDPs to determine upper limits for the heating experienced by individual grains during atmospheric entry. It was found that the hydrous IDPs generally experience minor atmospheric heating consistent with encounter velocities of about 12 km/sec, i.e. near Earth's escape velocity. This indicates that the hydrous IDPs arrive at 1 AU in nearly circular, prograde, low-inclination orbits and *suggests that the IDPs dominated by layer-lattice silicate minerals have an asteroidal origin.* In contrast, the olivine-rich IDPs, as a class, have been heated to higher temperatures than expected for a distribution of orbital velocities consistent with sporadic meteors, implying more eccentric, Earth-crossing orbits. *This suggests that the IDPs dominated by olivine minerals have a cometary origin* . As a class, the pyroxene-rich IDPs seem to have experienced heatings intermediate to those of the layer-lattice silicate and olivine IDPs. This suggests orbits which are only moderately elliptical and/or have modest inclinations. This suggests the pyroxene IDP class is also derived from comets, although the case is less conclusive than that for the olivine-rich IDPs. To summarize, the Earth encounter orbits inferred for the IDPs are consistent with previous conclusions, namely, the anhydrous IDPs are most likely from comets and the hydrous IDPs are most likely from asteroids.

At this point it is appropriate to make several comments about the source(s) of the larger particles (mostly spherules) collected from Greenland, Antarctica, and the ocean bottoms. These particles are probably derived predominantly from asteroids. Particles of this size (diameters on the order of 100 μm) are expected to be very strongly heated upon atmospheric entry (Love and Brownlee 1990). Calculations show that particles of this size arriving in Earth-crossing, cometary orbits will usually be heated to sufficiently high temperatures to be vaporized. In contrast, particles derived from asteroids could have low enough encounter velocities to survive, although a large fraction of the particles would be expected to be melted (as is observed). Also, studies of ^{26}Al and ^{10}Be in deep sea spherules show that the particles have cosmic ray exposure ages up to 10^7 years (Nishiizumi et al. 1990). Such long time scales are more consistent with exposure in an asteroidal regolith than cometary surfaces.

3. Implications

Three independent means of constraining the sources of the various classes of stratospheric IDPs have all yielded similar results: the anhydrous, olivine- and pyroxene-rich IDPs are most likely from comets, and the hydrous IDPs dominated by layer-lattice silicates are probably from asteroids. The majority of the particles collected from Greenland, Antarctica, and deep sea sediments are probably from asteroids. In this section, some of the implications of these suggested assignments are considered.

In many respects the properties of the stratospheric IDPs are consistent with general expectations of the properties of their source assignments . For example, the anhydrous IDPs generally contain many void spaces that may have once held volatile ices which were lost after ejection from a comet parent body. In addition, the anhydrous IDPs show larger chemical and mineralogical diversity than the hydrous IDPs. This suggests that the anhydrous IDPs are the more 'primitive' particles, at least in the sense that they have undergone the least alteration since they were incorporated into their parent body. Since comets are often assumed to have preserved their original starting materials better than asteroids, the suggested source identifications are consistent with general preconceptions.

The identification of the collected IDPs with different source types leads to several unanticipated conclusions, however. First, the assignment of the anhydrous IDPs to cometary parent bodies implies that most of the silicates in comets are crystalline, not amorphous. This is inconsistent with models that assume the cometary silicate grains consist of 'amorphous' olivine containing small amounts (5-15%) of crystalline olivine. Many IDPs contain some glassy materials, but these materials never dominate the mass. We know that most of the crystalline minerals in the particles are original to the particle, i.e. they are not formed by the heating of previously amorphous materials during atmospheric entry, because these mineral grains contain solar flare particle tracks. If the anhydrous IDPs really are from comets, models that assume cometary grains are made of mixtures of crystalline olivine and pyroxene are the most appropriate.

Raman spectra from the various IDP classes show that all three types contain C-rich materials (Allamandola et al. 1987). The exact state of the carbon is not well-defined but it is known that the material contains aromatic chemical units smaller than 25 Å. While not yet fully demonstrated, the C-rich material in IDPs may be similar to the polymeric kerogens found in meteorites. There is little or no graphite in IDPs and this is probably <u>not</u> an appropriate analog material for modelling of the carbonaceous component of comets and asteroids. The Raman spectra of IDPs rarely show silicate bands, even when the infrared spectra of the particles are dominated by silicates. This suggests that, while the silicates dominate the particle masses, the C-rich material mediates the interaction of the particles with visible light. Thus, models containing 'bare' silicate particles may not be appropriate. Finally, the IDP parent body assignments discussed here raise several interesting issues related to the isotopic compositions of the dust. Ion probe measurements of IDPs have demonstrated that many of the particles contain large deuterium excesses (McKeegan et al. 1985). These excesses are sufficiently large that they cannot be explained by simple Solar System processes and have been taken as an indication that the particles contain interstellar materials. Whether the D-rich materials exist in IDPs in discrete grains, or only represent a molecular 'memory' of altered interstellar materials, is not presently clear. In any event, the presence of isotopic anomalies can be considered to be an indication of 'primitiveness.' It is interesting to note, therefore, that D enrichments have so far only been detected in IDPs in the pyroxene and layer-lattice silicate classes, but not in the olivine-rich IDPs (McKeegan 1987). Given that comets are generally assumed to be more 'primitive' than asteroids, and that our best assignments connect the olivine-rich IDPs with comets and the hydrous IDPs with asteroids, this might be considered somewhat of a surprise. Why do the hydrous IDPs, which show properties characteristic of secondary alteration and elemental redistribution, contain 'primitive' isotopic anomalies, while the apparently cometary olivine-rich particles do not? Clearly, the presence of one 'primitive' characteristic within a material does not imply other primitive characteristics can be assumed. In the future it will be necessary to carefully define what criteria are being used when materials are referred to as 'primitive'.

4. Conclusions

Three independent means of constraining the sources of the different classes of stratospheric IDPs all yield similar conclusions, namely that the anhydrous, olivine- and pyroxene-rich IDPs are probably from comets and the hydrous IDPs dominated by layer-lattice silicates are probably from asteroids. It is likely that most of the particles collected from Greenland, Antarctica, and deep sea sediments are from asteroids. In many respects the observed properties of the stratospheric IDPs are consistent with general preconceptions of what dust from the assigned source types should look like. For example, the IDPs thought to be from comets show higher porosities and greater chemical and mineralogical diversity than those thought to be from asteroids. If the anhydrous IDPs do indeed represent cometary materials, they can be used as a source of ground truth for cometary models. It is then most appropriate to assume that the C-rich component of cometary grains contains little or no graphite, but is instead similar to meteoritic kerogens. The carbonaceous material is expected to mediate the interaction of the grains with visible light even when silicates are the dominant phase present, i.e. 'bare' silicates are not appropriate. Finally, the grains most likely consist largely of crystalline olivines and pyroxenes.

The detection of deuterium enrichments in particles from both the hydrous and anhydrous IDP classes demonstrates that both types of particles are 'primitive', at least in the sense that both preserve material that has a molecular memory of a pre-solar environment. Clearly, the assumption that comets are in all respects more 'primitive' than asteroids is called into question.

The information gleaned from the collected stratospheric IDPs in the past 15 years has resulted in significant advancements in our understanding of the interplanetary dust population and its sources. However, it is clear from observations like those of the D/H ratios in IDPs that there is still much to be learned. The interplanetary dust community can expect to see significant new results from the study of the collected IDPs in the future.

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