II

INTERPLANETARY DUST :

PHYSICAL AND CHEMICAL ANALYSIS

https://doi.org/10.1017/S0252921100066495 Published online by Cambridge University Press

PHYSICAL AND MINERALOGICAL PROPERTIES OF ANHYDROUS INTERPLANETARY DUST PARTICLES IN THE ANALYTICAL ELECTRON MICROSCOPE

J. P. Bradley, McCrone Associates, Westmont, Illinois 60559, USA

Abstract

The fine grained mineralogy and petrography of anhydrous "pyroxene" and "olivine" classes of chondritic interplanetary dust have been investigated by numerous electron microscopic studies. The "pyroxene" interplanetary dust particles (IDPs) are porous, unequilibrated assemblages of mineral grains, metal, glass, and carbonaceous material. They contain enstatite whiskers, FeNi carbides, and high-Mn olivines and pyroxenes, all of which are likely to be well preserved products of nebular gas reactions. Solar flare tracks are prominent in most "pyroxene" IDPs, indicating that they were not strongly heated during atmospheric entry. The "olivine" IDPs are coarse grained, equilibrated mineral assemblages that have probably experienced strong heating. Since most "olivine" IDPs do not contain tracks, it is possible that this heating occurred during atmospheric entry.

Introduction

Chondritic interplanetary dust particles collected from the stratosphere are believed to be derived from comets and asteroids [1,2]. They arrive at Earth-crossing orbits under the influence of Poynting-Robertson drag, and many of them survive atmospheric entry without significant modification [2,3]. They include compact strong objects (similar to CI and CM chondrites), as well as fragile, porous objects that could not survive atmospheric entry as larger (millimeter-sized) bodies [1,4]. Identification of the asteroidal and cometary subsets of interplanetary dust are primary goals of IDP research, because asteroidal IDPs probably sample a broader range of parent bodies than conventional meteorites [5], and cometary IDPs are presently the only available samples of comets. During the past decade new information about the chemical, isotopic, and mineralogical nature of IDPs has been obtained [6-8]. At the same time, data about interplanetary dust has been obtained from ground based and airborne telescopic observations and

A.C. Levasseur-Regourd and H. Hasegawa (eds.), Origin and Evolution of Interplanetary Dust, 63–70.

spacecraft measurements [9,10]. All of these data have focused attention on the relationship between IDPs collected from the stratosphere and possible parent bodies within the solar system.

This paper describes recent results obtained from studies of IDPs using the analytical electron microscope (AEM). The AEM has proven to be useful for analysis of IDPs because it is designed specifically for chemical and structural microanalysis of materials at the highest possible spatial resolution. Optimum performance of the AEM requires thin specimens, and most of the results described in this paper were obtained from ultramicrotomed thin (< 100 nm) sections [11]. The following text will first introduce the three classes of chondritic IDPs, and then describe the two **anhydrous** "pyroxene" and "olivine" classes. (The third **hydrated** "layer silicate" class is described by Tomeoka (this volume)). Finally, the properties of the anhydrous classes will be evaluated in terms of likely sources.

Chondritic Interplanetary Dust

The most common IDPs collected from the stratosphere belong to a group whose compositions generally agree with those of CI and CM carbonaceous chondrites [1]. The extraterrestrial origins of these chondritic IDPs have been confirmed by measurement of solar noble gases, D/H isotopic ratios, and solar flare tracks [2]. Sandford and Walker [12] first showed using infrared (IR) transmission absorption spectra that chondritic IDPs fall into three major groups referred to as "pyroxene", "olivine", and "layer silicate", after the minerals that provide the best match for the observed IR spectral features. The first two groups contain only **anhydrous** phases while the third contains (**hydrated**) layer silicates in addition to anhydrous phases. Electron microscopic studies have confirmed that pyroxene, olivine, and layer silicates are indeed major constituents of IDPs in their respective IR classes [13,14]. Because the anhydrous "pyroxene" and "olivine" classes contain only anhydrous phases, they have no known (mineralogical) counterparts among carbonaceous chondrites. The (hydrated) "layer silicate" IDPs, on the other hand, are mineralogically similar to CI and CM chondrites (see Tomeoka, this volume).

Anhydrous IDPs

[i] "Pyroxene" class

The "pyroxene" class of IDPs are unique in that they are highly porous aggregates (Fig. 1). Sometimes large ($\approx 1\ \mu m$) euhedral mineral grains can be observed embedded within the IDPs. The most distinctive are enstatite whiskers (Fig. 1), which have been the objects of a detailed mineralogical study [15]. Solar flare tracks (Fig. 2) and solar wind radiation damaged rims are usually prominent in "pyroxene" IDPs, indicating that most of them survive atmospheric entry without severe (>600°C) heating. Typical track densities are on the order of 10^{10}-10^{11} cm^{-2} (Fig. 2), which corresponds to an exposure age of $\approx 10^4$ years within the inner solar system [16].

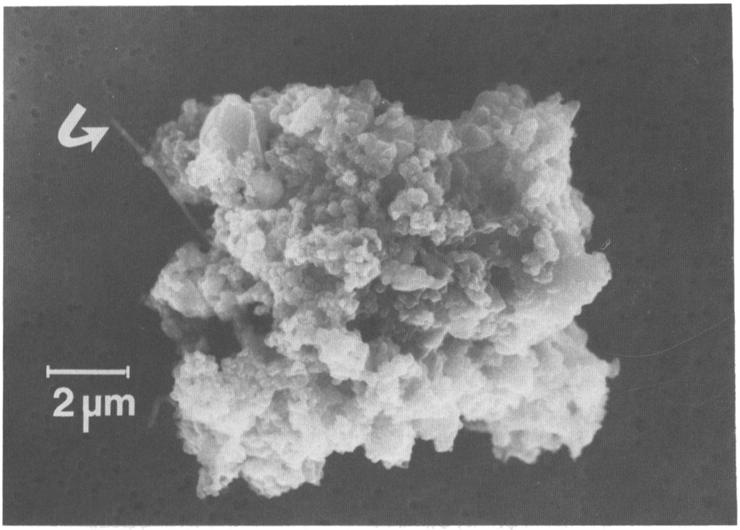

Figure 1 Scanning electron micrograph of the "pyroxene" IDP U220A19. An enstatite whisker is arrowed.

In thin section, each particle is composed of loosely agglomerated, predominantly submicrometer components (Fig. 3). These components can be single mineral grains, glass, carbonaceous material, and microcrystalline aggregates (Fig.4). The most common single mineral grains are enstatite and iron-rich sulfides (pyrrhotite). Less common are olivine (forsterite), troilite, and FeNi alloy or carbides. Glass is ubiquitous throughout pyroxene IDPs. It forms the groundmass of some microcrystalline aggregates, but it also occurs as discrete inclusions. The composition of the glass is variable and, in one IDP alone, three compositionally distinct glasses were identified. Typical glass compositions are (Na), Ca, Fe alumino-silicate, pure alumino-silicate glass, and pure Mg silicate. The carbonaceous material is a non-crystalline phase which can also occur as a groundmass containing embedded mineral grains or as discrete inclusions. Although it is possible that organic material is present, little is known about the molecular constitution of the carbonaceous material. All IDPs are collected in silicone oil, and washed with organic solvents to remove the oil. Bulk carbon contents as high as 16 wt % have been reported [17], but contamination and analytical difficulties could complicate interpretation of these abundances.

Microcrystalline aggregates are discrete 0.1-0.5 μm objects composed of nanometer-sized grains embedded in a glassy groundmass (Fig. 4). (They have also been referred to as "tar balls" [11] and

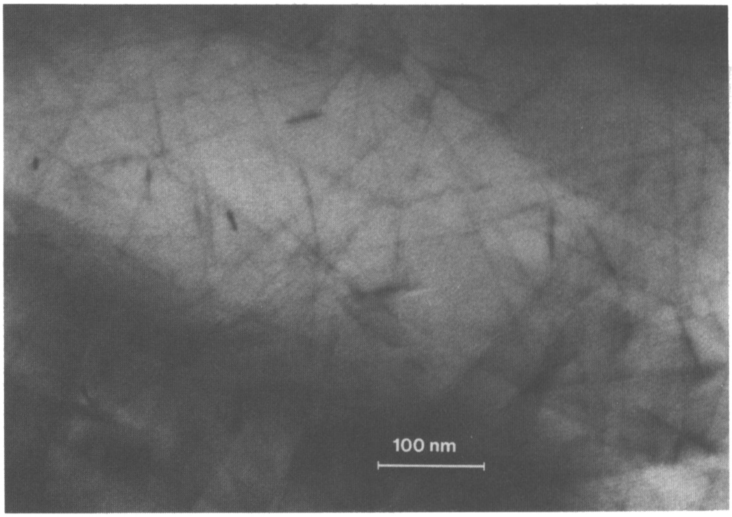

Figure 2 Darkfield electron micrograph of solar flare tracks in an enstatite crystal in IDP W7027C4.

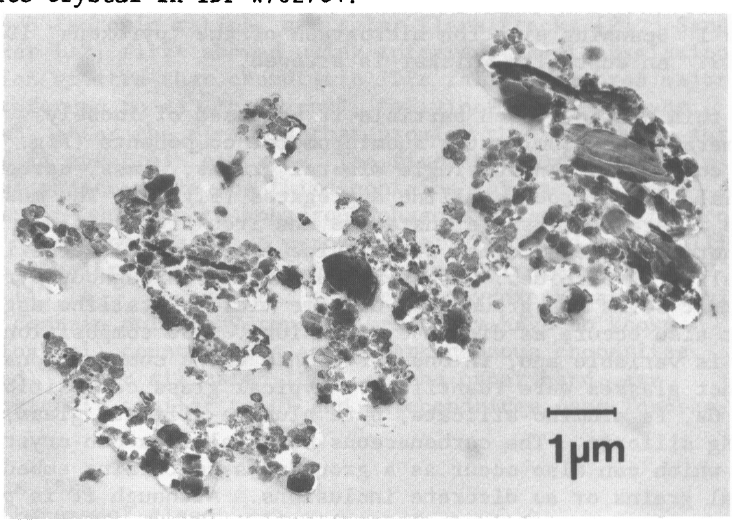

Figure 3 Brightfield electron micrograph of an ultramicrotomed thin section (≈80 nm thick) of IDP U222B42.

"granular units" [18]). They are perhaps the most fascinating components of chondritic IDPs, because they are discrete chondritic objects that have been incorporated into IDPs. Clearly, their formation predates that of the IDPs. The major crystalline component is body centered cubic kamacite (FeNi alloy), and most of the metal in "pyroxene" IDPs is contained as kamacite in

https://doi.org/10.1017/S0252921100066495 Published online by Cambridge University Press

microcrystalline aggregates. These (alloy) grains range from less than 5 to over 20 nm in diameter. Mg-rich pyroxene, Fe-sulfide, and possibly olivine are also present as nanometer-sized inclusions. Magnetite is sometimes present on the outer surfaces of the aggregates.

Crystallographic studies have indicated that the enstatite whiskers (Fig. 1) were formed by gas phase condensation [15], and FeNi carbides in "pyroxene" IDPs are biproducts of Fischer-Tropsch type catalytic reactions [19]. Klock et al [6,20] have studied the crystal chemistry of olivines and pyroxenes in "pyroxene" IDPs. All of the IDPs contained LIME (low iron manganese enriched) olivines and/or pyroxenes, whose high Mn abundances have been interpreted in terms of direct vapor phase condensation of olivine and pyroxene [6]. Most "pyroxene" IDPs exhibit a wide range of Fe/Mg ratios in olivine and pyroxene, indicating that these IDPs are truly unequilibrated [20].

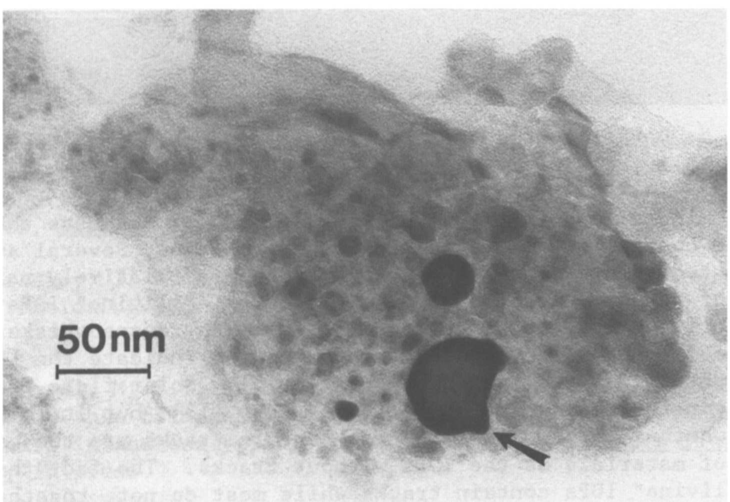

Figure 4 Brightfield electron micrograph of a microcrystalline aggregate in a thin section of U222B42. An unusually large kamacite (FeNi alloy) grain is arrowed.

[ii] "Olivine" class

Although the bulk compositions of "olivine" IDPs are similar to those of "pyroxene" IDPs, SEM images suggest that "olivine" IDPs are less porous and more coarse grained than the "pyroxene" class. In thin section most grains are between 0.1 and 1.0 μm in diameter (Fig. 5), although in some particles finer grained material is also present. The most common minerals are olivine and iron-rich sulfides. Less common minerals include pyroxenes, chromite, magnetite, Fe-Ni alloy (kamacite), carbonaceous material, and silica-rich glass. Glass is very abundant in some "olivine" IDPs

https://doi.org/10.1017/S0252921100066495 Published online by Cambridge University Press

where it forms a matrix between embedded mineral grains.

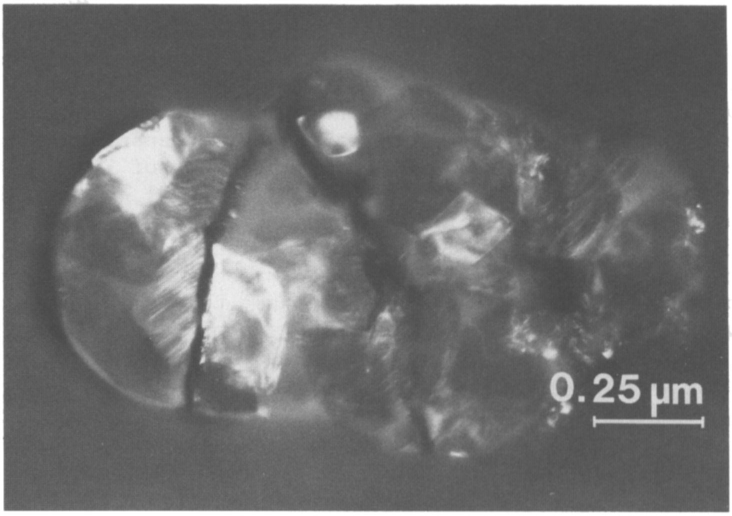

Figure 5 Darkfield electron micrograph of a thin section of part of the "olivine" IDP U220A14.

The mineral chemistry of "olivine" particles suggests that most of them contain equilibrated mineral assemblages. Several authors have noted that olivines and pyroxenes show a relatively narrow range of Mg/Fe ratios [13,20,21]. Moreover, "olivine" IDPs apparently do not contain LIME silicates or pyroxene whiskers and platelets, whose occurrences would otherwise indicate the preservation of pristine components [6,15]. Solar flare tracks have been found in only two "olivine" IDPs [13], but it is not yet clear whether the two IDPs that do contain tracks are the same types of materials as the IDPs without tracks. The fact that only two "olivine" IDPs contain tracks while most do not, together with the mineralogical diversity exhibited by this group [13,21], suggest that the "olivine" class of IDPs probably incorporates more than one genetic group. In any case, it seems that most "olivine" IDPs have experienced strong heating, which has produced both equilibrated silicate mineralogy and coarse grain size.

Sources of anhydrous IDPs

Since there are now morphological [4], isotopic [7], chemical [19], and crystallographic [15] data suggesting that "pyroxene" IDPs are among the most primitive meteoritic materials yet encountered, comets are prime candidates for their source(s). Mass spectrometry data from the PIA and PUMA instruments on the comet Halley probes yielded compositional data that are compatible with "pyroxene" IDPs but incompatible with "olivine" (and "layer silicate)" IDPs [11]. However, infrared spectra recorded from

Halley and other comets seem to require the presence of significant pyroxene and olivine to account for the observed spectral features [9]. Since solar flare tracks are conspicuously absent in almost all of the "olivine" IDPs so far examined, their status as a legitimate class of unmodified IDPs is uncertain. However, if the tracks are erased by heating during atmospheric entry, then comets are also the more likely source(s) for "olivine" IDPs [3]. The paper by Sandford (this volume) deals exclusively with the sources of chondritic IDPs.

Acknowledgment

This research was supported by NASA grant NAS-9-17749. Helpful comments were provided by S. Sandford and K. Tomeoka.

References

[1] Schramm, L. S., Brownlee, D. E. and Wheelock, M. M. (1989) Major element composition of statospheric micrometeorites. Meteoritics, 24, 99-112.

[2] Sandford, S. A. (1987) The collection and analysis of extraterrestrial particles. Fund. Cosmic Phys., 12, 1-73.

[3] Sandford, S. A. and Bradley, J. P. (1989) Interplanetary dust particles collected in the stratosphere: observations of atmospheric heating and constraints on their interrelationships and sources, Icarus, 82, 146-166.

[4] Bradley, J. P. and Brownlee, D. E. (1986) Cometary particles: thin-sectioning and electron beam analysis, Science, 231, 1542-1544.

[5] Germani, M. S.., Bradley, J. P. and Brownlee, D. E. (1990) Automated thin-film analyses of hydrated interplanetary dust particles in the analytical electron microscope, Earth Planet. Sci. Lett., in press.

[6] Klock, W., Thomas, K. L., McKay, D. S. and Palme, H.(1989) Unusual olivine and pyroxene composition in interplanetary dust and unequlibrated ordinary chondrites, Nature, 339,126-128.

[7] McKeegan, K. D., Walker, R. M. and Zinner, E. (1985) Ion microprobe isotopic measurements of individual interplanetary dust particles, Geochim. Cosmochim. Acta, 49, 1971-1987.

[8] Mackinnon, I. D. R. and Rietmeijer, F. J. M (1987) Mineralogy of chondritic interplanetary dust particles, Rev. Geophys., 25(7), 1527-1553.

[9] Bregman, J. D., Campins, H., Witteborn, S. C., Wooden, D. H., Frank, D. M., Allamandolla, L. J., Cohen, M. and Tielens, A. G. G. M. (1987) Airborne and ground based spectrophotometry of comet

P/Halley from 5-13 micrometers, Astron. Astrophys., 187, 616-620.

[10] Jessberger, E. K., Christoforidis, A. and Kissel, J. (1988) Aspects of the major element composition of Halley's dust, Nature, 332, 691-695.

[11] J. P. Bradley (1988) Analysis of chondritic interplanetary dust thin-sections, Geochim. Cosmochim. Acta, 52, 889-900.

[12] Sandford, S. A. and Walker, R. M. (1985) Laboratory infrared transmission spectra of individual interplanetary dust particles from 2.5 to 25 microns. Astrophys. J., 291, 838-951.

[13] Christoffersen, R. and Buseck, P. R. (1986) Mineralogy of interplanetary dust particles from the "olivine" infrared class, Earth Planet. Sci. Lett., 78, 53-66.

[14] Tomeoka, K. and Buseck, P. R. (1985) A carbonate-rich, hydrated, interplanetary dust particle: possible residue from protostellar clouds. Science 231, 1544-1546.

[15] Bradley, J. P., Brownlee, D. E. and Veblen, D. R. (1983) Pyroxene whiskers and platelets in interplanetary dust: evidence of vapor phase growth, Nature 301, 473-477.

[16] Bradley, J. P., Brownlee, D. E. and Fraundorf, P. (1984) Discovery of nuclear tracks in interplanetary dust, Science 226, 1432-1434.

[17] Blanford, G. E., Thomas, K. L. and McKay, D. S. (1988) Microbeam analysis of four chondritic interplanetary dust particles for major elements, carbon, and oxygen, Meteoritics, 23, 113-122.

[18] Rietmeijer, F. J. M. (1989) Ultrfine-grained mineralogy and matrix chemistry of olivine-rich chondritic interplanetary dust particles, Proc. 19th Lunar Planet. Sci. Conf., 513-521.

[19] Christoffersen, R. and Buseck, P. R. (1983) Epsilon carbide: a low temperature component of interplanetary dust particles, Science, 222, 1327-1329.

[20] Klock, W., Thomas, K. L., McKay, D. S. and Zolensky, M. E. (1989) Olivine compositions in anhydrous and hydrated IDPs compared to olivines in matrices of primitive meteorites (abstract), Lunar Planet. Sci. XXI, 637-638.

[21] Bradley, J. P., Germani. M. S. and Brownlee, D. E. (1989) Automated thin-film analyses of anhydrous interplanetary dust particles in the analytical electron microscope, Earth Planet. Sci. Lett., 93, 1-13.