Discovery of Nuclear Tracks in Interplanetary Dust

Abstract. *Nuclear tracks have been identified in interplanetary dust particles (IDP's) collected from the stratosphere. The presence of tracks unambiguously confirms the extraterrestrial nature of IDP's, and the high track densities (10^{10} to 10^{11} per square centimeter) suggest an exposure age of approximately 10^4 years within the inner solar system. Tracks also provide an upper temperature limit for the heating of IDP's during atmospheric entry, thereby making it possible to distinguish between pristine and thermally modified micrometeorites.*

Interplanetary dust particles (IDP's) that enter the atmosphere without melting (micrometeorites) are now routinely collected in the stratosphere. They are the only available meteoritic materials whose surfaces were recently exposed to space (the surfaces of conventional meteorites melt during atmospheric entry). An early expectation of studies of micrometeorites was that they would contain solar flare tracks, which are essential for determination of (i) the degree to which micrometeorites have been heated during atmospheric entry, (ii) the residence time of IDP's in the interplanetary medium, and (iii) the possibility of preaccretional exposure of IDP mineral grains to solar or galactic irradiation. Dust particles are eventually destroyed in the interplanetary medium by collisions and Poynting-Robertson drag (*1*), but, since they can have theoretical interplanetary lifetimes on the order of 10^4 years, track densities on the order of 10^{10} cm^{-2} could be expected (*1, 2*). High concentrations of helium, neon, and argon detected in some particles (*3*) were consistent with recent exposure to the solar wind, but a primordial origin for the implanted gas could not be ruled out. Earlier attempts to find tracks have not been successful; this result suggested either that IDP's simply did not contain significant track densities or that the tracks had somehow been erased. In the absence of evidence to the contrary, it was always assumed that tracks were annealed during atmospheric entry, but recent studies (*4–6*) have indicated that many micrometeorites were probably never heated to sufficient temperatures to anneal tracks.

We report here the discovery of solar flare tracks in two micrometeorites, both of which had been retrieved from the stratosphere at an altitude of 18 to 20 km by U-2 aircraft (*7*). The tracks were observed by conventional transmission electron microscopy with 200-keV incident electrons. However, successfully identifying them and recording them on photographic plates depended on the electron microscope operating configuration, sample preparation, and properties of the IDP's themselves. We determined the optimum microscope configuration at the outset of this study by examining a stratospheric micrometeorite (U2-14-6-9A) that had been exposed to an iron ion beam at the Super Heavy-Ion Linear Accelerator Facility in Berkeley, California (*8*). This sample was irradiated twice (at incidence angles differing by 15°) with a total dosage of between 10^{10} and 5×10^{10} ions per square centimeter, thereby providing a "standard" IDP in which we could search for a known density of tracks in fine-grained micrometeoritic material. After successful identification of tracks in this "standard," we also identified tracks in two pristine particles (U2-20B11 and U2-20B37). Tracks are most easily seen (in both "standard" and pristine IDP's) in grains that are relatively free of other types of crystallographic imperfections (for example, stacking faults or strain contours) and residual adhering material, and therefore sample preparation and properties of the IDP's themselves are important. Usually the most suitable samples for track searches are those that have been crushed and dispersed as a large number of well-separated, monomineralic grains on thin carbon (<500 Å) support films (*4*). All the grains in which tracks were encountered were either olivines or pyroxenes. Olivines are particularly ideal for viewing tracks because they are usually free of defects. On the other hand, pyroxene grains commonly consist of twinned crystals with stacking defects, and the strong image contrast arising from these structures often masks the subtle contrast modulation arising from tracks.

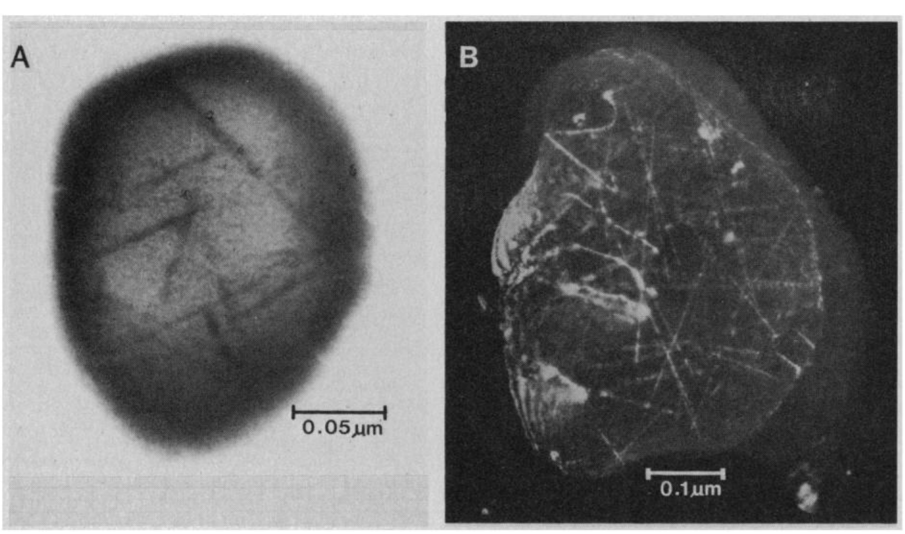

Fig. 1. Transmission electron micrographs of solar flare tracks in olivine [(Mg,Fe)SiO_4] grains from micrometeorite U2-20B11: (A) bright-field image (olivine, with ~40 mole percent forsterite); (B) dark-field image (olivine, with ~45 mole percent forsterite). The observed track densities for both of these grains are between 10^{10} and 10^{11} cm^{-2}.

Figure 1 shows electron micrographs of tracks in well-rounded olivine grains from micrometeorite U2-20B11. They can be imaged in both bright-field (Fig. 1A) and dark-field (Fig. 1B) image modes, and they maintain their strongest image contrast when 200-μm second condenser and 20-μm objective apertures are positioned in the beam path. Rapid fading of partially annealed tracks under electron irradiation has been a problem with 100-kV electrons (*8*), but, because of reduced ionization cross sections at higher energies, this problem is not as pronounced with 200-keV electrons. The tracks can be distinguished from other types of crystallographic defects in that they form randomly oriented straight-line defects that anneal slowly in the electron beam (*9*). The measured track densities found in many grains in particles U2-20B11 and U2-20B37 are between 10^{10} and 10^{11} cm^{-2}. Three other micrometeorites (U2-20-SP57, U2-11B6, and U2-20-SP75) were also searched for tracks. Particle U2-20-SP57 was selected primarily because it contained an unusually large (>10 μm) olivine crystal. This crystal was first examined whole and was then removed from its substrate, crushed between glass slides, and remounted as a large number (>20) of micron- and submicron-sized fragments. Despite a prolonged search, no tracks were found in this particle, nor were tracks identified in micrometeorites U2-11B6 and U2-20-SP75.

We determined the elemental abundances for micrometeorites U2-20B11 and U2-20B37 by electron microprobe, using the quantitative particle analysis routine of Armstrong and Buseck (*10*). These particles exhibit classical chondritic compositions, and for all elements the abundances agree to within a factor of 2 with those of type CI carbonaceous chondrites (Table 1). In particular, the particles are highly enriched in sulfur relative to all other meteorite types except CI's. Most chondrite groups have similar abundances, so it is not reasonable on the basis of compositions to actually assign the particles to any chondritic subgroup. However, it is significant that the S/Si ratio of both micrometeorites is distinctly higher than that of all other chondrites except CI's. Sulfur is the only element of those analyzed that is significantly fractionated among chondrites, and it is also the only volatile species whose abundance would indicate low-temperature formation and lack of strong heating during atmospheric entry.

All of the particles studied belong to the class of micrometeorite we refer to as "chondritic" (*11*), because they invariably exhibit compositions similar to those shown in Table 1. Chondritic IDP's are aggregates of predominantly submicron grains and carbonaceous material, and we chose them to search for tracks because their porous structures and fragile textures suggest that they may have been derived from contemporary comets. Comets are major suppliers of dust to the interplanetary medium (*12*) and of solar system bodies are most likely to contain well-preserved samples of the primordial particulate material that formed the outer planets. Furthermore, chondritic IDP's exhibit mineralogical evidence of primordial processes; for example, enstatite whiskers and platelets found in most chrondritic micrometeorites were almost certainly formed by direct gas-to-solid condensation (*13*), and iron-nickel carbides in some IDP's appear to have been emplaced via Fischer-Tropsch type heterogeneous catalysis reactions (*4, 5*). Large deuterium/hydrogen fractionation recently measured in two IDP's is strong evidence for primordial isotopic fractionation (*14*).

Identification of tracks provides further confirmation of the well-preserved state of some chondritic micrometeorites, and the measured track densities (10^{10} to 10^{11} cm^{-2}) in particles U2-20B11 (Fig. 1) and U2-20B37 are consistent with exposure ages within the interplanetary medium on the order of 10^4 years (*2*). The predicted track production rate in micron-sized particles at 1 AU is between 3×10^5 and 10^7 tracks per square centimeter per year (*8*). The measured densities are also consistent with exposure ages for millimeter-sized particles, obtained by measuring ^{53}Mn, ^{10}Be, and ^{26}Al in cosmic deep-sea spheres (*15*). Transient defects observed (with 100-keV electrons) in two other micrometeorites, which in retrospect were probably solar flare tracks, suggested exposures between 10^3 and 10^4 years (*8*). However, although relative exposure ages of collected IDP's can be inferred easily from track density measurements (if the tracks are stable to electron irradiation), extrapolation to absolute exposure ages is uncertain because the observed track densities may have been influenced by an earlier presolar irradiation interval. Even greater uncertainty arises from our lack of knowledge of the low-energy solar flare flux (in the range 0.2 to 2 MeV per atomic mass unit), which produces tracks in micron-sized particles exposed to space. Measurements of this flux averaged over 2.6 years were made on Surveyor glass and over a longer time by examination of lunar crystals that are believed to have been exposed with only minor dust shielding (*9*). It is possible that an even better measurement of the solar flare energy spectrum (averaged over the lifetime of IDP's) may be obtained from future studies on micrometeorites that contain tracks in olivine and pyroxene grains.

Table 1. Atom abundances of elements (normalized to silicon).

Element	Particle U2-20B11*	Particle U2-20B37*	CI chondrites†
Na	0.139	0.111	0.057
Mg	0.959	0.933	1.075
Al	0.064	0.044	0.085
S	0.540	0.620	0.515
Ca	0.045	0.057	0.061
Cr	0.017	0.014	0.013
Mn	0.01	0.017	0.01
Fe	0.656	0.791	0.900
Ni	0.027	0.035	0.049

*Relative error, ±10 percent. †From Anders and Ebihara (*18*).

Nuclear tracks also provide a very accurate upper temperature limit for the heating of micrometeorites during atmospheric entry. Pulse heating experiments (*8*) have shown that tracks in olivine and pyroxene anneal rapidly between 500° and 600°C, and therefore particles U2-20B11 and U2-20B37 cannot have been heated to these temperatures. However, since tracks were identified in only two of the five particles studied, it is apparent that some micrometeorites have suffered heating above this temperature. In the future, it will be imperative to investigate the presence of tracks in IDP's prior to discussing particle chemistry and mineralogy, especially low-temperature mineralogy. The observation of tracks of course confirms, on an individual particle basis, the extraterrestrial nature of the particles in which they are found and supports the noble-gas evidence (*3*) that these objects have been exposed as small particles in the inner solar system.

In addition to confirming the existence of solar flare tracks for the first time, the observations described here provide data on tracks in more than one grain from the same micrometeorite. If irradiation of some grains occurred prior to accretion into micrometeorites (*16*), it might show up as differences in track densities between grains. A potentially important use of variable track densities would be distinguishing between solar nebula and presolar interstellar grains within the same micrometeorite. The ability to detect tracks also makes it possible to measure the distribution of lifetimes of particles orbiting the sun, which is important for evaluating the effects of light pressure drag and collision (*1*) in the solar system. In a broader context, the ability to measure grain lifetimes in our solar system provides a means of testing grain survival models, which may be useful for interpreting the newly discovered (*17*) and apparently common dust rings around other nearby stars.

J. P. BRADLEY
Walter C. McCrone Associates, Inc., 2820 South Michigan Avenue, Chicago, Illinois 60616

D. E. BROWNLEE
Department of Astronomy, University of Washington, Seattle 98195

P. FRAUNDORF
Monsanto Electronics Materials Company, St. Louis, Missouri 63167, and *Department of Physics, Washington University, St. Louis 63130*

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13 August 1984; accepted 2 October 1984

Aldehyde Pheromones in Lepidoptera: Evidence for an Acetate Ester Precursor in *Choristoneura fumiferana*

Abstract. *Labeling studies of the eastern spruce budworm in vivo indicate that* trans-*11-tetradecenyl acetate is synthesized specifically in the pheromone-producing gland and is degraded in concert with pheromone release; hence it may be a precursor to the* trans-*11-tetradecenal pheromone. Radioactivity from exogenously added labeled fatty acids did not appear to be directly incorporated into the ester, suggesting that de novo biosynthesis from acetate is the major route of ester biosynthesis. Conversion of the acetate ester to alcohol and aldehyde functional groups may be the principal method of regulating pheromone specificity between species of* Choristoneura.

Most lepidopteran sex attractants are characterized by a long, monounsaturated carbon chain and an oxygen-containing functional group that can be an aldehyde, an alcohol, or an acetate ester of the alcohol. Although a mechanism involving Δ^{11} desaturation and chain shortening was recently proposed to explain biosynthesis of monounsaturated acyl chains (*1*), little attention has been focused on the functional groups.

In the genus *Choristoneura* (order Lepidoptera, family Tortricidae), pheromones from different species appear to be distinguished principally by different functional groups, as the pheromones all contain Δ^{11-14} carbon chains (*2*). The pheromone of *C. occidentalis*, for example, is a mixture of roughly equal amounts of aldehyde, alcohol, and acetate ester (*3*), whereas in *C. fumiferana* the pheromone is 99 percent aldehyde (*4*) and the alcohol and acetate esters are inhibitory to the attraction of male insects (*5*). The presence of 11-tetradecen-1-ol acetate (TDA) in the gland of *C. fumiferana* first suggested a precursor role for the acetate ester (*4*). Although the subsequent identification of pheromone gland enzymes capable of producing the aldehyde pheromone (ratio of *trans*- to *cis*-11-tetradecenal, 96 to 4) from TDA (*6*) support this hypothesis, a precursor role of TDA has not yet been clearly demonstrated in the spruce budworm.

We report here that TDA in *C. fumiferana* is specifically synthesized de novo only in the pheromone gland. During the period of pheromone release (*7*) there was a large decrease in the amount of radioactivity associated with labeled TDA, suggesting that this lipid is a precursor of the pheromone. Storage of the aldehyde pheromone as a less-reactive precursor is an attractive hypothesis, since it allows the biosynthetic steps that require large expenditures of energy to occur continuously and not simply during the period of pheromone production. The hypothesis also raises the possibility that a similar metabolic relation exists between the aldehyde, alcohol, and acetate ester pheromones of other lepidopteran species (*2*).

Figure 1A (lanes 2 to 5) shows the time course of incorporation of radioactivity from [1-^{14}C]acetate into lipids by the pheromone-producing gland in vivo. In these experiments, ~1 nmol of the labeled acetate in dimethyl sulfoxide (DMSO) was topically applied to the gland or another body component of the living insect (*8*). The tissue was subsequently extracted with hexane and analyzed by thin-layer chromatography (TLC) on silica gel. After a 2-hour labeling period (lane 4), a substantial amount of radioactivity comigrated with an unlabeled TDA standard. Radioactivity was not incorporated into this lipid when labeled acetate was topically applied to the abdomen or other body parts, even if a large excess of the sample was analyzed, whereas all other lipids were still synthesized (lane 1 in Fig. 1A).

To confirm the chemical identity of the gland-specific lipid as TDA, we extracted the labeled lipid from the silica gel and subjected it to further analysis. The ester nature of the functional group is indicated by the finding that the long-chain saponification product (*9*) comigrated with TDA (Fig. 1B). Between 75 and 80 percent of the radioactivity was recovered as the fatty alcohol, indicating that synthesis of the alcohol was occurring de novo in the gland and that the radioactivity was not incorporated simply by acetylation of preexisting fatty alcohol.

The lipid migrated in a reversed-phase TLC system with a TDA standard (Fig. 1C), confirming that the chain length was consistent with an acetate ester of a

Table 1. Incorporation of radioactively labeled fatty acids into TDA. Each labeled fatty acid, dissolved in dimethyl sulfoxide, was topically applied to the glands of groups of female insects 4 to 6 days old (*8*). At least two groups of 15 to 20 insects each were used per treatment, and approximately the same amount of material was applied to each gland. Incorporation was measured by scintillation counting of TDA cut from the silica gel after visualization of the radiolabeled lipids by autoradiography. All incubation periods were 2 hours long.

Precursor	Specific activity (mCi/mmol)	Amount applied (nanomoles per insect)	Incorporation into TDA (percent)
[1-^{14}C]acetate	56	0.8	0.23 ± 0.01
[^{3}H]acetate	2800	0.7	0.15 ± 0.03
[1-^{14}C]laurate	36	0.8	0.38 ± 0.03
[1-^{14}C]myristate	31	1.7	0.39 ± 0.09
[1-^{14}C]palmitate	56	0.5	0.30 ± 0.01
[9,10-^{3}H]myristate	31	1.6	0.08 ± 0.04