COMPLEMENTARY LABORATORY MEASUREMENTS OF INDIVIDUAL INTERPLANETARY DUST PARTICLES

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ABSTRACT. Complementary analysis techniques including electron microscopy (SEM/EDX and TEM), molecular spectroscopy (FTIR and Raman), and secondary ion mass spectrometry (SIMS), are used to study individual dust particles collected in the stratosphere. Large deuterium enrichments and solar flare tracks show that most particles in the "chondritic" class are interplanetary dust particles (IDPs). Infrared transmission spectra of most IDPs fall into three major classes (layer-lattice silicates, pyroxenes and olivines). TEM and Raman measurements confirm this classification. The IR spectra show certain similarities to spectra observed in comets and protostars. In particular the 6.8 μm features observed in protostars and IDPs may have a common origin. Large D excesses are observed in IDPs of the first two IR classes. The correlation of D/H ratios with the C concentration indicates a carbonaceous carrier of the excess D. The D enrichments and IR spectra provide links to interstellar molecular cloud material.

1. INTRODUCTION

"Chondritic" dust particles collected in the stratosphere [1] consist primarily of interplanetary dust material. The extraterrestrial origin is shown by solar-type gases [2-3], large D excesses [4,5] and solar flare tracks [6]. In spite of the small mass (1-50 ng), it is possible to perform a number of microanalytical measurements on a given dust grain. Table 1 gives a summary of analyses performed on nine different IDPs. Arbitrary names are given to individual particles.

2. MEASUREMENT TECHNIQUES

Energy dispersive x-ray analysis (EDX) is used to select particles of the "chondritic subset" [7]. These are then examined by other techniques.

Infrared transmission spectra from 2.5 to 25 μm are measured by

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Table 1. A summary of the analysis techniques applied to the study of each stratospheric dust particle.

Particle name	Infrared Class[6]	Isotopic Measurements H	C	Mg	Si	Other Analyses Done EDX	TEM	Raman
Mosquito		X	X	X	X	X		X
Skywalker	layer-	X	X	X	X	X	X[12]	X
Calrissian	lattice	X	X			X	X[14]	X
Lea	silicates	X				X		X
Low-Ca						X	X[13]	
Spray-2	pyroxene	X		X	X	X	X[14]	X
Essex		X				X	X[14]	X
Attila	olivine	X				X	X[17]	X
Jedai						X	X[14]	X

FTIR spectrometry [8]. These measurements show that the majority of IDP spectra fall into three different classes termed "layer-lattice silicates", "pyroxenes" and "olivines" based on similarities to terrestrial mineral spectra [9]. Figure 1 shows representative spectra of the three IR classes. While no individual spectral type matches the emission spectrum of Comet Kohoutek, a reasonable match is obtained by adding roughly equal amounts of "layer-lattice silicate" and "pyroxene" IDP spectra [8,9]. The lack of agreement in the position and width of the 10 μm silicate feature of the "olivine" class with the Comet Kohoutek spectrum shows that olivine cannot be a major component of that comet's dust. Besides the 10 μm silicate feature and 3.0 and 6.0 μm hydration bands, a prominent band at 6.8 μm is seen in the spectra of the "layer-lattice silicate" group. This band is strongest in Calrissian, where an accompanying band at 11.4 μm suggests that these features are due to a carbonate mineral. The 6.8 μm feature is seen in the spectra of some protostars [10] where it might have a similar origin.

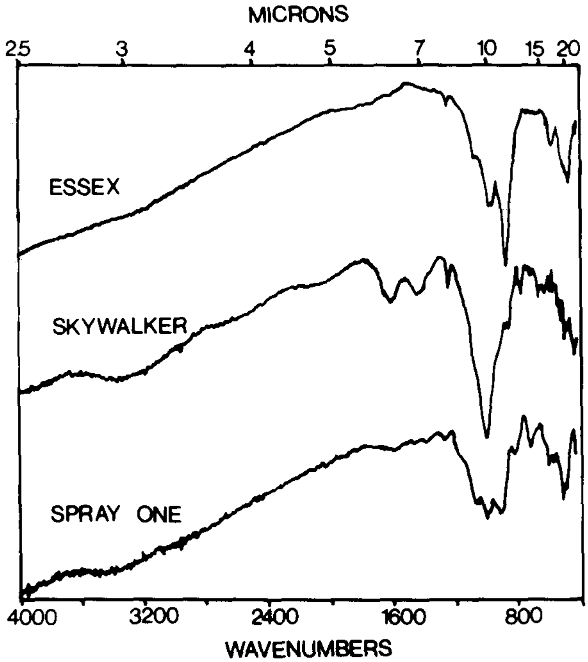

Figure 1

Infrared transmission spectra of three IDPs representative of the "olivine" class (Essex), "layer-lattice silicate" class (Skywalker) and "pyroxene" class (Spray One).

High resolution transmission electron microscopy including electron diffraction measurements provide information on the mineralogy and morphology of the IDPs. Previous TEM observations have shown that IDPs contain highly unequilibrated material which is distinct from that seen in meteorites [11-13]. The recent discovery of solar flare tracks in IDPs [6] provides a novel way to prove the extraterrestrial origin of stratospheric dust particles. All the TEM observations on the IDPs listed in Table 1 were made at Arizona State University [14-16,19].

Some information on the chemical state of C in the IDPs can be provided by the laser Raman microprobe [17,18]. Such information is of special interest since the D enrichments correlate with C concentration. Fig. 2 shows Raman spectra obtained from Calrissian and Attila. The two lines seen in the spectra are due to graphite. The relative strength, widths, and exact positions of the two peaks are known to vary with the degree of crystallinity of the graphite. In IDPs a constant pattern is seen in different fragments of a given particle but differences are observed between particles.

SIMS isotopic measurements of several elements (H, C, Mg, Si in this study) can be made in individual fragments of a single IDP [5]. D/H measurements show large D excesses in most of the IDPs measured so far (Fig. 3). The D excess is distributed heterogeneously on a size scale of several μm and is correlated with the C/O, N/O, and S/O ratios, indicating a carbonaceous, probably organic, carrier for the excess D. In contrast, Mg and Si measured in three particles exhibit isotopically normal values. The C isotopic composition is homogeneous in a given IDP, but there seem to be slight differences between different particles.

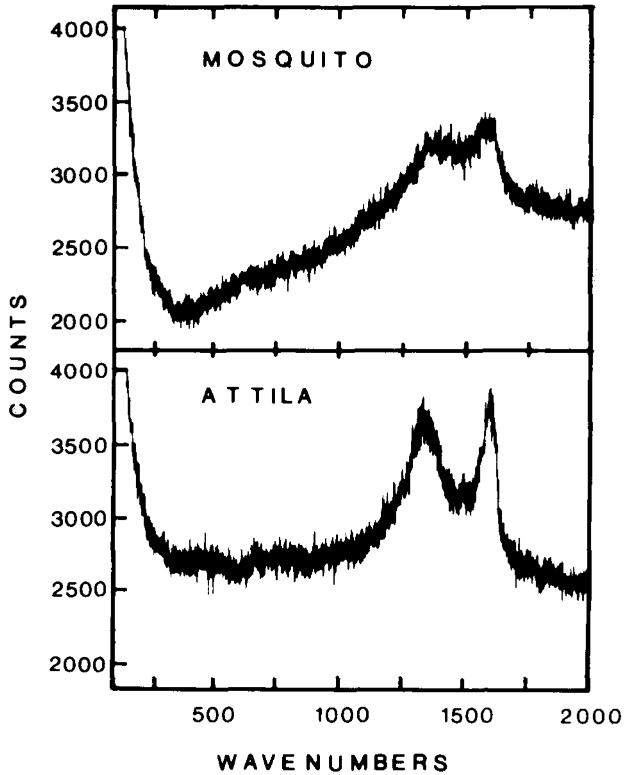

Figure 2:

Raman spectra of two IDPs. The two lines are associated with graphite.

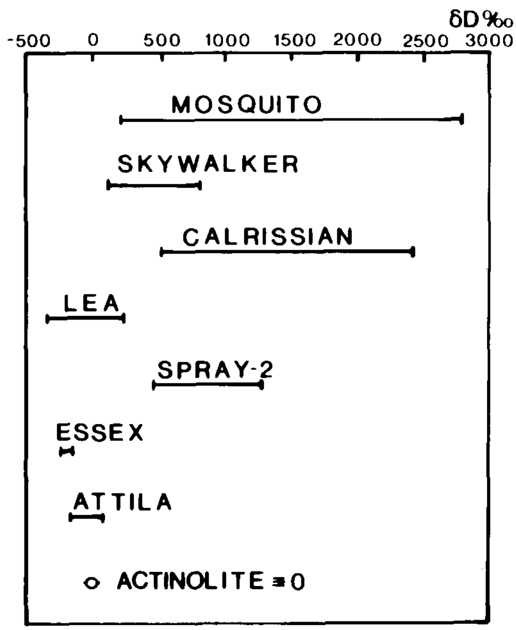

Figure 3:

Range of δD values measured in seven IDPs. Terrestrial actinolite was used as a standard defining the δD scale.

3. COMPARISON OF RESULTS OBTAINED BY DIFFERENT TECHNIQUES.

IR spectroscopy is the simplest method found so far for classifying particles of the chondritic subset into different groups. We next discuss the relationships that exist between an IDP's IR classification and its properties measured by other analytical methods.

3.1 IR and TEM

Two particles in the "layer-lattice silicate" class, Skywalker and Low-Ca, have been studied in the TEM by Tomeoka and Buseck [14,15]. In both cases an abundance of poorly crystalline phyllo-silicates was observed. Both are distinct from meteorites and there are considerable differences in the detailed mineralogy of the two particles. Solar flare tracks were seen in Skywalker (Tomeoka, private communication) proving its extraterrestrial origin. In the "olivine" class, Jedai, Essex and Attila, have been examined by Christoffersen and Buseck [19]. Jedai and Essex are primarily composed of fosterite crystals of irregular and equidimensional shape. These two IDPs also show differences in detail: the Fe content of the olivines in Jedai is typically 5-8% whereas it is 15-20% in Essex. Attila also contains abundant olivines, in addition to FeS, and a form of Fe-Zn sulfide not seen previously in IDPs. Tracks are abundant in the olivine crystals of Attila, thus providing proof that some particles of the "olivine" class are extraterrestrial. The only particle of the "pyroxene" class examined in the TEM, Spray-2, contains both small pyroxene and olivine crystallites imbedded in a low-Z matrix. A pyroxene line is also seen in the Raman spectrum of this particle.

In summary, TEM observations confirm that the IR classifications reflect the major silicate phases present in different particles. However, particles whose IR spectra are nearly identical can show substantial differences in their detailed mineralogical structures when viewed at high magnification.

3.2 IR and SIMS

Figure 3 shows the range of δD values measured in different fragments of seven IDPs. Two of the three particles from the "layer-lattice silicate" class, Skywalker and Calrissian, show large D excesses. D excesses in Lea are smaller, but still outside the limits of terrestrial materials, proving the extraterrestrial origin of all three particles. The extraterrestrial origin of Calrissian is especially significant since the strong 6.8 µm feature in the IR spectrum of this particle, likely due to a carbonate, is similar to features observed from protostars [10]. Spray-2 of the "pyroxene" class also exhibits large D excesses. The two particles of the "olivine" class, Essex and Attila, show no excess D. While Essex is slightly depleted in D, Attila's hydrogen isotopic composition is terrestrial within the measurement errors. Nevertheless, the existence of abundant solar flare tracks in Attila proves that it is extraterrestrial. Thus there are interplanetary dust particles with a terrestrial hydrogen isotopic composition.

Large deuterium enrichments seen in certain fractions of primitive meteorites have been interpreted as showing the presence of "interstellar" material [20]. Similar arguments suggest that IDPs also contain primordial molecular cloud material.

4. CONCLUSIONS

Large D excesses and the presence of solar flare tracks confirm that many particles in the chondritic subset of the stratospheric collection are interplanetary dust particles. The magnitude of the D excesses and their association with a carbonaceous phase suggests that, like certain primitive meteorites, IDPs contain material formed in interstellar molecular clouds [20]. The similarity of the IR spectra of "layer-lattice silicate" particles that exhibit large D excesses with those of protostars surrounded by dust shells provides an additional link between IDPs and interstellar molecular clouds. The 10 μm feature in the emmission spectrum of the Comet Kohoutek can be fitted by a mixture of the spectra of the "layer-lattice silicate" and "pyroxene" types, consistent with, although not proving, a cometary source for these IDPs.

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