

DENSITIES AND MINERALOGY OF COMETARY AND ASTEROIDAL INTERPLANETARY DUST PARTICLES COLLECTED IN THE STRATOSPHERE

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ABSTRACT

Atmospheric entry velocities were estimated on 31 stratospheric IDPs (interplanetary dust particles) using measured atmospheric entry temperatures from stepped He-release release measurements [4] and the atmospheric entry model of Love and Brownlee [5]. Twelve IDPs with atmospheric entry velocities > 18 km/s are believed to have been derived from comets while 4 IDPs with atmospheric entry velocities < 14 km/s likely originated in asteroids. Significant differences in density, morphology and mineralogy exist between the cometary and asteroidal groups. The cometary IDPs have an average density of 1.0 g/cm³ and are largely dominated by high internal porosities and anhydrous mineralogy. One cometary IDP, which is dissimilar to the others, is principally composed of hydrated silicate minerals. The asteroidal IDPs have a much higher average density of 3.3 g/cm³ compared to the cometary IDPs. Three of the four asteroidal IDPs are principally composed of hydrated minerals with low porosities arranged in compact structures. One asteroidal IDP, however, is similar to the majority of cometary IDPs; it contains anhydrous minerals with high internal porosity.

1. INTRODUCTION

Interplanetary dust particles (IDPs) which are collected in Earth's stratosphere are composed of materials believed to have originated primarily from short period comets and asteroids. Asteroidal IDPs are collisional debris from main belt asteroids, whereas IDPs derived from comets are particles dislodged from the surfaces of comets from devolatilization during heating from the Sun. Once free of their parent bodies, both asteroidal and cometary particles spiral toward the Sun due to Poynting-Robertson drag and thus have the potential to be captured in Earth's atmosphere.

Asteroidal IDPs spiraling in from low inclination, low eccentric asteroidal sources will enter Earth's atmosphere, on average, at relatively lower velocities than cometary IDPs, thus atmospheric entry speed can be used to discriminate between particles from source

regions as having either likely cometary or asteroidal origin. Here, we use the term 'asteroidal IDP' to mean particles that have low atmospheric entry velocities; conversely, we use 'cometary IDP' to refer to particles with high atmospheric entry velocity.

Spectroscopic measurements taken on comets [1] have shown that these bodies are composed of assemblages of crystalline and non-crystalline grains. CP IDPs (chondritic porous IDPs) are thought to have been derived from comets because of their generally low porosities and their high abundance of pre-solar grains [2]. CP IDP minerals include olivines, pyroxenes, bulk silicate glasses, GEMS, Fe sulfides (including pyrrhotite and pentlandite), Fe-Ni metals, amorphous carbon and organic compounds. Since comets accreted in the solar nebula at distances greater than ~30 AU from the protosun, cometary IDPs should contain materials that were the early primary components in the Solar System.

Here we present a brief summary of densities and some of the major minerals that we have observed in both 'asteroidal' and 'cometary' IDPs. The cometary IDPs are of particular importance for comparison to particles that were returned to Earth from Comet Wild-2 which are now being studied by a variety of laboratory techniques.

2. ANALYTICAL METHODS

Thirty one chondritic stratospheric IDPs ranging in size from 5 – 15 μm were systematically processed after removal from six collector flags. Masses and bulk compositions were measured in the Cosmic Dust Lab at the University of Washington using a scanning electron microscope (SEM). Densities were obtained by measuring particle masses, heights and x-sectional areas using a combination of SEM and TEM (transmission electron microscopy) techniques [3]. The particles were individually embedded in either epoxy resin or sulfur and microtomed for mineralogical studies by TEM. Following microtoming, the remainder of each IDP was sent to the University of Minnesota for stepped-He release measurements [4]. Standard TEM techniques were used to study the mineralogy from the microtomed

sections including microanalytical EDX by STEM (scanning transmission electron microscopy), high-resolution TEM, SAED (selected area electron diffraction) and bright and dark field imaging.

3. MEASUREMENT OF ATMOSPHERIC ENTRY TEMPERATURES

The temperature to which an IDP is heated during atmospheric entry depends on size, density, entry velocity and entry angle. The measurement of atmospheric entry temperature is possible due to abundant quantities of He gas which was implanted into grains largely from solar wind. In these grains, He atoms are trapped in multiple sites including crystal defects, as interstitial atoms, and in voids and bubbles. Because He gas is released over a range of temperatures as an IDP is heated, trapped He can be used as a thermometer to estimate peak heating temperature during atmospheric entry. This is done by generating a He release profile for an IDP by stepwise heating in a mass spectrometer and measuring the ^4He gas abundance at a series of temperature steps [4].

Atmospheric entry temperatures were obtained from 31 stratospheric IDPs using the stepwise He-release method. The peak heating temperature for each IDP was taken at the 50% release point from its corresponding He-release curve. Measured temperatures from 16 particles that have a likely cometary or asteroidal origin (Section 4 below) are given in Table 1. Temperatures measured on the cometary IDPs vary from 721 °C – 1016 °C while temperatures from the asteroidal group range from 505 – 1067 °C.

4. ATMOSPHERIC ENTRY VELOCITIES

The likely cometary or asteroidal origin for an IDP was determined using the peak heating temperature obtained from a stepped-He release curve and applied to the atmospheric entry model of Love and Brownlee [5, 6]. In the model, both size and density are accounted for; the greatest uncertainties are particle shape dependence, possible changes during atmospheric entry heating, emissivity effects, and thermal effects from transformations from heating of low temperature phases. The model assumes an entry angle of 45°, the most probable entry angle for particles encountering Earth.

Atmospheric entry velocities were obtained from 31 IDPs and are shown in the histogram in Fig. 1 The figure shows that velocities from 10 km/s to greater than 26 km/s were measured. We suggest that IDPs with velocities less than 14 km/s are likely to have been derived from asteroids while IDPs with velocities greater than 18 km/s are likely to have a cometary origin. IDPs with intermediate velocities (14 km/s < V

< 18 km/s) could have been derived from either comets or asteroids. These velocity boundaries are somewhat arbitrary and we do not intend to imply that these values

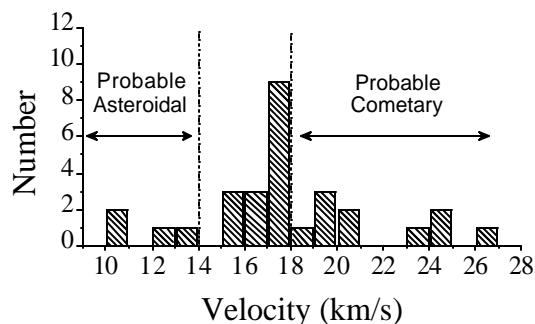


Fig 1. Histogram showing modeled atmospheric entry velocities from 29 chondritic IDPs. Four low speed IDPs ($V < 14$ km/s) are believed to have originated from asteroids while 12 high speed IDPs ($V > 18$ km/s) were likely derived from comets. Two IDPs with $V \gg 26$ km/s are not shown in the histogram.

are hard limits but rather that particles with entry velocities less than 14 km/s vs particles with entry velocities greater than 18 km/s are **statistically more likely** to have been derived from asteroids vs comets, respectively. Numerical simulations of the orbital evolution of dust particles from short period comets imply Earth encounter velocities of $> 12 - 15$ km/s [7]. Using an upper limit of 14 km/s for asteroid-derived particles and a lower limit of 18 km/s for comet-derived particles, 12 stratospheric IDPs from 31 particles measured are likely to have been derived from comets while four IDPs are likely to have originated in asteroids (Fig. 1). Intermediate velocity IDPs, between 14 and 18 km/s, may have been derived from either comets or asteroids.

5. IDP DENSITIES

Density is a fundamental property of IDPs that may be useful to help discriminate between cometary vs asteroidal origin. IDPs derived from comets - which often contain high concentrations of volatile ices - can be expected to have lower densities compared to asteroidal IDPs which are dominated by Fe-Mg silicate minerals and generally have lower pore space due to more compact mineralogy.

Using combined SEM and TEM techniques we measured the densities of 31 stratospheric IDPs [3]. Densities from 12 cometary and 4 asteroidal IDPs are listed in Table 1 and plotted as a function of atmospheric entry velocity in Fig. 2. The figure shows

that on average the cometary IDPs, ranging in density from 0.7 – 1.7 g/cm³ are much lower than asteroidal IDPs which have densities varying from 1.5 – 3.7 g/cm³. With the exception of one particle with anomalously low density, asteroidal IDPs have densities more than 2x higher than cometary IDPs.

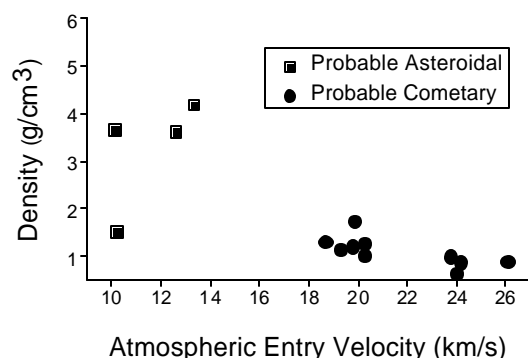


Fig. 2. Ten cometary and 4 asteroidal IDP densities plotted against atmospheric entry velocity. On average the cometary IDPs have much lower density than asteroidal IDPs. Two cometary IDPs with $V > 26$ km/s are not shown.

6. MINERALOGY

We have performed mineralogical investigations on microtomed sections of both cometary and asteroidal IDPs. A comparison of some of the common minerals observed – olivines, pyroxenes, GEMS and phyllosilicates – in both the cometary and asteroidal IDPs is given in Table 1. Specific compositions for olivines and pyroxenes are also provided. We should emphasize that many other minerals and phases including Fe-sulfides, silicate glasses, Fe+Ni metals, and carbon compounds are also present in these particles but are not listed in the table.

6.1. Cometary IDPs ($V > 18$ km/s)

Both crystalline and non-crystalline silicates are observed in the cometary IDPs. Olivines, pyroxenes and GEMS, in particular, are common in these particles. Olivines with $Mg/(Mg+Fe) < 0.9$ are present in at least 7 cometary IDPs. A wide range of pyroxenes – from enstatite to diopside – were observed. Most of these mineral grains are typically 100 – 200 nm in size with rounded to subhedral shapes. Microtomed slices show that interior pore space is often high.

A single IDP (U2070A-10A) with a measured entry speed of 20.3 km/s is composed primarily of the hydrated silicate minerals saponite and cronstedtite

which occur in compact structures. This IDP is mineralogically distinct from the other cometary IDPs and more closely resembles the asteroidal IDPs due to its abundant phyllosilicate minerals. A few nearly pure forsteritic olivine grains were present.

6.2. Asteroidal IDPs ($V < 14$ km/s)

The phyllosilicate minerals saponite and cronstedtite are present in three of the four asteroidal IDPs (Table 1). These minerals are generally poorly crystalline (this may be due to decomposition from atmospheric entry heating) but have approximately correct stoichiometric compositions and morphologies typical of these phyllosilicates. Occasional 0.71 nm or 1.0 – 1.4 nm lattice fringes that were observed are consistent with cronstedtite and saponite, respectively. Compared to cometary IDPs, only minor abundances of olivine and pyroxene are present.

One asteroidal IDP with an atmospheric entry speed of 10.2 km/s and an anomalously low density (1.5 g/cm³) is phyllosilicate-free and composed of a mixture of grains typical of the cometary group – olivine, pyroxenes and possibly GEMS.

7. DISCUSSION

Twelve IDPs with atmospheric entry velocities greater than 18 km/s that are likely to have a cometary origin have relatively low densities ranging from 0.62 – 1.73 g/cm³. Four IDPs with low atmospheric entry velocities believed to have been derived from asteroids have densities from 1.5 – 4.2 g/cm³.

The average density of the cometary IDPs is 1.0 g/cm³ which compares to 3.3 g/cm³ for the asteroidal IDPs. Cometary IDPs, which often have high porosities and abundant carbon contents should have relatively low densities compared to asteroidal IDPs. This is consistent with Fe-Mg silicate hydrated minerals and the compact morphologies that are present in these IDPs.

Mineralogically distinct differences are evident between cometary and asteroidal IDPs. Cometary IDPs do not contain abundant phyllosilicate minerals (with one exception) but are typically composed of anhydrous Fe-Mg silicate minerals and GEMS. This mineralogy is similar to materials observed in IR spectroscopic measurements taken by spacecraft on comets [8]. ISO SWS IR spectra taken on comet Hale-Bopp by the ESA spacecraft suggest that nearly identical mineralogy as that observed in some of the cometary IDPs – crystalline Fe_{0.9}, crystalline pyroxenes ($Mg/(Fe+Mg) = 0.9$) and amorphous Fe-Mg silicates – was required to fit the IR spectra [8]. Hydrated silicates could also be present at the 1% level or less.

8. CONCLUSIONS

From 31 stratospheric IDPs studied, 12 have atmospheric entry velocities greater than 18 km/s, and are believed to have a cometary origin. These IDPs have low densities of 0.6 – 1.7 g/cm³, generally high porosities and anhydrous mineralogy - Fe-rich olivines, low and high-Ca pyroxenes and GEMS – similar to IR observations made on comets such as Hale-Bopp. One cometary IDP, however, is morphologically and mineralogically distinct from the other cometary particles. It is composed of hydrated silicates, principally cronstedtite and saponite and has low porosity.

Four IDPs with atmospheric entry velocities < 14 km/s are likely to have originated from asteroids. Three of four IDPs in this group contain hydrated silicate minerals (cronstedtite and saponite) similar to carbonaceous chondrite meteorites. Densities for this group vary from 1.5 – 4.2 g/cm³ which are generally much higher than densities measured for cometary IDPs. One asteroidal IDP, however, contains mineralogy similar to IDPs from the cometary group. Fe-rich olivines, pyroxene and possible GEMS were observed.

9. REFERENCES

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IDP	Vel (km/s)	Temp (°C)	Density (g/cm ³)	Olivine	Pyroxene	GEMS	Phyllo-silicates
Cometary IDPs							
U2070A-4A	18.7	1000	1.29	Fo _{80-84, 97}	CEn ₉₉ , En ₉₉ , Aug	Yes	----
U2012A-2G	19.3	872	1.13	Fo ₈₈₋₉₃	En ₉₆ , Di?	Yes	----
U2073B-8B	19.8	920	1.19	Fo _{80-87,97}	En ₉₆₋₉₇	Yes?	----
U2-30C-4B	19.9	957	1.73	----	----	Yes?	----
U2012A-10G	20.3	736	1.00	----	----	Yes	----
U2070A-10A	20.3	928	1.25	Fo ₉₉₊	----	----	Cron,Sap
U2073A-9A	23.8	1016	0.98	Fo _{72-80,90}	En ₉₃ , Ca-Px	Yes?	----
U2073A-7F	24.0	844	0.62	Fo _{81-87,98}	En _{92,97} ; Pig	Yes?	----
U2073B-2I	24.2	931	0.86	Fo ₉₅	En _{94,99} ; Aug, Pig	Yes	----
U2073B-3C	26.1	967	0.88	Fo ₈₈	CEn ₈₆ , Di, Pig	Yes	----
U2012A-4J	>26	721	0.78	----	----	----	----
U2073B-3A	>26	1009	0.70	Fo _{77-78, 91}	En _{87,97} ; Di, Pig	Yes	----
Asteroidal IDPs							
U2012A-1G	10.1	599	3.68	----	Di	----	Sap?
U2012A-3G	10.2	505	1.54	Fo _{65-67,87-97}	En ₉₄ , Pig	Yes?	----
U2012C-1B	12.6	861	3.64	----	En ₈₇	----	Sap
U2073A-9F	13.3	1067	4.20	Fo ₆₀₋₆₂	Aug	----	Cron?

Table 1: Atmospheric entry velocities, stepped ⁴He release temperatures, densities and partial mineralogy from cometary and asteroidal IDPs. Fo=forsterite, En=enstatite, CEn=clinoenstatite, Pig=pigeonite, Aug=augite, Di=diopside, Ca-Px=Ca pyroxene, Sap=saponite, Cron=cronstedtite.