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Meteors: The other interplanetary dust particles

By

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Abstract: The question underlying this paper is how to exploit existing data to try gaining new insights that lead to testable predictions. The complete data set for aggregate particles collected in the lower stratosphere supports the hypothesis of hierarchical dust accretion for cometary dust. The hypothesis predicts the mineralogical and chemical properties of cometary meteoroids up to pebble-sized objects. These testable predictions can be tested by quantitative determinations of the physical and chemical properties of shower meteors. The synergy between such systematic meteor studies and the laboratory analyses of aggregate particles offers a way to learn about the formation, accretion and evolution of the icy protoplanets that became comet nuclei.

1. INTRODUCTION

Meteors are a spectacular short-lived light display that can be analyzed to derive physical properties (e.g. mass; tensile strength) of meteoroids (Spurny & Borovicka 1999) and chemical composition (McNeil et al. 1998; Borovicka 2001; Borovicka et al. 1999). Combined airborne and ground-based Leonid campaigns deployed state-of-the-art observational tools and high-speed computing power for systematic observations on known meteor phenomena and new features (Jenniskens et al. 2000). For example, (1) humped light curves (Murray et al. 2000), extreme beginning heights of visual ablation >135 km (Spurny et al. 2000), jetting activity (Taylor et al. 2000) and survival of meteoroid fragments (Borovicka & Jenniskens 2000). For reasons of space limitation, I rely heavily on review articles that will show the original papers that contain many excellent photographs of particles, minerals and other features I will describe here. I review the mineralogy and the major rock-forming element chemistry of interplanetary dust particles (IDPs) and discuss how this information can be relevant to meteor research (Rietmeijer 2000, 2002a; Rietmeijer & Nuth 2000).

The nice thing about meteors is that they can be linked to a specific short-period comet or near-Earth asteroid (NEA), e.g. 2201 Oljato that shows intermittent comet-like behavior. The interplanetary dust particles (IDPs) decelerate in the Earth's middle atmosphere without a light show, they can not be linked to a specific source but they can be collected for laboratory studies (Brownlee, 1985). Most IDPs are heated to a temperature between ~300°C and ~1,100°C (typically~750°C), causing the loss of volatile elements (S, Na, H, C, O, N from light organics)

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and ultimately complete melting (Rietmeijer 1998). Flash heating (5–15s) also causes thermal alteration of minerals. The recognizable changes used together with particle mass and size will constrain the entry velocity of a surviving IDP (Love & Brownlee 1991). In this manner it is possible to broadly establish a parent body source for individual IDPs with an entry velocity between ~11 km/s (asteroidal) and ~25 km/s for cometary debris that in fact means "low-velocity cometary" sources (Rietmeijer 2000).

2. IDPS, MICROMETEORITES AND METEORS

Extraterrestrial materials in the range of 10^{-12} g to 10^{-4} g include IDPs (Brownlee 1985) and micrometeorites, 20 to 500 microns in diameter, found at the Earth's surface (Kurat 1998). These meteoroids produce not even extremely faint meteors because their mass is orders of magnitude less than faint millimeter-sized meteors that already show variations in the chemical and structural properties of their source (Koten & Spurny 2001). About 95% of the typically spherical micrometeorites have mineralogical properties and a chemical composition indicating an affinity to several types of carbonaceous chondrite meteorites (Kurat 1998; Rietmeijer 2000, 2002b) that formed by complex alteration processes on parent bodies often in the presence of abundant water (Shearer et al. 1998). These conditions indicate objects in the inner and main asteroid belt. Interestingly, almost the non-aggregate IDPs, a subset of collected chondritic IDPs, resemble CM meteorites. A preponderance of type CM materials among micrometeorites and IDPs and scarcity among regular meteorites indicates specific material strength properties of their sources (Rietmeijer 2000). 'IDP silicate spheres' were linked to high-velocity meteor showers (Rietmeijer & Jenniskens 2000).

Based on their infrared reflectance spectra, comet nuclei, the majority of NEAs and objects in the outer asteroid belt, from which dust but not meteorite-sized objects could reach the Earth, are classified as primitive (P) and dark (D) bodies. Similar infrared properties were determined for the collected chondritic aggregate IDPs that have unique chemical, isotopic (e.g. D/H ratios) and mineralogical properties (Mackinnon & Rietmeijer 1987; Rietmeijer 2000, 2002b, c). Can we prove that aggregate IDPs, or a fraction of these particles, originated in active comets? No, we can not. We can make the statement that they are solid debris from small P- and D-class bodies with properties defining the physiochemical environments and processes in these bodies. This understanding will be used to predict the chemical and physical properties of larger meteoroids that could be tested by meteor observations.

3. COMETARY AGGREGATE IDPS

A comet nucleus is a rubble pile of boulders and pebbles, that resemble type CI or proto-CI materials, that are held together by dirty-ice with 'aggregate particle' dust (Rietmeijer 2002b, c). These ingredients will vary among comets and within a comet nucleus. I accept a cometary origin for the friable CI chondrites to explain fragmentation of some meteors with comet-like orbits and velocities entering the atmosphere (Ceplecha et al. 1998). These ingredients delineate an accretion hierarchy whereby dust evolved into pebbles and pebbles accreted into km-sized boulders. The whole sequence started with non-equilibrium gas-to-solid condensation of dust with simple compositions. This early dust is preserved in the matrix of aggregate and cluster IDPs that are 'solar system sediments' with a record of spatial and temporal variations in dust accretion and evolution which is described by the hypothesis of hierarchical dust accretion.

3.1 Hierarchical accretion

The hypothesis describes the formation and processing of ever-larger aggregates, viz. (1) matrix aggregates (2–5 microns), (2) aggregate IDPs (10–15 microns), (3) cluster IDPs (60–100 microns) and (4) (hypothetical) 'giant' cluster IDPs and so forth. Each stage is defined by an aggregate from the preceding accretion stage plus a limited number of non-chondritic dusts of similar size as the aggregate fraction (Rietmeijer 1998, 2002c). It describes the evolution of the presolar, molecular cloud, dust through multiple cycles of accretion – protoplanet modification – their catastrophic disruption – reintroduction of dust and fragments among the accreting solar nebula dust population. At each stage of the accretion hierarchy the relative abundances of the accreting dust types and processed debris reflected their availability at the time of accretion in the accretion regions. These mixing ratios highlighted the efficiency of dust and larger debris across the accretion zones of growing protoplanets. The hypothesis predicts that the smallest dusts that are not due to catastrophic fragmentation will be the oldest surviving dusts. They will be original circumstellar condensates with well-constrained chemical compositions or grains of processed condensed dust. Hierarchical accretion started with a few different dusts types each with a non-chondritic composition and as it continued two processes changed the chemical and mineralogical compositions of growing aggregates:

1. The growing aggregates gradually acquired a chondritic (CI or solar) bulk composition by accreting non-chondritic dust. Initially, the 'aggregate fractions' were chondritic for most rock-forming elements except for one or two elements, e.g. Ti and Al, and
2. The accreting dust sizes increased along with an increasingly diverse mineralogy when initially trace amounts of certain elements (e.g. Na, K, Al) became concentrated via fusion of amorphous silica-rich dust into larger eventually crystalline mineral grains.

3.2 Matrix aggregates and Aggregate IDPs (Rietmeijer 2002a, c)

Accretion began with principal components (PCs) that are the smallest, oldest surviving dust. The three different PCs (1) carbonaceous, (2) carbon-bearing ferromagnesiosilica and (3) (C-free) ferromagnesiosilica PCs accreted in randomly variable proportions into the matrix aggregates of aggregate and cluster IDPs. The matrix aggregate density was as low as 0.1 g/cc. These PCs resemble CHON (carbon-hydrogen-oxygen-nitrogen), mixed-particles and silicate particles in comet Halley. The Mg-rich ferromagnesiosilica PCs formed by agglomeration of condensed amorphous dusts with unique magnesiosilica and ferrosilica compositions but the formation of Fe-rich ferromagnesiosilica PCs required thermally induced fusion of processed dusts. Aggregate IDPs contain a limited number of dusts with non-chondritic compositions that occur in variable relative proportions among different particles, viz.

1. **Principal components:**
    - carbonaceous PCs: refractory hydrocarbons, amorphous and poorly graphitized carbons, and turbostratic carbons,
    - carbon-bearing ferromagnesiosilica PCs: <50 nm-sized Mg, Fe-olivines [$(Mg, Fe)_2 SiO_4$], Mg, Fe-pyroxenes [$(Mg, Fe)_2Si_2O_6$], Fe,Ni-sulfides [$(Fe,Ni)_7S_8$], Fe-oxides embedded in a refractory hydrocarbon and amorphous carbon matrix, and
    - ferromagnesiosilica PCs:

(a) *Mg-rich coarse-grained PCs* with a (Mg, Fe)$_6$Si$_8$O$_{22}$ (smectite dehydroxylate) bulk composition consisting of a coarse-grained (10–410 nm) Mg, Fe-olivine and Mg, Fe-pyroxene plus amorphous aluminosilica material (± traces of Ca, Na, K), and

(b) *Fe-rich ultrafine-grained PCs* with a (Mg, Fe)$_3$Si$_2$O$_7$ (serpentine dehydroxylate) bulk composition with an amorphous matrix and embedded grains (<50 nm) of Mg, Fe-olivine, Mg, Fe-pyroxene, Fe,Ni-sulfide, and low-Ni, Fe-metal,

2. **Mostly Mg-rich Mg, Fe±Ca-silicates** (olivines, Ca-free and low-Ca pyroxenes, and Ca-rich clinopyroxene (diopside: CaMgSi$_2$O$_6$), and
3. **Fe, Ni-sulfides**
4. **Refractory aggregates** (~5 to ~15 microns) that consist (almost) entirely of mostly small (<500-nm) grains of hibonite (CaAl$_{11}$Ti$_{0.5}$Mg$_{0.5}$O$_{19}$), gehlenite (Ca$_2$Al$_2$SiO$_7$) and perovskite (CaTiO$_3$) but also contain corundum (Al$_2$O$_3$), spinel (MgAl$_2$O$_4$), melilite (Na, Mg, Fe-bearing gehlenite), plagioclase (CaAl$_2$Si$_2$O$_8$) and diopside. Refractory aggregates are not found yet as part of aggregate or cluster IDPs but their individual constituents occur in these IDPs.

3.3 Cluster IDPs (Rietmeijer 2002a, c)

Aggregate and cluster IDPs are both aggregate particles that are not fundamentally different except in the overall size of their dust constituents. Cluster IDPs are randomly variable mixtures of (1) aggregate IDPs with (2) olivine, Ca-poor and Ca-rich pyroxene and Fe,Ni-sulfide dust that is > 10 and up to 25 microns in size. In cluster IDPs large (~15 microns) stoichiometric plagioclase grains make their first appearance in the accretion hierarchy. Stoichiometry means that a mineral has the exact chemical composition that is dictated by its crystallochemical properties. Deviations from this condition might occur when minerals grow from an amorphous solid (i.e. glass). Smaller non-stoichiometric plagioclase and feldspars (NaAlSi$_3$O$_8$–KAlSi$_3$O$_8$) minerals in aggregate IDPs formed when smaller amorphous aluminosilica grains fused together whereby trace amounts of Ca, Na and K became gradually concentrated to form stoichiometric plagioclase. In similar sequences of chemical and mineralogical evolution and processing other 'complex' silicates such as diopside were formed. Thus, as time went by the increasingly larger aggregates will show an increasingly greater diversity of its minerals due to the formation of new 'complex' minerals from chemically simple precursors and concentration of initially trace elements in these new minerals. For example, the Na/Si (atomic) ratio is 0.1 for aggregate and cluster IDPs but it is 0.3 in Na-feldspar. If during accretion this mineral had formed aggregates, the resulting meteor had a much higher than the chondritic Na/Si ratio of 0.05. Variations in the relative proportions of the dusts that accreted into evolving aggregate particles were a critical, composition-controlling parameter.

3.4 Porous and compact Aggregate IDPs (Rietmeijer 2002a, c)

Most aggregate and cluster IDPs are porous (fluffy) particles but compact aggregate and cluster IDPs exist. The latter could form by (1) co-accretion of massive dusts and (2) by collapsing porous aggregates. Accretion of massive dust, such as silicates, Fe,Ni-sulfides and refractory minerals typically leads to the formation of compositionally-extreme, compact aggregates. This accretion feature reflects high abundances of silicates, for example, but a paucity of aggregate dust in the accretion regions. At each stage of the accretion hierarchy the constituents of newly forming aggregates, and thus their bulk composition, reflect the relative abundances of available dusts, which could cause random co-accretion of porous (chondritic) aggregates and compact non-chondritic aggregates.

At this point, stepping back a little, I would like to observe that carbon (and associated H, N and O) is uniquely associated with carbonaceous PCs and to a lesser extent with the mixed carbon-silicate PCs. As a result, the typically high, bulk carbon content of aggregate and cluster IDPs ranging from 1 to 44 element wt % (Thomas et al. 1996) was established very early in the accretion history. None of the PC types recur as larger entities during continuing accretion, which is consistent with a gradual depletion of the oldest dusts.

The second process to make compact aggregates is textural collapse of porous aggregate particles. This typically post-accretion change required particle residency in small, evolving icy protoplanets. In such bodies hydrocryogenic water exists at the interface of dust embedded in the ice. This water acted as a whetting agent of grain surfaces and caused hydration. The surface tension of this interfacial water layer will pull the porous texture together leading to a gradual decrease of accreted aggregate dust porosity (Rietmeijer 1996). Most collapsed aggregates show evidence for at least partial, if not complete, hydration.

4. HYPOTHETICAL "GIANT" CLUSTERS AND METEORS

Despite their low aggregate density cluster IDPs are the largest porous meteoroids entering the Earth's atmosphere without a light show. The dimensions of the largest non-chondritic IDPs that can either be compact clusters or melted spheres (Rietmeijer 2000, Rietmeijer & Jenniskens 2000) support the existence of larger, 'super-cluster' meteoroids that are aggregates of cluster IDPs and > 60 micron-sized silicate and sulfide grains or massive particles. The hierarchical dust accretion hypothesis predicts a broad linear correlation between the sizes of the constituents and the size of the aggregate particle. This linearity disappeared when processing through evolving protoplanets had caused the gradual collapse of the accreted aggregate fractions. The resulting low-porosity 'giant' clusters are still friable materials because compaction was due to 'passive' collapse and not lithification ('rock-formation') that required hydrostatic pressure and sustained thermal regimes in protoplanets. On these protoplanets large volumes of accreted aggregates would be compressed into the pebbles and boulders of comet nucleus rubble piles.

The hypothesis described here also constrains the mineralogical properties of cometary meteoroids. Ablation of a texturally heterogeneous aggregate would not produce a smooth light curve but rather a 'humped' light curve with two or more humps. Murray et al. (2000) analyzed the 'humped' light curve for a composite Leonid meteoroid with a dustball component and a single massive grain, each with a $(2.4 - 2.5) \times 10^{-4}$ g mass. Using measured densities of IDPs (see, Rietmeijer 1998) I assumed 1 g/cc for the dustball, 3.3 g/cc for a Mg-rich silicate grain and 4.8 g/cc for a Fe,Ni-sulfide grain. This composite meteoroid contained a porous aggregate component, 575 micron in diameter, plus either a massive 525-micron silicate grain or compact aggregate, or a Fe-sulfide grain, or massive aggregate, of 460 micron in diameter. Assuming a porous meteoroid, it was at 'giant' cluster of 2,100 to 4,800 microns in size.

The measured density of aggregate IDPs ranges from 0.4 to 3.4 g/cc (see, Rietmeijer 1998) but with continued accretion the mass of larger accreting aggregates is increasingly determined by massive silicate a nd sulfide grains or their compact aggregates. Thus, bulk aggregate density will gradually approach several grams per cubic centimeter but which is strongly affected by the amount of pore space of growing aggregates. Could CI chondrites be the 'end members' of the accretion hierarchy? Sulfide grains in CI chondrites are 50 to 150 microns (Kerridge et al. 1979) and silicate grains range from 50 to~500 microns (McSween 1977, Richardson & McSween 1978). The upper range of the silicate dimensions is similar to the (calculated) silicate grain size in the composite Leonid meteoroid that could be a compact pebble and not a porous aggregate.

What, if anything, does it mean? It might well be true that this composite Leonid meteoroid and CI chondrites are end-members of the accretion hierarchy. But we actually do not know the meteoroid's density and how it compares with the CI chondrite density of 1.6 g/cc that would be consistent with a collapsed aggregate in the presence of water. Indeed, pervasive layer silicates in CI chondrites prove that water was present for the transition from proto-CI to hydrated CI chondrites with 35% porosity (Rietmeijer & Nuth 2000, Fig. 1). The mass of the proto-CI or CI materials supports a resemblance with pebble-sized cometary meteoroids (Borovicka & Betlem 1997) that have a density of 2 g/cc and possibly even 3.5 g/cc (Spurny & Borovicka 1999). This density is suggestive of a coarse-grained anhydrous (proto-CI) 'giant' cluster or an even larger aggregate depending on the porosity. When in the presence of water aggregate porosity could be decreased, the detection of hydrogen in meteors could be used to define the origin of meteoroid density either as a secondary feature or a primary accretion feature. Knowing its density might then provide an estimate of its porosity and its composition, i.e. bulk-CI or non-CI deviations might then provide a glimpse of its mineralogical make-up.

5. PREDICTIONS FOR METEORS

I will highlight three issues that I find of particular interest, which deserve the attention of systematic meteor studies using all meteor parameters in an interactive and iterative manner.

5.1 Aging meteoroids (Rietmeijer 2002a)

Upon release from a comet nucleus there is ample opportunity for erosion of ejected debris in the coma, space weathering in dust trails and thermal erosion during the meteor phase. Volatile materials in this debris will be the most susceptible to these processes. Meteoroid fragmentation shortly after release from the nucleus was reported for 1999 and 2001 Leonids to explain short-duration pulses of several tens of meteors in a few seconds (Toth et al. 2002; Watanabe et al. 2002). These outbursts are prime targets for quantitative chemical analyses because these young releases lost only their most volatile compounds and would still contain other volatile materials that would be lost during high altitude ablation. That dust trails of a specific release age can be recognized (Asher 2000) is just fantastic because it provides an opportunity to track weathering of volatile compounds such as those that formed an 'organic glue' holding meteoroids together. The loss of this organic material yields fragments that are (further) depleted in H, C, O and N before they enter the Earth's atmosphere. Other volatile compounds such as salt minerals (carbonates; sulfates) in hydrated meteoroids could also be eroded causing loss of Na and K, among others. There are probably other mineralogical effects. It seems likely that original volatile element abundances are gradually decreased in aging trails. All else being equal, the chemical compositions of Leonid meteor of different age could show this effect.

5.2 Unpredictable, non-CI bulk compositions

A combination of meteoroid size and density used in conjunction with bulk composition, differential ablation and fragmentation behavior is a powerful tracer of hierarchical evolution of aggregate particles that merely sampled available dusts at the time of accretion. The initial bulk compositions will be simple although huge variations in the C/Si ratios are possible (see below). Increasingly younger aggregates with variable porosity are a chaotic mixture of millimeter-sized fluffy aggregates, compact silicate and/or sulfide clusters and refractory aggregates or grains. Differential ablation of this composite meteoroid would show a chondritic signal, strongly coupled Mg,Si(±Ca) (olivine; pyroxene) and Al, Ca, Si(±Na, K) (plagioclase) signals, an Fe(±S) and a coupled signal for Al, Ti, Ca(±Mg). In reality various combinations will occur but the point is that 'pure Fe' or 'refractory' meteors could still be cometary meteors. A meteor's chemical signature could range from the CI value for each of its elements and the amount allowable by the mineral hosts (Na/Si ratio, see above). Laboratory measurements of IDPs and (micro)-meteorites produce quantitative chemical data. It is much harder to obtain such data for meteors when ablation efficiency among other factors, will determine the measured chemical signature. Ternary diagrams using emission efficiencies of the constituent elements, e.g. Mg-Fe-Na in shower meteors (Borovicka 2001), are an excellent step towards integrating these different data sets. Element depletions relative to CI are neither instructive nor realistic when lacking a physical ablation process for its explanation. Systematic absences of a particular element or element combination might be an indigenous property with information on aggregate formation.

5.3 Hydrogen

Hydrogen is associated with the carbonaceous and mixed carbon-silicate PCs in the matrix of aggregates (section 3.2). The often fused carbonaceous PCs contain vesicles when volatile elements boiled-off during atmospheric entry flash-heating. This process contributed to the survival of carbon-rich particles when residual refractory hydrocarbons and amorphous carbons fused into contiguous sheets increasing particle cohesion (Thomas et al. 1993). Hydrogen is also associated with layer silicates in hydrated aggregates that could range from being almost fully hydrated to mostly anhydrous porous aggregates with a low abundance of layer silicate grains (Rietmeijer 1998, 2000c). Hydration experiments of amorphous magnesiosilica material such as in Mg-rich ferromagnesiosilica PCs showed that hydration and formation of ultrafine-grained layer silicates (Rietmeijer 1996) would be possible in comet nuclei at perihelion (Nelson et al. 1987). Thus, cometary meteors might contain a significant amount of hydrogen. Part of it was in PCs that accreted very early during hierarchical dust accretion, part of it was due to protoplanet hydration. As massive silicates and sulfides will dominate the mass of larger aggregates, the hydrogen content of cometary meteors wherein these massive constituents will not be hydrated might decrease towards larger (pebble-sized) meteors. Hydrogen resides in different materials that might reach maximum ablation at different times along a cometary meteor path, which 'diluted' the strength of the diagnostic spectral feature. Apart from other considerations but given that PCs are common (e.g. comet Halley) and the ease of hydration, the really surprising finding will be the systematic absence of a hydrogen signature in a cometary meteors.

6. CONCLUSIONS

This paper started with a summary of data and context for aggregate particles collected in the Earth's lower stratosphere followed by an introduction of the hypothesis of hierarchical dust accretion and evolution that mixes observation and prediction in order to weave a coherent tale. Gradually, yet unavoidably, the paper becomes speculative at the transition from observational data on collected cometary debris and information present in meteors, 'the other interplanetary dust particles'. The hypothesis predicts numerous possible permutations in the mineralogy and chemistry of cometary meteoroids, which presents a daunting but not hopeless task to explore. Systematic analyses of 'humped' light curves, fragmentation behavior, differential ablation, and quantitative reduction of meteor spectra from a large number of meteors in a single shower, or accumulated for annual showers from a specific source, will make it possible to reconstruct the accretion and evolution of individual comets. The information continuum from aggregate IDPs to cometary meteors will show the existence of similarities and differences among comets.

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