FROM COMETS TO METEORS

J. MAYO GREENBERG
Raymond and Beverly Sackler Laboratory for Astrophysics,
Leiden Observatory, Leiden University, Niels Bohrweg 2,
Leiden 2300 RA, The Netherlands
E-mail: greenber@strw.leidenuniv.nl

(Received 8 May 2000; Accepted 15 July 2000)

Abstract. A summary of comet nucleus and dust properties is used to suggest a basis for predicting the properties of meteor shower particles originating as comet debris.

Keywords: comets, dust, meteors, meteoroids

1. Introduction

The Leonid showers are a classic case of periodic meteors associated with the passage of a comet - Tempel/Tuttle - through the orbit of the earth. The largest particles in the dust distribution - those that would be seen as the anti-tail - remain in an orbit approximately that of the comet itself and as they return to the region of the Earth are seen as meteor showers. Each shower is associated with a particular Earth orbit crossing of 55P/Tempel-Tuttle. It is the purpose of this paper to provide a general background on the chemical and physical properties of comets and comet dust which may provide a basis for understanding the observed properties of cometary debris and, in particular, of the Leonid meteors.

I find it interesting to quote here from the conclusion of a paper written earlier in which the *comet properties were derived from the character of meteors* "The aggregated dust model makes it possible to derive comet nuclear densities from a comparison of evaporated comet debris with meteor densities. It is shown that a high degree of porosity is to be expected with at least 60% of a comet being vacuum." (Greenberg, 1986a,-b). The large uncertainty in extracting particle density from meteor data could have rendered that result suspect but it turns out to have been confirmed. The situation now is reversed. The post Halley era has led to more direct evidence of the low density nature of comets and we can more usefully invert the meteor–comet connection to make predictions of meteor properties based on comets rather than the other way around. The additional results now available on interplanetary dust particles (IDPs) should help to tie down the connections.

2. Chemical composition of comets

The chemical composition of a comet nucleus can be very strictly constrained by combining the latest results on: the core-mantle interstellar dust model, the solar system abundances of the elements, the space-observed composition of the dust of comet Halley, and the latest data on the volatile molecules of comet comae. A detailed discussion of how interstellar dust comes to be incorporated into comets during the formation of the solar system is beyond the scope of this paper. However, it is certainly recognized that both the comet coma volatiles and the comet dust composition are very closely related to what we infer to be the composition of the primitive solar nebula dust as it existed 4.6 billion years ago. There are striking similarities between the volatile composition of comets and hot cores of regions of star formation. In the very beginning there are the silicate particles blown out of cool evolved stars. These accrete mantles in the denser clouds, which are photoprocessed. The mantles contain molecules created by surface reactions, by gas phase reactions and by photoprocessing. What is followed here are the "large" tenth micron (mean radius) grains which contain much of the mass of the dust - all the volatiles and all the silicates. Other populations of interstellar dust consist of very small carbonaceous particles and even smaller particles, which are presumed to resemble large polycyclic aromatic hydrocarbons. The large grains cycle between low-density (diffuse) clouds and high-density molecular clouds and star forming clouds.

Those that are left over from star formation are shown at the top left of Figure 1. They consist of silicate cores with highly photoprocessed organic mantles. The very small particles/large molecules are also present in the diffuse cloud phase as separate particles. Going back to the molecular cloud phase the process is repeated. Those particles that are confined to the region of star formation in the final collapse phase are presumed to have accreted all the remaining molecules and the small particles as part of the outer mantle. Some of the evidence for these final accreted phases is provided by the observation of gas phase species found in molecular hot cores. They are dense warm clumps located close to the massive young stars where the molecules are presumed to have been evaporated from dust grains that did not aggregate in the stellar nebula. Actually a closer comparison must be found by probing the envelopes of low mass stars more characteristic of our Sun. As stated in Bockelée-Morvan *et al.* (2000) "A quantitative comparison shows that chemical abundances in Hale-Bopp parallel those *inferred* (my italics) in interstellar ices, hot molecular cores and bipolar flows around protostars". The organic mantle beneath the ice had its confirmation with the mass spectra obtained in situ for comet Halley dust which led Kissel and Krueger (1987) to infer a core-mantle structure of the dust particles. Thus according to Jessberger and Kissel (1991) "The existence of the previously postulated (Greenberg, 1982) core-mantle grains seems to be substantiated by data".

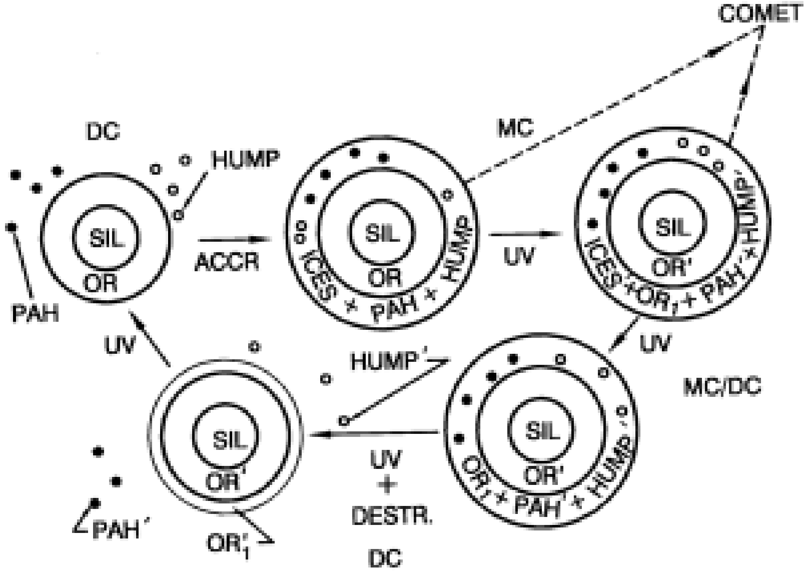
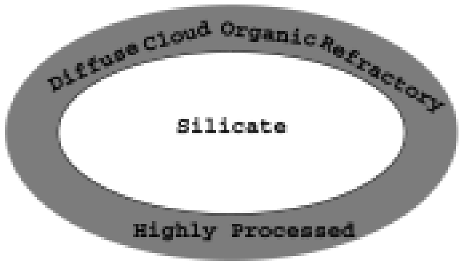
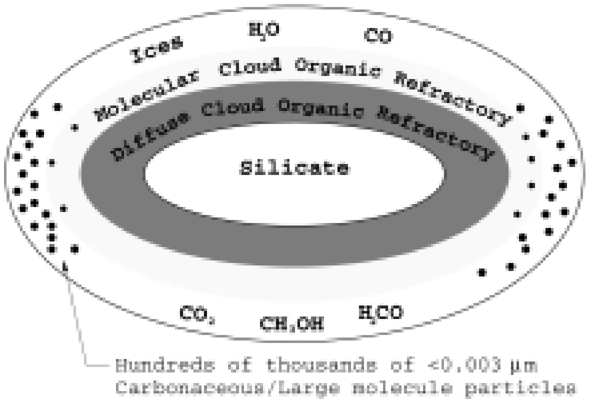


Figure 1. Cyclic evolution of interstellar grains. Upper left is an average tenth micron radius silicate core-organic refractory mantle grain in the diffuse interstellar medium (DC). The mantle is the heavily processedorganic material as in Greenberg et al (2000). Schematically illustrated are the hundreds of thousands to millions of very small carbonaceous (hump, denoting their effect on the interstellar extinction) particles and even smaller PAH particles as in Li and Greenberg (1997). Following clockwise, the next phase depicts what happens after entering a molecular cloud (MC) showing the accretion of a complex ice mantle along with the very small particles and, simultaneously with accretion, the ultraviolet photoprocessing of the outer mantle and the organic inner mantle as well as the PAH and hump particles (primes denote modified material). The next phase corresponds to the emergence out of the molecular cloud (MC/DC) after star formation when the ices are evaporated/destroyed leaving first generation organics (OR_1). And finally, the ultraviolet processing and partial destruction of the newly added first generation organic material (OR_1 -> OR_1') as well as reemergence and reforming of PAH and hump particles leading back to the “original” diffuse cloud (DC) dust. The arrows leading upward depict the kinds of dust, which would make up the protostellar material aggregating to form comets. In this representation it is assumed that this occurs with little or no evaporation and reforming of ices. A single cycle lasts about 10^8 years and as many as 50 may occur before the dust is consumed in star formation.

The basic model of interstellar dust consists of three populations of particles (Li and Greenberg, 1997). The major mass is in tenth micron particles consisting of silicate cores with organic refractory (complex organic molecules) mantles. Additionally there are very small carbonaceous particles/large molecules. In molecular clouds the large particles accrete additional mantles of frozen molecules and in the dense clouds there is also accretion of the very small particles which are imbedded in the "ices". This is schematically shown in Figure 2.



Diffuse Cloud Core-mantle Grain



Pre-Cometary Core-mantle Grain

Figure 2: Upper figure depicts a diffuse cloud silicate core-organic refractory mantle particle. It has to be nonspherical (here elongated) in order to provide for interstellar optical polarization. Lower figure depicts a fully accreted grain in the protosolar nebula.

The nature of the organic mantle material varies depending on whether the dust is in a low density diffuse cloud or a molecular cloud (Tielens *et al.*, 1996; Greenberg and Li, 1997). There are significant variations in the relative proportions of C, N, O and H in the complex organics in different regions. In diffuse clouds the organic mantle is strongly depleted in oxygen and hydrogen, whereas in molecular clouds complex organic molecules are present with more abundant fractions of oxygen and hydrogen. Furthermore, the ratio of the mass of organic mantles to the silicate core is highly variable. In the unified model for diffuse cloud dust of Li and Greenberg (1997) this ratio is $V_{OR}/V_{sil} = 0.95$, whereas matching the silicate polarization in the Orion B-N object requires V_{OR}/V_{sil} is about 2 (Greenberg and Li, 1996a). It is of interest to note that the mass spectra of comet Halley dust - as obtained by Kissel and Krueger (1987) and presumably representing the ultimate molecular cloud collapse phase - gave about equal masses of organics and silicates in the dust which implies a volume ratio of about 2. While the presence of organics is observed via a 3.4 μm absorption feature this represents only the aliphatic molecules and much if not most of the diffuse cloud organic mantles consist of aromatics (Greenberg *et al.*, 2000). We shall assume that the organic refractory mantles in the final stages of cloud contraction are most closely represented by the properties obtained for Halley dust; i.e. $M_{OR}/M_{sil} = 1$ and with an atomic distribution as given in Table I for comet dust organics. Table I gives the stoichometric distribution of the elements in laboratory organics (residues of ultraviolet photoprocessed ices) (Greenberg and Li, 1997) compared with the comet Halley mass spectra (Krueger and Kissel, 1987) normalized to carbon.

TABLE I

	Laboratory Organics			Comet Halley		
	Volatile*	Refractory*	Total*	PICCA(gas)@	dust@	total@
C	1.0	1.0	1.0	1.0	1.0	1.0
O	1.2	0.6	0.9	0.8	0.5	0.6
N	0.05	> 0.01	> 0.03	0.04	0.04	0.04
H	1.70	1.3	1.5	1.5	1.0	1.2

* Division between volatile and refractory is here taken at a sublimation temperature less than or greater than ~ 350K respectively.

@ Assuming equal amounts of dust and gas.

Combining a representative distribution of volatile components from comet comae with the inferred chemical composition of the silicate core-organic refractory component one can arrive at a "canonical" distribution of comet nucleus chemical components as given in Table II. Table II gives the distribution by mass fraction of the major chemical constituents of a comet nucleus: as derived from comet volatiles and dust refractories (Greenberg, 1998). Included in "others" are SO, SO_2, HC_3N, NH_2CHO, HCOOH, $HCOOH_3$, etc. (Bockelée-Morvan *et al.*, 2000). Note that water, while abundant, is certainly not dominant.

TABLE II

Materials	Mass fraction
Silicates	0.26
Carbonaceous (very small)	0.086
Organic Refractory	0.23
H_2O	0.31
CO	0.024
CO_2	0.030
CH_3OH	0.017
H_2CO	0.005
(Others)	0.04

3. Aggregate properties of comet dust

The thermal emission from comet dust, and particularly the presence of a 10 μm excess characteristic of the silicates, have been used to demonstrate the very fluffy character of the particles. I will discuss a limited number of comets for which a fluffy dust model has been applied.

3.1. COMET HALLEY

The uniqueness of comet Halley with regard to the dust was that for the first time three major properties were simultaneously observed: chemical composition, size (mass) distribution, and infrared emission. Greenberg and Hage (1990) showed that, in order to satisfy simultaneously such independent properties of Halley coma dust as (1) 9.7 μm emission (amount and shape), (2) dust mass distribution, and (3) mass spectroscopic composition of both rock and organic elements, one demanded – as the most consistent configuration - that the dust be very fluffy aggregates of sub-micron interstellar dust silicate core-organic refractory mantle particles. The major thrust of this is that comet dust consists of intimately related silicate and carbonaceous materials (core-mantle structure) rather than separate silicate and carbon components. In light of the current understanding that interstellar volatile species are well preserved as seen in comet comae (see-Bockelee-Morvan *et al.*, 2000 and references therein) it seems even more reasonable to expect the refractory silicate core-organic mantle underlying the molecular cloud ices to be well preserved as well. One of the observational supports of the model is that the in situ mass-spectra of Halley dust with high dynamic range show that, except for the very small (attogram) grains (Utterback and Kissel, 1990), neither pure organic (so-called CHON) nor pure silicate particles exist. Instead, they are intimately mixed on a very fine scale in such a manner that they form the sub-units with a core-mantle structure in the aggregates (Lawler and Brownlee, 1992). This is additionally reflected by the fact that the CHON ions have on the average a higher initial energy than the silicate ions in measuring the mass spectra (Krueger and Kissel, 1987).

In summary, the result of the intertwining of the three basic Halley dust observations is: (1) comet dust consists of aggregates of ~0.1 μm silicate core-organic refractory mantle particles; (2) the average porosity of the comet dust is $0.93 < P < 0.975$. The inferred Halley comet dust density is $0.07 < \rho_{CD} < 0.19$ g cm^{-3}; i.e. ρ_{CD} ~0.1 g cm^{-3} is a suggested canonical value. Note that we have used $\rho_{CD} = \rho_{solid}$ x $(1-P)$, where ρ_{solid} is the mass density of the compact core mantle particles assumed to be about 2.7 g cm^{-3}. If one reconstitutes the original comet material by adding back the volatiles on the comet dust skeleton, as well as the *very* small interstellar dust particles, and about 1/2 of the original (relatively volatile) organic refractories, which were removed by the solar heating, the reconstituted comet nucleus density may be inferred to be $0.26 < \rho_C < 0.51$ g cm^{-3}. Later works (Greenberg and Li, 1998a; Greenberg, 1998) have not modified these results significantly and representative values are suggested for comet Halley dust density as ρ_{CD} ~0.1 g cm^{-3} and for its nucleus density as ρ_C ~0.33 g cm^{-3}. The latter is consistent with the low density suggestion proposed by Rickman (1986) based on the analysis of non-gravitational forces although, using the same kind of data, Sagdeev *et al.* (1988) arrived at a value 0.61 g cm^{-3}.

3.2. COMET P/BORRELLY (1994*l*): A JUPITER-FAMILY SHORT-PERIOD COMET

The fluffy aggregate comet dust model has also been applied to short-period (SP) comets (see Li and Greenberg, 1998a). As an example, we have calculated the dust thermal emission spectrum of comet P/Borrelly (1994l), with an orbital period P ~ 7 years, from 3 - 14 μm as well as the *weak* 10 μm silicate feature in terms of the comet modeled as a porous aggregate of interstellar dust (Li and Greenberg, 1998a). It seems that, compared to the Halley dust, the dust grains of P/Borrelly appear to be relatively more processed (more carbonized), and less fluffy. A *not so fluffy* aggregate model of silicate core- *amorphous carbon* mantle grains with a porosity $P = 0.85$ appears to match the observational data obtained by Hanner *et al.* (1996) quite well. This would imply that comet P/Borrelly is substantially denser than Halley. Since P/Borrelly has passed through the inner solar system many more times than P/Halley and therefore been subjected much more to the solar irradiation, could it be that because of thermal processing the outer layers of the nucleus could have been significantly modified? Could a layer of more compacted material have been produced? In particular, could the organic refractory materials have undergone further processing and annealing (Jenniskens *et al.*, 1993)? Observations do show that some Jupiter-family short-period comets are depleted in C_2 and C_3 but are approximately constant in CN (A'Hearn *et al.*, 1995). This is consistent with the idea of carbonization since CN is mostly produced from grains while some C_2 and C_3 come directly from the volatile nuclear ices which are relatively depleted in SP comets (A'Hearn *et al.*, 1995). Perhaps the dust of short-period comets lacks the small particles seen in the Halley size spectra. Are they more strongly bound and less susceptible to fragmentation? These questions require substantial further discussion but clearly while it appears that comets may start out consisting of the same material they can evolve to look rather different (see Greenberg and Li, 1999).

Since up to now only two SP comets were known to have silicate emission and *weak at that* (P/Borrelly and P/Fay; see Hanner *et al.*, 1996), we are not able to generalize the dust properties of short-period comets. Systematic observations of the thermal emission spectra and the silicate features for a large set of samples are needed.

3.3. COMET HALE-BOPP (C/1995 O1): A VERY LARGE LONG-PERIOD COMET

Comet Hale-Bopp (C/1995 O1) is an exceptionally bright long-period comet (P ~2000 years). It was so active and so bright that it became visible even at a heliocentric distance of ~7 AU. Its strong activity and strong thermal emission features provide a rare opportunity to study the origin of comets and to constrain the comet dust morphology, composition and size. Li and Greenberg (1998b) have calculated the dust thermal emission spectrum based on the model of comet dust consisting of very porous aggregates of interstellar dust. Both the continuum emission and the 10 μm silicate feature are well matched (see Li and Greenberg, 1998b for details). The presence of large numbers of very large particles in Hale-Bopp was confirmed by the submillimeter continuum emission observation (Jewitt and Matthews, 1999). It has been argued that these large particles may dominate the total dust mass of the coma (Fulle, 1999; Jewitt and Matthews, 1999). Assuming a spherically symmetric dust coma with uniform radial outflow, adopting the water production rate on Feb.23.9, 1997 (Dello Russo *et al.*, 1997) of 4.3×10^{30} mols/s, and an average dust outflow velocity of 0.12 km s^{-1} (calculated from $v_d \approx 05\ (r_h/6.82)^{-0.5}$ (where r_h is the heliocentric distance in AU; Sekanina, 1996), the dust-to-water production rate ratio was estimated to be as high as 41 or even higher (see Li and Greenberg, 1998b). If a higher dust outflow velocity of 0.60 km s^{-1}, which may be more realistic, is adopted, the dust-to-water ratio would be about 200! However, one should keep in mind that the IR emission alone can not give a reliable dust production rate since very large particles are too cold to contribute to the limited wavelength range of the infrared radiation considered here (as long as the size distribution for those cold particles is not too flat). Therefore the total mass of the large particles is not well constrained, as was already noted by Crifo (1987). Of equal importance is the fact that the large particles actually can act like mini-comets and preserve their ices until far from the nucleus so that *their* volatiles are not observed and therefore do not contribute to the gas part in the dust to gas ratio.

3.4. COMET 55P/TEMPEL-TUTTLE

For comet 55P/Tempel-Tuttle no silicate emission feature was seen (Lynch *et al.,* 2000). This is along the lines indicated by comet Borrelly, that Jupiter-family short-period comets have weak or no silicate features. A possibility is that this difference from long-period comets can be attributed to the different degree of evolution of the comet nucleus. This could lead to the fact that even though the basic composition of the comet is similar the dust appears different either because the porosity is lower, or that the dust is less fragmented; i.e. contains less small particles in its size distribution. In any case we suggest that the basic composition of the initial *large* cometary dust fragments should be derivable from aggregates of core-mantle interstellar dust particles. However, after lift off perhaps there survives more processed material on the grains so that the volatility of the mantle is less and the particles have a greater strength against fragmentation. Thus even the relatively small ones are initially poor silicate emitters, being filled with more non-absorbing material (ices) and having a lower porosity, both of which lead to lower temperatures. However, ultimately even the very large ones must lose their volatiles so that, as meteors, we shall assume them capable of achieving the ultimate porosity of the skeleton core-organic refractory particles as a reasonable possibility. By ultimate I mean during the time spent near the first perihelion passage. However, the physical evolution of the remaining fluffy structure may subsequently undergo some compaction as could result from the process of differential evaporation considered by Mukai and Fechtig (1983). Solar wind effects are not expected to modify more than the outermost (tenth micron or less) layer of the large comet dust particles.

4. Large comet dust particles

4.1. METEOIDS

Meteors are generally much larger than the comet dust particles observed in the visual or infrared. While these observations may be used to derive the morphological structure they tell us little about the population which shows up as meteors. Submillimeter observations (Jewitt and Matthews, 1999) extend the evidence for larger particles. The existence of even larger particles has been obtained from dust impacts on spacecraft detectors by comets Halley (McDonnell *et al.*, 1991) and Gicobinni-Zinner (McDonnell *et al.*, 1993). Other evidence has been provided by radar echoes from near-Earth comets (Goldstein *et al.*, 1984; Harmon *et al.*, 1989, 1997).

4.2. INTERPLANETARY DUST PARTICLES

Interplanetary dust particles (IDPs) collected in the earth's atmosphere are presumed to be debris from comets and asteroids. Since they were first discovered by Brownlee (1978, and references therein) it was hoped that they would provide the closest available link to the material of the protosolar nebula. The most important point about these particles is that they can be studied in the laboratory (for a recent review see Rietmeijer, 1998). Since some of the IDPs are likely to be of comet origin it would be handy to be able to use them as representative of comet dust. The fact that this is often done leaves open a number of questions. If comets are aggregated interstellar dust, why do we not see the tenth micron core mantle structure? If comet dust is extremely porous (P = 0.95) how have the particles been compacted to, say 0.7–0.8, as in one of the groupings of densities by Rietmeijer (1998)? The mean density of IDP's in the 10 μm to 50 μm size range is about $\rho_{IDP} \approx 0.5$ g cm^{-3} according to Rietmeijer (private communication) although densities on average much higher have been obtained by Love *et al.* (1994). Even the low density implies a porosity of P_{IDP} less than P = 0.8, if the material density of the solid components is = 2.5 g cm^{-3} (a mixture of silicate with a small fraction of organics). The dust of Comet Borrelly comes close to this value. One thing to be considered is that the IDPs have probably been around in the solar system for 100,000 years or more while comet dust, in the form of periodic meteor showers, is only hundreds of years old. Perhaps more fully evolved cometary particles such as meteors resemble the IDPs although the latter correspond to the smaller end of the pre-meteor size spectra. Chemically, it has been shown that H and N isotopic anomalies in the more fragile (porous) cluster IDPs which may be attributed to surviving (but likely altered) organic molecules are closer to those for interstellar molecules than in other IDPs or meteorites (Messenger, 2000). Furthermore cluster IDPs have fine grained structure comparable to the tenth micron characteristic of interstellar dust and are rich in volatile elements and carbon although the core mantle structure is not seen.

5. Concluding remarks

It appears that meteors may be thought of as intermediate between comet dust and IDPs with the further proviso that the comet dust we are thinking of is in the millimeter to meter size range rather than the 10 –100 micron size range of IDPs. What is needed to simulate expected properties of the Leonid meteors is a calculation (or simulation) of the evolution of mg to kg-size cometary dust "grains". These "grains" *initially* consist of aggregates of protosolar dust with mean comet porosity which, including the ices as well as the organics would be $0.5 < P < 0.8$. The evolution of mg to kg mass pieces of such mini-comet nucleus material should be further studied particularly with regard to losses in organics and to possibility of compaction. As of now it appears that a working model approximation to meteor properties is to assume something *between* aggregates of silicate core-organic refractory tenth micron particles ($m_{sil}/m_{OR} \geq 2$, mean aggregate density of < 0.5 g cm^{-3}, porosity of at least $P = 0.7$) and large cluster IDPs with $P = 0.7$.

Acknowledgments

I like to thank Peter Jenniskens and Noah Brosch for inviting me to present my ideas on comets as related to meteors. I would also like to thank the editor Frans Rietmeijer for his very helpful suggestions and ideas and Don Brownlee for his useful criticisms related to IDPs. An anonymous reviewer probably led to my clarifying some obscure points. *Editorial handling:* Frans Rietmeijer.

References

A'Hearn, M.F., Millis, R.L. Schleicher, D.G., Osip, D.J., and Birch, P.V.: 1995, *Icarus* **118**, 223–270.

Bockelée-Morvan, D., Lis, D.C., Wink, J.E, Despois, D., Crovisier, J., *et al.*: 2000, *Astron. Astrophys*. **353**, 1101–1114.

Brownlee, D.E.: 1978, in J.A.M. McDonnell (ed.) *Cosmic Dust*, J. Wiley, N.Y., pp.295–336.

Crifo, J. F.: 1987, in Z. Ceplecha and P. Pecina (eds.), *Interplanetary Matter*, *Publ. Astron. Inst. Czech. Acad. Sci*. **67**, 59–66.

Dello Russo, N., DiSanti, M. A., and Mumma, M.J.: 1997, *IAU Circ*. **6604**.

Fulle, M. 1999, Adv. Sp. Res. **24**, 1087–1093.

Goldstein, R., Jurgens, R., and Sekanina, Z.: 1984, Astron. J. **89,** 1745–1754.

Greenberg, J.M.: 1982, in L.L. Wilkening (ed.), *Comets*, Univ. of Arizona Press, pp. 131–163.

Greenberg, J.M.: 1986a, in C.-I. Lagerkvist and B.A. Lindblad, et al (eds), *Asteroids, comets, meteors II*, Reprocentrum HSC, Uppsala, 1986, pp. 221–223.

Greenberg, J.M.: 1986b, *Nature* **321**, 385.

Greenberg, J.M.: 1998, *Astron. Astrophys*. **330**, 375–380.

Greenberg, J.M. and Hage, J.I.: 1990, *Astrophys. J*. **361,** 260–274.

Greenberg, J.M. and Li, A.: 1997, *Adv. Space Res.* **19,** 981–990.

Greenberg, J.M. and Li, A.: 1998, *Astron. Astrophys*. **332,** 374–384.

Greenberg, J.M. and Li, A.: 1999, *Planet. Space. Sci*. **47**, 787–795.

Greenberg, J.M., Gillette, J.S., Munoz-Caro, G.M., Mahajan,T.B., and Zare, R.N, *et al.*.: 2000, *Ap.J. Lett*. **531,** L71–L73.

Hanner, M.S., Lynch, D.K., Russell, R.W., Hackwell, J.A., and Kellogg, R.: 1996, *Icarus* **124**, 344–351.

Harmon, J.K., Campbell, D.B., Hine, A.A., Shapiro, I.I., and Marsden, B.G.: 1989, *Ap.J.* **338**, 1071-1093.

Harmon, J. K. Ostro, S.J., Benner, L.A.M., Rosima, K.D., and Jurgens, R.F.: 1997, *Science* **278**, 1921-1924.

Jenniskens, P., Baratta, G.A., Kouchi, A., de Groot, M.S., Greenberg, J.M., and Strazzulla, G: 1993, *Astron. Astrophys*. **273**, 583-600.

Jessberger, E.K., and Kissel, J.: 1991, in R. Newburn, M. Neugebauer, and J. Rahe (eds.), *Comets in the Post-Halley Era*, Kluwer, Dordrecht, pp. 1075-1092.

Jewitt, D., and Matthews, H.: 1999, *Astron. J.* **117**, 1056-1062.

Kissel, J., and Krueger, F.R.: 1987, *Nature* **326**, 755-760.

Krueger, F.R. and Kissel, J.: 1987, *Naturwissenschaften* **44**, 312-316.

Lawler, M.E., and Brownlee, D.E.: 1992, *Nature* **359**, 810-812.

Li, A., and Greenberg, J.M.: 1997, *Astron. Astrophys*. **323**, 566-584.

Li, A., and Greenberg, J.M.: 1998a, *Astron. Astrophys*. **338**, 364-370.

Li, A., and Greenberg, J.M.: 1998b, *Astrophys. J*. **498,** L83-L87.

Love, S.G., Joswiak, D.J., and Brownlee, D.E.: 1994, *Icarus* **111**, 227-236.

Lynch, D.K., Russell, R.W., and Sitko, M.L.: 2000, *Icarus* **144**, 187-190.

Mcdonnell, J.A.M., Lamy, P., and Pankiewicz, G.: 1991, in R. Newburn, M. Neugebauer and J. Rahe (eds.), *Comets in the Post- Halley Era*, Kluwer, Dordrecht, pp. 1043-1073.

McDonnell, J.A.M., *et al.*: 1993, *Nature* **362**, 732-734.

Messenger, S.: 2000, *Nature* **404**, 968-971.

Mukai, T. and Fechtig, H.: 1983, *Planet Space Sci.* **31**, 655-658.

Rickman, H.: 1986, in O. Melitta (ed.), *Comet Nucleus Sample Return Mission*, **ESA SP-249**, pp. 195-205.

Rietmeijer, F. J. M.: 1998, in J.J. Papike (ed.) *Planetary Materials*, *Reviews in Mineralogy* **36**, 2-1 – 2-95, The Mineralogical Society of America, Washington, D.C.

Sagdeev, R.E., Elyasberg, P.E., and Moroz,, V.I.: 1988, *Nature* **331**, 240-242.

Sekanina, Z.: 1996, in K.S. Noll *et al.* (eds.), *The collision of comet Shoemaker-Levy 9 and Jupiter*, Cambridge Univ. Press, pp. 55-80.

Tielens, A.G.G.M., Wooden, D.H., Allamandola, L.J., Bregman, J., and Witteborn, F.C: 1996, *Astrophys. J*. **461**, 210-222.

Utterback, N.G., and Kissel, J.: 1990, *Astron. J*. **100**, 1315-1322.