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THE INTERSTELLAR DUST MODEL OF COMET DUST CONSTRAINED BY 3.4 μm AND 10 μm EMISSION

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ABSTRACT

The bulk and microstructure of comet nuclei are derived from the morphological structure and chemical composition of submicron sized interstellar dust grains which have undergone cold aggregation in the pre-solar nebula. The density, size distribution and chemical composition of comet dust deduced from observations of masses, mass spectra, and infrared emission in the 3.4 μm, 10 μm and the continuum are compared with models of fluffy aggregates of interstellar dust. It is shown that the 10 μm emission of comet Halley is produced by predominantly interstellar amorphous silicates with a small (~ 5% admixture) of crystalline silicates. The organic refractory mantles on interstellar silicates are absolutely required to raise the emitting grain temperature high enough to make the 10 μm peak observable. Pure silicates would be too poor emitters even at submicron sizes without this extra heating. Furthermore it is shown that even silicate particles as small as 0.5 μm radius are still too large even with organic mantles to provide efficient 10 μm emission and that the most probable silicate core size is ~ 0.05 μm with a mantle thickness $\gtrsim$ 0.02 μm . Finally, it is shown that the number of small cometary particles with masses $\lesssim 10^{-9}$ g must be substantially larger than has generally been assumed, and that they must be fluffy.

INTRODUCTION

The question of when and how comets were born in the early or pre-solar system nebula has led to many suggested answers. Although it is generally recognized that comets are the most primitive bodies in the solar system, are they made completely of the protosolar nebula interstellar dust or has this material been completely or partially evaporated before becoming a part of comets? The latter idea has been proposed by quite a few theoretical arguments. However, the interstellar dust model /1,2/ provides a good basis for many of the known properties of comets and, in fact, has made it possible to predict some of the Comet Halley observations. One of the predictions was that comet dust should be fluffy aggregates of submicron core-mantle particles /3/. After evaporation of the predominantly H_2O volatile ices left over from the pre-solar molecular cloud dust, the mantles consist of an organic refractory material which has undergone up to billions of years of ultraviolet photoprocessing in interstellar space /4/.

Figure 1 shows, schematically, both fully accreted interstellar dust and the "diffuse cloud" dust which is what is left after volatile mantle evaporation. It has been proposed /5/ that comets are made up originally of aggregates of the fully accreted particles with a packing factor of ≈ 0.2 (80% vacuum) in a tangled (bird's nest) structure (see Fig. 2a) which provides rigidity /6/. One of the justifications of the pure interstellar dust model was the observation of S_2 as a parent molecule in comet IRAS-Araki-Alcock which was shown not only to be created in interstellar space by ultraviolet processing of icy mantles but was shown to constrain the temperature of comet formation to below that of H_2O evaporation /7/. This would mean that certainly the organic refractory inner mantle and, of course, the silicate cores should be totally unmodified during comet formation. The infrared emission properties of comet dust - in particular the 3.4 and 10 micron emission features then appear naturally i.e. without further ad hoc assumptions. This precludes the heating (and certainly evaporation) of the silicates in the interstellar dust of the protosolar nebula to the extent required to convert the silicates into the crystalline forms seen in other solar system materials such as the low density IDP's which are presumed to be of cometary origin /8/.

The connection between interstellar particles and low density chondritic porous IDP's (Fig. 2b) is, however not totally obscured by whatever processing of the cometary dust has taken place in the solar system. Although the original open fluffy structure of Fig. 2a is lost, the basic 0.1 micron (diameter) silicates in Fig. 1 remain. Furthermore it is known that all the silicates in the IDP's still have some organic mantles. When IDP's are subjected to Raman

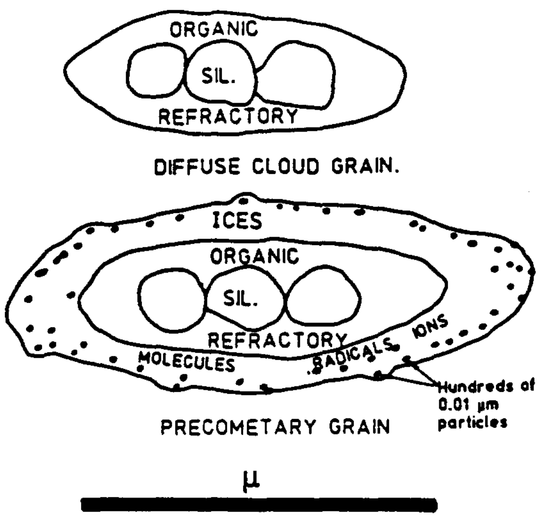

Fig. 1. Interstellar grains as core-mantle structures

Spectroscopy the silicate feature is obscured by the presence of mantles of ~ 0.01 µm thickness /9/. The fraction of organics relative to silicates in IDP's appears to be at least about 5% which is, in fact, about 10 times less than the approximately 50% organic refractories in interstellar dust and in comets. This is to be expected since a fraction of the interstellar organic refractories must be volatile at the temperatures $T \geq 300$ K and even less which are characteristic of cometary and solar system dust. Thus it is not surprising that, during the 10,000 to 100,000 years solar system sojourn of the IDP's after being shed as dust from comets, they have lost a large fraction of their original organics. Substantial evaporation losses of organics in comet dust can already be seen by the reduction in the organic - silicate ratio in comet dust relative to interstellar dust even in freshly produced comet dust at about 1 AU /10/. In this paper we shall show that interstellar dust size sub-units like those within low density IDP's are required to provide the observed 3.4 and 10 µm infrared excess emission by comet dust.

Infrared Emission by Small Particles in the Coma

As the gas carries the dust particles off the surface of the comet, the solid particles are heated to temperatures governed by their respective size and optical properties. Large particles - independent of their composition and structure - approach the black body temperature characteristic of the distance to the sun. The spectral distribution of the radiation which is emitted by the large dust particles is thus close to that of the local black body temperature and hence should contain no information about their material composition. On the other hand, for sufficiently small particles, the emissivity will exhibit peaks at wavelengths corresponding to specific material absorptivities.

Whether a body is considered large or small is defined by the ratio of its size (any characteristic linear dimension, such as the radius of a sphere) to the wavelength of the radiation. In order for a particle to emit (or absorb) most efficiently per unit mass at a wavelength λ_{em} at which there is a specific material absorptivity it must satisfy (conservatively)

$$2\pi a/\lambda_{em} \lesssim 0.5 \quad (1)$$

where a is the particle radius (for a sphere). For example, for $\lambda_{em} = 10$ µm, silicate particles with a $\lesssim$ 1 µm will contribute the most effectively to the 10 µm excess in the comet emission. For the 3.4 µm emission the restriction is to particles with a $\lesssim$ 0.3 µm which, for a density of ~ 2 g cm^{-3} for organic material, gives a limiting mass in the particle of ~ 2×10^{-13} g - a bit larger than the mass of an average individual interstellar grain /11/.

Mass Flux as Deduced from Dust Emission (I)

We assume that, averaged over comet revolutions, the dust emission may be approximated as spherically symmetric with an expansion velocity v.

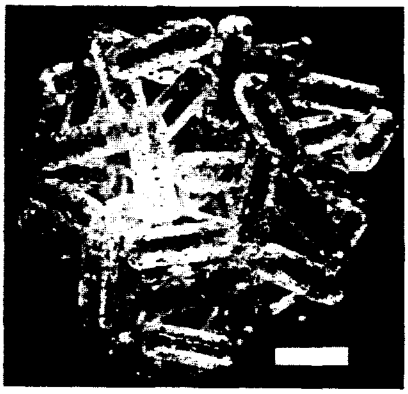

Fig. 2a: A piece of a fluffy comet: Model of an aggregate of 100 average interstellar dust particles each of which consists of a silicate core, an organic refractory inner mantle and an outer mantle of predominantly water ice in which are embedded the numerous very small (< 0.01 μm) particles responsible for the interstellar 216 nm absorption and the far ultraviolet extinction (See Fig. 1). Each particle as represented corresponds to an interstellar grain ½ μm thick and about 1½ μm long. The mean mantle thickness corresponds in reality to a size distribution of thicknesses starting from zero. The packing factor of the particles is about 0.2 (80% empty space) and leads to a mean mass density of 0.28 gm cm^{-3} and an aggregate diameter of 5 μm.

Fig. 2b: A highly porous chondritic IDP /35/. Note that the bird's nest particle (Fig. 2a), the IDP (Fig. 2b) and the average interstellar core-mantle particle (Fig. 2b insert) are equally scaled to 1 μm.

The energy arriving at the earth contained within the aperture defined by the radius s, at the comet, is

$$\int_{\delta\lambda_{em}} F_\lambda d\lambda \qquad (2)$$

Where $\delta\lambda_{em}$ is the emission band width. We shall use for F_λ only that observed part in excess of the continuum emission (and/or scattering) background so that the black body contributions by the larger particles are automatically subtracted from the total. This concept of excess emission relative to the continuum is basic to our discussion and unless otherwise stated the 3.4 μm and 10 μm emissions are only the excess amount observed and due to the small particles.

The mass production rate for the small particles is then /12/

$$Q'_{em} = \frac{2v\Delta^2}{\pi s} \frac{\int_{\delta\lambda_{em}} F_\lambda d\lambda}{\int_{\delta\lambda_{em}} \kappa(\lambda) B_\lambda(T_{em}) d\lambda} \qquad (3)$$

Where Δ = geocentric distance, $B_\lambda(T_{em})$ is the Planck function at the dust temperature T_{em}, κ is the mass absorption coefficient in the absorption band. Equation (3) may be replaced by using the peak emissions under the integrals

$$Q'_{em} = \frac{2v\Delta^2}{\pi s} \frac{F_{\lambda_{em}}}{\kappa_{\lambda_{em}} B_\lambda (T_{em})} \qquad (4)$$

We shall conservatively use v = 0.5 km s^{-1} as representative of small and fluffy particles which are carried out with the gas /13,14/. The remaining parameters $k_{\lambda_{em}}$, T_{em} are strongly dependent on the dust material and size as well as its morphological structure so that we treat them separately.

Mass Absorption Coefficients

For the 3.4 μm absorption of the organic refractory material the direct measurement of $\kappa_{3.4}$ for first generation laboratory organic residues is about 800 cm^2 g^{-1} /15/. These residues result from ultraviolet irradiation and warmup of simple ices and represent only the first stage in the photochemical evolution of true interstellar organic refractories. Subjecting this kind of material to substantial further ultraviolet photoprocessing leads to "carbonization" of the molecules and relatively less oxygen, and hydrogen /1,15/. As the H:C ratio is decreased there is a reduction in the number of CH_2 and CH_3 groups and thus a reduction in the 3.4 μm absorption per unit mass. A value of κ = 600 cm^2 gm^{-1} appears to be consistent with grain modelling towards the galactic center and is also implied by laboratory results on the photochemistry of complex organic molecules which clearly demonstrate a substantial reduction in the H:C ratio as a function of photolysis time /15/.

For the silicate 10 μm absorption, we adopt $\kappa_{9.7}$ = 3000 cm^2 g^{-1} as a reasonable value for interstellar silicates. This value is consistent with arguments based on the cosmic abundance of silicates assumed to have a mean molecular weight (~ 150) and an interstellar silicate absorption to visual extinction ratio of $(\tau_{9.7}/A_V)^{-1}$ = 18.5 /16/. The value of 3000 cm^2 gm^{-1} is also supported by other observational criteria /17,18/ The value of κ = 2,000 $cm^2 gm^{-1}$ for amorphous laboratory silicates measured by Day /19/, appears to be somewhat low but is perhaps not out of the question. The 10 μm absorption strength is constrained at the upper end by the non existence of a polarization reversal /20/ and at the lower end by cosmic abundance. The peak absorption strength of crystalline silicates is almost an order of magnitude higher: ~ 7 to 10 times /21/.

The mass absorption coefficients quoted above are for bulk material and for small particles ($2\pi a/\lambda \lesssim 0.5$). For larger particles the mass absorption coefficient is substantially reduced. Table 1 gives a clear demonstration of how the mass absorption coefficient decreases with size so that the emission per unit mass (κ^{eff}) for a 10 μm particle is not only ten times smaller than that for a 1 μm (and smaller) particle but its 10 μm peak-emission relative to that at the 7 μm continuum is down by a factor of $\frac{8.3}{.1}$ = 80!

TABLE 1 Mie theory calculations of the effective mass absorption coefficient and selective 9.7 μm emission cross section contrast of small silicate particles. Optical constants from Draine and Lee /17/ with $\kappa^0_{9.7}$ = 3000 cm^2 g^{-1}.

Size (μm)	$\left(\frac{\kappa^{eff}_{9.7}}{\kappa^0_{9.7}}\right)$	$\left(\frac{C_{9.7}}{C_7}\right)$	Contrast $\left(\frac{C_{9.7} - C_7}{C_7}\right)$
0.01	1	13	12
0.1	1	13	12
0.5	1	12	11
1	1	9.3	8.3
2	0.62	4.3	3.3
3	0.41	2.9	1.9
4	0.29	2.1	1.1
5	0.22	1.7	0.7
10	0.09	1.1	0.1

Dust temperatures

We shall first consider the temperature of individual small compact particles of either silicates or organic refractory material or compound particles with silicate cores and organic refractory mantles. For simplicity all particles are taken as spherical in shape. The optical constants assumed for the silicate are taken from ref. 17; the optical constants for the organic refractory are from Chlewicki and Greenberg /22/ but with an added imaginary part in the ranges $0.4 \leq \lambda \leq 0.75$ μm and $1.0 \leq \lambda \leq 5$ μm.

In Table 2 the temperatures for the silicate particles are much lower than those of organic refractory particles and, as expected, with increasing thickness the organic mantles raise the temperature.

TABLE 2 Silicate core-organic refractory mantle small particle temperatures in the solar radiation field. Total dust radius $a_{c-m} = a_c + \Delta a_m$. Underlined values are those "acceptable" (T > 430 K) at 1.11 A.U. (See Table 3).

a_c	Δa_m	Solar distance (AU) 0.8	1.0	1.11	1.5	2.0
0.0	0.05	689	628	602	531	472
0.0	0.1	742	676	650	569	511
0.0	0.5	651	604	575	515	459
0.0	1.0	551	498	484	437	392
0.05	0.0	336	298	285	250	221
0.05	0.01	438	388	367	312	273
0.05	0.02	517	459	434	369	317
0.05	0.05	662	595	565	488	424
0.1	0.0	379	333	315	278	242
0.1	0.01	441	391	369	314	274
0.1	0.02	492	437	413	350	300
0.1	0.05	604	536	507	432	372
0.1	0.1	680	612	582	505	439
0.5	0.0	400	353	328	284	254
0.5	0.01	406	360	340	292	258
0.5	0.05	427	379	358	305	268
0.5	0.5	496	448	427	372	326
1.0	0.0	351	311	295	258	229
1.0	0.01	353	314	298	261	231
1.0	0.5	395	354	336	291	258
1.0	1.0	401	361	344	299	266
Blackbody		311	278	264	227	197

Mass flux from dust emission (II)

Using the highest emissivities in Table 1 (a < 1 µm) we may show the influence of particle temperature on the dust mass production required to produce the silicate and organic refractory excess emissions on March 28 1986 when both were observed.

For the silicate 9.7 µm flux we take the excess value $F_\lambda = 1.2 \times 10^{-16}$ w cm^{-2} µm^{-1} as deduced by subtracting the continuum on March 28.6 obtained by Gehrz and Ney /23/ in the 10 µm region. This is almost the same as the value 1×10^{16} w w cm^{-2} µm^{-1} observed by Hanner et al. /24/ on March 24.8. For the 3.4 µm flux we average the two excess values of $F_\lambda = 1 \times 10^{-17}$ and 3.5×10^{-17} w cm^{-2} µm^{-1} which is about 20% less than the value deduced from Danks et al. /25/ on March 28. These values and the value of r = 1.11 AU, Δ = 0.62 AU and v = 0.5 km s^{-1} are used in Equation 4 to find the dust production rate.

In Table 3 we show how strong the mass flux depends on the dust temperature. Since the dust temperature depends critically on particle size and composition we can already begin to discriminate among the types of possible comet dust particles. It is immediately apparent that no pure silicate particle no matter how small will get hot enough to provide enough excess 10 µm emission. Even if all the dust in the comet were in the form of 0.1 µm radius silicate particles there would not be enough. Going to core-mantle particles relieves the situation considerably. But, even here, the silicates have to be significantly less than 0.5 µm in radius and even 0.1 µm radius silicates require at least 0.02 µm thick organic mantles to be acceptable.

If the excess emission were restricted to compact particles in the above size range the particle fluences would have more than saturated all VEGA and GIOTTO particle detectors. In fact, one would have required 10^4 times (yes 10^4!) the fluence given in McDonnell et al. /26/ for particles less than 0.5 µm in radius (mass limit $\lesssim 10^{-12}$ g).

We may substantially relax this upper limit on the mass by extending the emissivity to that by fluffy particles.

Because of the evidence that comet dust is fluffy we should consider how aggregates of small particle may effect their temperatures as well as their specific emissivities. We shall consider here the 10 µm emission but note that much of what we say applies essentially also to the 3.4 µm emission. Let us first consider the requirements that the particles are fluffy aggregates more carefully.

TABLE 3 Dust production rates

Mass production rates	T 320	420	460	480
$Q'_{3.4}$ (g s^{-1})	9.46 (6)	4.11 (5)	1.70 (5)	1.15 (5)
$Q'_{9.7}$ (g s^{-1})	6.94 (5)	2.26 (5)	1.64 (5)	1.43 (5)
Q'_d (g s^{-1})	1.01 (7)	6.37 (5)	3.34 (5)	2.58 (5)
Q'_d/Q'_g	1	0.06	0.032	0.024

If the optical depth of an aggregate is small compared with unity it may still act like a sum of its individual components. Thus, in order for an aggregate of submicron size particles to emit effectively at 10 μm (and not, by self absorption, act like a black body), the maximum allowable size is limited to $\tau_{10\ \mu m} \ll 1$. For the purpose of discussion we shall assume a volume packing factor of the basic units of 0.1 where we take for a mean individual particle size that of an average interstellar dust grain without volatiles. This is derived from an original comet packing factor of 0.2 for the icy coated interstellar grains, and implied comet mass density 0.28 g cm^{-3}. Using $\kappa_{9.4\ \mu m} = 3000$ cm^2 g^{-1} and $\rho_d = 0.1$ g cm^{-3} gives a maximum particle radius of R < 16 micron for $\tau_{9.7} < 0.5$. The mass of such a "large" fluffy particle is 2 x 10^{-9} g and this then is preliminarily taken as the maximum which may effectively emit the 10 μm spectral feature. This is significantly larger than the upper limit of 10^{-12} g for an individual compact particle and represents an aggregate of about 300 particles like those pictured in Fig. 2a (but without ices); i.e. about 30,000 interstellar grains!

We are now in a position to make more realistic estimates of the total mass requirements for the emitting particles. We consider the March 28 date for which both silicate and organic refractory emissions were observed.

The theoretical calculation of particle temperatures for the 0.05 + 0.02 μm silicate core-organic refractory particles in Table 2 is about T = 430 K at r = 1.11 AU. These dimensions are chosen for two main reasons: (1) it gives about the right m_{OR}/m_{sil} ratio; (2) the mean silicate radius in Brownlee particles and in core-mantle interstellar dust models /22/ is about 0.05 μm. The value T = 320 in Table 3 is considered as typical of the continuum temperature (somewhat > black body) for the bulk of the coma dust exclusive of the spectral emitting particles. Using the particle mass limit of 2 x 10^{-9} g and a size distribution (in this size range) given by $dn/dm = 249\ m^{-1.85}$ (approximating that of reference /26/) we get a total Halley dust production rate (in the units of Table 6 in ref. /26/) of ~ 50 kg s^{-1}. On this basis McDonnell et al. would derive a dust to gas ratio of $(Q'_d/Q'_g) = 0.0024$ where the gas production rate is taken as of March 13 (2.1 x 10^7 g s^{-1}). However, even at a high temperature like T = 430 K we derive a value of about $(Q'_d/Q'_g) = 0.06$ for the emitting particles. i.e. we require at least 25 times the integrated mass in the particles with mass < 2 x 10^{-9} g. Note that, within the fluffy aggregates, the mean individual particle temperature is generally lower than if treated as purely isolated components so that, if anything, we are still on the conservative side of required mass fluxes by using T = 430 K. Probably the acceptable individual (as isolated) particle temperature should be closer to 500 K.

Discussion

Since it appears that we have extended the mass limit as far as possible by considering very fluffy grains and since compact grains - or even insufficiently fluffy grains - exacerbate the problem, perhaps we should look more deeply not only into the assumptions which have gone into the currently accepted mass size spectrum but also into our assumptions. Let us first look at how other observations relate to the latter.

The discovery of particles appearing as clusters encompassing a wide range of masses with small velocity and spatial dispersion, led Simpson et al. /27/ to suggest that large conglomerates of small particles (~ 10^{-13}g) gently disintegrate as they travel outwards from the nucleus. Again the typical interstellar dust size shows up as the basic unit of the aggregates which continues to be observed at great distances from the nucleus because of fragmentation.

The need for consideration of low density (~ 0.3 g cm^{-3}) irregular particles has also been demonstrated by Krasnopolsky et al. /13/ in the interpretation of the Vega-2 three-channel spectrometer data. Clearly such low densities are not compatible with compact particles as is additionally confirmed by the evidence for fragmentation and the suggestion that the very small particles detected by the plasma impact detectors on Vega-1 and Vega-2 are secondary ones which continue to be created as the dust moves outwards in the coma /14/. It is further stated in /14/ that the mass spectrum in the range 10^{-14} - 3 x 10^{-17}g shows a continued rise, the larger masses (10^{-14}g) being the basic dust units (≲ 0.1 µm) which we have required for the high temperature high emissivity in the 10 µm and 3.4 µm regions.

In attempting to evaluate the structure of cometary dust particles, Smirnov et al. /28/ conclude that particles in the mass range ≳ 10^{-12} g are predominantly particles of very low density or of complicated structure. The smaller ones (10^{-17} g) in the interstellar dust size spectrum /29,30/ could also play a role in providing additional high temperature emission as their volume is a significant although not major fraction of the total of the dust in the interstellar medium.

Gehrz and Ney /23/ observations of the 10 µm silicate signature showed a wide variety of strengths but it was always present except at distances substantially greater than 1 AU. They noted that the dust albedo appeared to decrease where the silicate feature was weak. This may not be such a remarkable coincidence when interpreted in terms of the aggregated interstellar dust morphology. At large heliocentric distances the aggregates would tend to remain larger because the volatile grain components remain to bond the aggregate more strongly. At smaller heliocentric distances the fluffy particles lose their volatiles by sublimation thus leading to a greater degree of fragmentation. As already noted, the larger aggregates can not emit spectrally because their optical depths at 10 µm are too high and, furthermore, with the implied large optical depths in the visual their albedos are very low. The large fluffy dust emits as black bodies or, as Gehrz and Ney say about comet Kohoutek, "... the 'black' thermal infrared energy distribution characteristic of the 'gravel' [our large fluffies] in the anti-tail, and the 10 µm and 20 µm emission features produced by the small silicate grains [our fluffy fragments] which dominate the coma and dust tail". Certainly by the time the tail region is reached a high degree of fragmentation must have taken palce.

Although Crifo /31/ has carried out an impressive set of calculations on his "radiative hydrodynamic" model of the comet Halley coma he encountered some stumbling blocks in achieving a fully acceptable representation of the silicate signature excess. He considered a wide range of grain masses from 10^{-17} g, to 100 g using the "observed" size spectrum /26/ and with grain densities either constant but varying from .3 to 3 gm cm^{-3} or the "ESA Working Group Formula". In all the models the silicate signature is weak at best and in many cases non-existent when using the higher densities whereas his best results were obtained using his minimum value of 0.3 g cm^{-3}. This begins to approach our assumed value of 0.1 g cm^{-3} and may already be taken as an indication of the need for particle fluffiness. It would be interesting if the Crifo type calculation could be carried out using densities as low as 0.1 gm^{-3} however the appropriate scattering and absorption data on such fluffy structures remain to be studied.

Although one source of the discrepancy between our prediction of the number of small particles in the Halley dust size spectrum and that of McDonnell et al. may have been the variablity of the overall dust production rate we must also consider the questions of the basic calibration procedures and theoretical methods used in analyzing the raw data. In general these were restricted to calibrations based on compact, relatively high density particles which we know now are clearly inconsistent with the observed properties of comet dust. We would, in fact, suggest that only the smallest particles in the size distribution - those with masses ≲ 10^{-13} g - should be characterized by densities as high as 1-3 g cm^{-3} and that for all particles with masses > 10^{-12} g one should use densities ≈ 0.1 g cm^{-3} and accordingly very open structures. Both the impact properties as well as the hydrodynamics and optical properties of such particles require considerable study. Problems associated with the former have, in fact, been noted by Smirnov et al. /28/ who say that in the counting rates of the Sp-1 plasma impact detector on Vega 1 "It is possible that these [fluffy] particles will be destroyed by the foil and will give very low recorded charge amplitudes."

A few remarks on where one may or may not expect to observe the 3.4 µm and 10 µm emissions in view of the fluffy dust model. First of all it is clear that a substantial amount of fragmentation is required. It is therefore unlikely that the very large particles which dominate in the antitail direction will show emission features. Similarly at large solar distances, where the evaporation rate of volatiles is low, the particles will be inhibited from fragmenting and showing emission features. Too close to the sun, the 3.4 µm emission from solid organics will probably disappear because the organic refractory mantles will evaporate along with the volatiles, leaving only the silicate signature and gaseous molecular emissions, as detected by Vega 1, to be observable. It is interesting to note that the relative amount of organics and silicates observed on March 28 is within the range of both the predicted ratio in the interstellar dust model /5/ and that detected by the PUMA mass

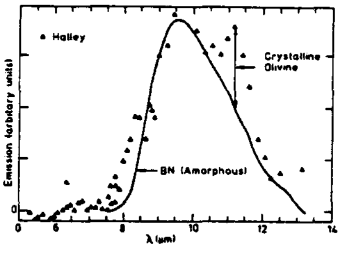

Fig. 3a: Comparison of Comet Halley 10 μm emission with interstellar 10 μm absorption

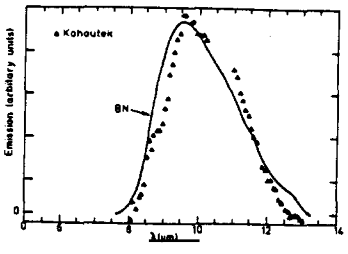

Fig. 3b: Comparison of Kohoutek 10 μm emission with interstellar 10 μm absorption.

spectrometer on board Vega 1 /10/. In fact, for T = 500 K we get a silicate to organic mass ratio in the dust of ~ 2 which compares well with 1.8 as given by Kissel and Krueger /10/, while for T = 420 K we get an organic to silicate mass ratio of 1.8 which is like that of the original interstellar dust. There are sufficient remaining uncertainties both in the fluffy dust temperature and in the relative peak mass absorptivities of the silicates and organics to make it difficult to be more precise at this time.

We have chosen to use the amorphous (interstellar) silicate value of the absorptivity to derive the mass of silicates. What if we had used a value of κ more appropriate to crystalline silicates as suggested for comet Halley dust by Sandford and Walker /32/. In that case an appropriate value of κ would have been about 20,000 $cm^2\ g^{-1}$ /21/ instead of the 3000 $cm^2\ g^{-1}$ we used so that then the implied mass ratio of silicate to organic refractory would have been reduced from 1.8 to 0.27. In view of the Kissel and Krueger value and the interstellar dust value of > 0.75 (0.75 is a real lower limit because it applies only if there is no evaporation of the organics at 500 K which is highly unlikely), we believe that the Comet Halley silicates are predominantly amorphous. This is borne out by subtracting the amorphous silicate interstellar absorption (BN) from comet Halley emission (See Fig. 3a) to derive an excess emission at 11.2 (crystalline silicate) relative to the 9.7 peak of 0.4 which when multiplied by $\frac{3000}{20000}$ gives $m_{cryst}/m_{amorph} = 0.06$. For Kohoutek, similar spectral comparison (See Fig. 3b) leads to a value < 0.01. It is not unreasonable therefore to assume that the difference in silicates between comets Halley and Kohoutek are due to the fact that Kohoutek is a new comet and Halley has been heated many times so that some (but only a small amount) of its orginally amorphous silicates may have been converted to crystalline forms. Thus, the interstellar silicates are preserved in the Oort cloud in their original amorphous form.

Any modification by heating in the Oort cloud by passing stars or supernova is much smaller than estimated by Stern and Shull /33/ who used a mean thermal comet conductivity of about 100 to 1000 higher than that estimated in ref. /34/ by overestimating the thermal conductivity of low temperature amorphous ice by 10 to 100 and underestimating the effect of fluffiness also by a factor between 10 and 100. Cosmic ray effects are also limited to the outer 1-5 meters /5,34/.

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