INTERSTELLAR DUST, COMETS, COMET DUST AND CARBONACEOUS METEORITES

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ABSTRACT

Evidence is adduced to show that comets, and carbonaceous meteorites have a common origin via aggregation of interstellar dust. The dust to gas ratio for comets and the trend in its variation with solar distance is derived from the sequential evaporation of the various comet dust constituents. The "missing carbon" in comets is explained as residing predominantly in the ~ 20% fraction of the comets consisting of the complex organic component of interstellar dust. The $^{12}C/^{13}C$ isotopic ratios in interstellar dust, comets and carbonaceous meteorites are linked by dividing the carbon into its "pure" and molecular parts. The silicate signature in circumstellar, interstellar, comet and interplanetary dust is compared.

INTRODUCTION

It is an interesting historical fact that the dirty ice model of interstellar dust (van de Hulst, 1949) and the icy conglomerate model of the comet nucleus (Whipple, 1950, 1951) were conceived, apparently independently, within just a few years of each other. However, the concept that comets could have aggregated directly out of the interstellar dust has had a "roller coaster" history depending on whether or not it was believed that where they formed had become hot enough to have evaporated the pristine dust and erased its original form before recondensation of the material could take place. According to the Oort theory (1950) the comets were formed within the orbit of Jupiter and were later thrust outward by gravitational perturbations to form a cloud of comets. Since it was then generally accepted that the presolar nebula at this distance had achieved temperatures > 1000 K (Cameron and Pine, 1973) most of the interstellar dust would have first evaporated before leading to the condensation sequence in which the first things to condense would have been the refractory (silicates etc.) and the last thing to condense would have been the ices like H_2O. This led to the rocky core-icy mantle comet nucleus. Perhaps such bodies did indeed form but there have been recently developed some convincing theoretical arguments in favor of the idea that cometesimals formed either very far out (~ 10^4 AU) in the presolar nebula (Biermann and Michel 1978) or even in a fragment of the molecular cloud which is separated from, but gravitationally a part of, the presolar nebula (Cameron, 1973; Biermann, 1981). In either of these cases the temperature is unlikely to have been higher than ~ 20 K so that the aggregating dust would be unmodified from its interstellar (or rather prestellar) form (Greenberg, 1983).

Although the dust constitutes by mass only about 1% of the total interstellar medium which is dominated by hydrogen and helium, it contains a substantial fraction of the bulk of the condensable constituents. In molecular clouds a good deal may be observed in the gas phase but the dust grains in all cases contain no less than 20-25% of the cosmically abundant O+C+N atomic species and ~ 100% of the Si, Mg and Fe species (Greenberg, 1978). With increasing cloud density the condensed O+C+N fraction is observedly inferred to

increase to at least ~ 35-40%. A laboratory and theoretical study of the evolution processes of grains has been made from which the observed properties of dust may be shown to provide a plausible composition for precometary dust as it appears when it coagulates.

In the following sections I shall take up in turn the precometary dust, and some of its consequences on ideas and observations of comets, comet dust and carbonaceous chondrites.

PRECOMETARY DUST

Generally there are three components of interstellar dust (Greenberg and Chlewicki 1983): 1) core-mantle particles of thickness $\geq$ 0.1 μm consisting of ~ 0.05 μm radii silicate cores with accreted and photo-processed mantles of molecules containing mostly O+C+N; 2) small carbon particles of size $\leq$ 0.01 μm; 3) small refractory particles - perhaps iron oxides (e.g. magnetite) or silicates - of size $\leq$ 0.01 μm. The core-mantle particles produce almost all the visual extinction whereas the small carbon particles produce the well known 2200 Å absorption bump in interstellar extinction, and the small silicates or oxides are required to produce the far ultraviolet extinction. The core-mantle particles are generally at temperatures $\simeq$ 10 K and, by consequence, most gases freeze onto their surfaces. The carbon and metal oxide particles are inhibited from accreting mantles by any of several physical mechanisms attributable to their smallness (Greenberg and Hong, 1974; Greenberg, 1979).

The birth, growth and death of interstellar grains is a continuing process so that what we see in various regions of the Milky Way is always a passing phase. Whether in the vast, almost empty regions between the stars or in the dense active regions of new star formation, the grains are always undergoing change.

We start with the birth of a grain, assumed here to be in the form of an elongated silicate particle of mean radius ~ 0.05 μm. Such small particles are formed in the atmospheres of cool evolved stars and are blown out by radiation pressure into the surrounding space. Ultimately they are swept up into the general gaseous matter and, being coupled to the gas atoms and ions, begin to partake in the evolution of the clouds. From the fact that the clouds can not be static - either because they are observed to be in motion, or because we infer or see such dramatic energetic events as star formation occurring within them - it is obvious that the physical conditions of density and temperature represent different stages in their evolution. The densest parts of clouds seem to correspond to times just before, during, or just after star formation.

A combination of observations and laboratory and theoretical investigations has led to the description of core-mantle grains in various regions of space as illustrated in Figure 1. The grains in low density ($\leq$ 10 hydrogen atoms cm^{-3}) diffuse clouds have mantles which consist of a complex organic material which has evolved from the simpler accreted O+C+N containing molecules. An important physical property of this organic residue is that it is relatively refractory (compared with its volatile antecedents) having an evaporation temperature of 400-500 K. Laboratory evidence shows that the organic refractory (for lack of a better name referred to as yellow-stuff) contains about twice as many carbon as oxygen atoms. As a result of this, only a small fraction of the cosmically abundant

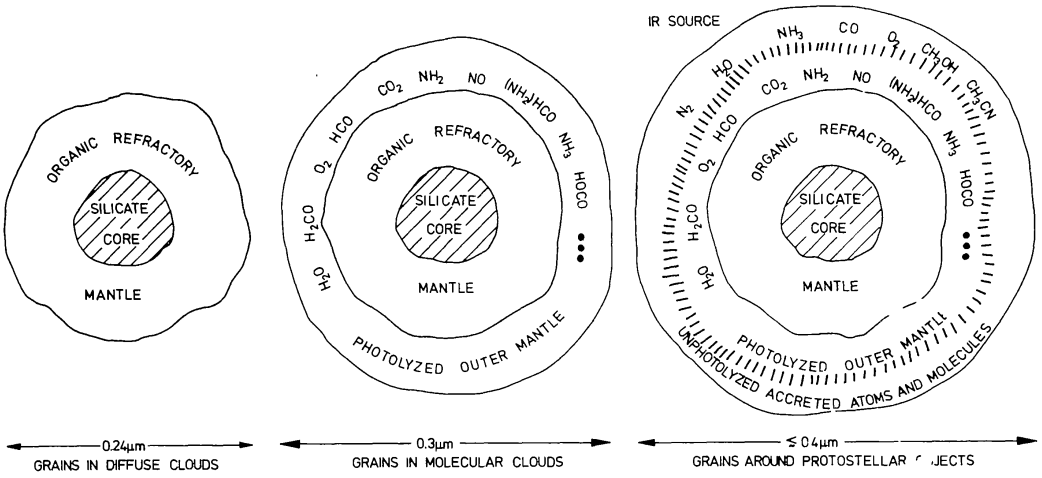


Fig. 1.Schematic cross-section structures of grains in various regions of space. Individual grains are substantially elongated as implied by interstellar polarization. The mean silicate core radius is taken as 0.05 μm. Left: grains in diffuse clouds have only the nonvolatile organic refractory mantle; middle: grains in molecular clouds have an additional mantle of accreted and photoprocessed molecules and radicals; right: grains in prestellar conditions are presumed to have accreted all the remaining molecules of the gas with little or no photolysis, the outer layers remaining for a finite time after the protostar turns on.

oxygen is tied up in the diffuse cloud grains so that the gas which is in the state of contracting towards the molecular cloud phase contains an oxygen to carbon ratio $[O:C]_{diff-cloud} \simeq 5:1$ as compared with the cosmic ratio $[O:C]_{C.A.} \simeq 2:1$. This superabundance of oxygen shows up subsequently in the formation of grain mantles with a high fraction of H_2O. Both theoretical arguments (d'Hendecourt, 1983) and observational evidence (Willner et al. 1982) using laboratory data (Hagen, Tielens and Greenberg 1983) show that H_2O is much more abundant in the solid grains than in the gas (Greenberg 1982). We thus picture the grains in molecular clouds to have accreted an outer mantle on the organic refractory mantle as shown in the middle of Figure 1. Ultimately as the cloud becomes very dense in the approach to final collapse leading to star (and planet) formation the grains may accrete all the remaining condensable constituents from the gas. In the ensuing stage of star formation those grains which are very close to the star will have their volatile mantle constituents evaporated or otherwise destroyed, while those grains which are farther away from the young star will be shielded from the stellar radiation and can be cool enough to maintain the H_2O in their outer mantle and, for some time perhaps, even more volatile species. This leads to the grain model pictured on the right in Figure 1.

COMETS AND COMET DUST

We use the basic interstellar dust model to derive a chemical and morphological picture of the comet nucleus material. The chemical composition is shown in Table 1. The amounts of silicate, carbon, organic refractory and H_2O components are fairly directly derived from observations and are probably good quantitative estimates. The

Table 1. Suggested mass and volume distribution of the principal chemical constituents of a cometesimal.

Component	Mass Fraction	Volume Fraction
Silicates + Metal oxides	0.20	0.08
Carbon (Graphite ?)	0.06	0.03
Nonvolatile Complex Organic Refractory	0.19	0.21
H_2O	0.20	0.28
CO	0.03	0.04
CO_2	0.04	0.05
Other Molecules + Radicals (H_2CO, NH_3, HCN, CN, N_2, HCO, $HCONH_2$,....)	0.23	0.31

existence of other components, such as CO, CO_2, NH_3, H_2CO, $HCONH_2$, cyanogen containing molecules, etc. are indicated from laboratory and astronomical data but the quantities suggested must be considered tentative.

The relative atomic composition of the comet nucleus in the various components (note particularly volatile versus nonvolatile) is shown in Tables 2 and 3. An immediate consequence of the interstellar dust model is that it naturally accounts for the "missing" carbon in the comet because only a fraction of the carbon is available in the volatiles while the remainder is bound up in the photochemically evolved organic refractory "yellow stuff" plus the more or less pure carbon required to account for the observed 2200 Å absorption in the interstellar extinction curve. I shall return to other consequences of this "hidden carbon" later when considering isotopic abundances.

Table 2. Atomic constituents of various comet components as fractions of cosmic abundance

	Silicates Metal Oxides	O.R.	Carbon	H_2O	CO	CO_2	Other
H*		1.7 (-4)		4.7(-4)			4.4 (-4)
C		0.45	0.27		0.06	0.05	0.17
N		0.25					0.75
O	0.09	0.13		0.35	0.03	0.05	0.34
Mg	1.00						
Si	1.00						
Fe	1.00						

* The hydrogens are estimated as follows: 1 for each C in the O.R., 2 for each O in H_2O, 1 for each C in "other", 1 for each N in "other", 1 for each O in "other".

Table 3. Mean abundances of the light elements in the cometary constituents

	Volatiles Relative to O		Relative to cosmic abundance		
Element	"CI chondritic" Delsemme, 1982	Int. dust model Greenberg, 1983	Volatiles	O.R.	Silicates Metal Oxide Carbon
H	1.5	1.75	9.1 (-4)	1.7(-4)	
C	0.2	0.20	0.28	0.45	0.27
N	0.1	0.17	0.75	0.25	
O	1	1	0.77	0.13	0.09

The suggested morphological structure of a sample piece of a comet is shown in Figure 2. The individual core-mantle particles are assumed to be elongated as required by the birefringence of the interstellar medium. Scattered throughout the sample (but not shown) are the hundreds or thousands of small carbon and metal oxide particles. This leads to a birds nest type structure which has been used to predict the scattering properties of comet dust (Greenberg and Gustafson 1981; Greenberg 1982).

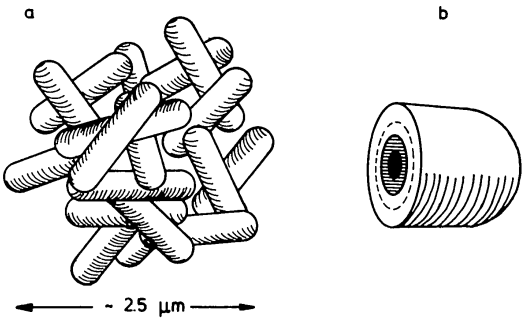


Fig. 2. Aggregation of typical prestellar core-mantle interstellar grains leads to a morphological structure of tangled submicron sized particles each of which has the cross section shown at the right. Not included in the drawing of the birdsnest structure are the thousands of $\lesssim 0.01$ μm sized carbon, silicate and metal oxide particles.

Except where the comet approaches very close to the sun, its dust consists minimally of the organic refractory yellow stuff along with the silicates, metal oxide and carbon. This material constitutes about 32% of the comet volume which is remarkably close to the value 31% derived for the comet dust in the friable sponge model (see Horányi and Kecskeméty, this volume). At sufficiently large solar distances volatile components like H_2O may survive within the dust. For decreasing solar distances, first the volatiles, then the organic refractories, then the silicates and finally the metal oxides and carbon will evaporate, with the sequence depending to some extent on the sizes and morphology (crystalline, amorphous) of the various constituents. There is some indication of this effect in the decrease of the dust to gas ratio depending on the comet approach distance to the sun. Including the organic refractory component in the dust leads to a dust-to-gas volume ratio of $(D/G)_{vol} = 0.32/0.68 \simeq 0.5$. Averaging the density of the dust over its components leads to a mean density ≈ 2 which with a (solid) volatile density of ≈ 1 leads to

a dust-to-gas mass ratio of $(D/G)_{mass} \simeq 1.0$. This is to be compared with the observed $(D/G)^{obs.}_{mass} = 0.8 \pm 0.2$ (Delsemme, 1982). If we assume that the O.R. has been totally evaporated, we get $(D/G)_{vol} \simeq 0.11/0.88 = 0.13$ where most of the dust is the form of silicates and metal oxides so that the mean density is > 3 and we get $(D/G)_{mass} \simeq 0.4$ which is to be compared with $(D/G)^{obs.}_{mass} = 0.6 \pm 0.2$ as given by Delsemme. The trend of the theoretical dust to gas ratio is rather similar to that observed. What is clearly needed is continuous data on individual star grazing comets as a function of solar distance.

Essentially all the iron is bound up in the oxides so that atomic iron is never observed except where the solar approach is close enough (Whipple, 1978) for evaporation of the oxides and subsequent photodissociation of the individual molecules to occur. On the other hand it has often been postulated that solid H_2O may survive if the dust is far enough out. Evidence for solid H_2O has recently been suggested from observations by Campins et al. (1983). In the following I show a comparison between the wavelength dependence of their measured dust albedo with that which one may expect from a comet dust particle of either pure H_2O or one whose H_2O fraction is like that in protostellar dust (Greenberg and van de Bult, 1983). The results given in Figure 3 are for spherical particles of radii 1,2,5 and 10 μm. The latter size should be fairly representative, in its albedo properties, of the rather larger particles ~ 0.02 cm assumed by Campins et al. It appears that the single observed point is insufficient to discriminate between particles either of different size or of different H_2O composition. If one takes the unpublished data of A'Hearn, Tokunaga and Dwek quoted in Campins et al. as correct it would appear that we can definitely exclude the pure H_2O ice dust of any size. On this basis, the 1 μm ice mixture particles provides a reasonable approximation however. A far more discriminating measurement must be made in the 2.8-3.2 μm region in combination with better measures in the 3.5-4.0 μm region. It is to be noted that the albedo of ice mixture particles of large size is very similar to that of Callisto which may indicate that its surface is a rough dirty ice agglomerate. It is planned to simulate in our laboratory the chemical and morphological structure shown in Figure 2. We should then be able directly to measure the infrared reflectivity of such model cometary dust.

CARBON

We see that the carbon component of the comet is divided approximately 1/4:1/2:1/4 between volatile, organic refractory, and "pure" carbon. As already pointed out, since only 1/4 of the cosmically abundant carbon is in the volatiles whereas about 80% of the oxygen is in volatile form, the relative proportion of carbon to oxygen to be expected in the comet coma is only 1:5 which seems to provide a natural explanation of the "missing" carbon problem since the normally observed carbon must originate in the volatile component. When the total atomic composition of the dust is observed by space vehicles which can provide a mass spectrum of the dust one should retrieve the remaining "missing" carbon.

By dividing the carbon into its volatile and nonvolatile components we may be able to reveal an explanation for the anomalously high (relative to solar) average observed (Vanýsek and Rahe, 1978) carbon isotope ratio $^{12}C/^{13}C = 100\text{-}135$ where the value of 135 has by far the widest error bars. If the comets and solar system originated about the same time the value of the ratio $^{12}C/^{13}C$ averaged over all

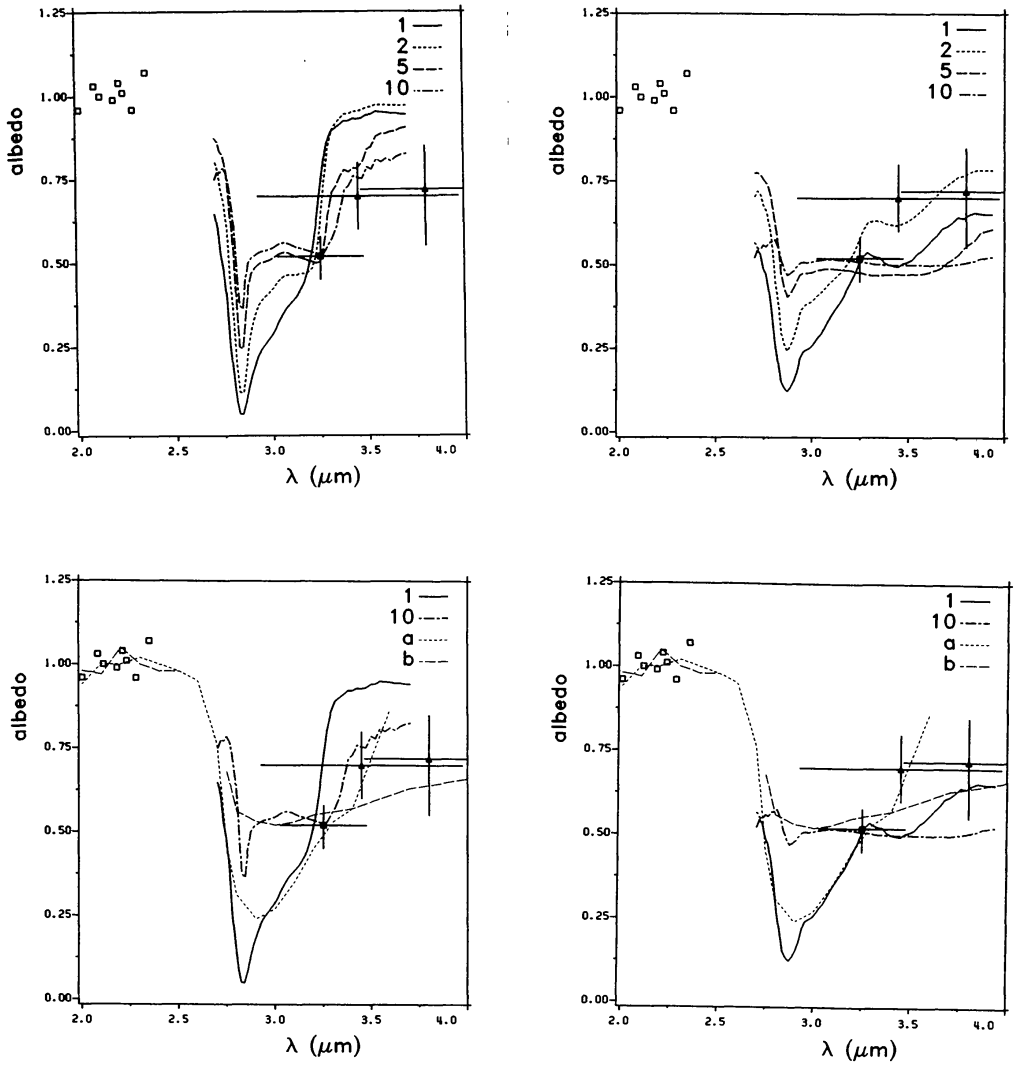


Fig.3. Calculated albedos of spherical particles containing either pure annealed amorphous H_2O ice or an annealed H_2O mixture which resembles that observed in such objects as the Becklin-Neugebauer protostar (see Greenberg et al. 1983). Particle sizes are 1,2,5, and 10 μm: a) Comparison of 1,2,5,10 μm pure H_2O particle albedos with observations of Comet Bowell: square points from Campins et al., triangular points by A'Hearn et al. as quoted in Campins et al.; b) Same as a) for 1,2,5,10 μm particles with annealed H_2O: NH_3 = 3:1 as representative of dirty or complex ice band.; c) Comparison of 1 and 10 μm pure annealed H_2O particle albedos with reflectivities of Orgueil meteorite; a) and Callisto b) d) Same as c) for annealed H_2O ice mixtures.

constituents should be the same as that which prevailed 4.5×10^9 years ago in the interstellar medium. The source of carbon is nucleogenesis in stellar sources and the average is that which is produced by all stars whose $^{12}C/^{13}C$ ratio varies from 4 to > 100 (Wallerstein, 1973). However the solid carbon component (the 2200 Å bump component) is presumed to have as its source only cool carbon rich stars, which tend to be rich in ^{13}C. We write the current

solar system (S.S.) average in terms of the dust as it aggregated in the comet 4.5×10^9 years ago as (See Table 2)

$$[^{12}C/^{13}C]^{SS} = 0.28\,[^{12}C/^{13}C]^{comet}_{vol.} + 0.45\,[^{12}C/^{13}C]^{comet}_{O.R.} + 0.27\,[^{12}C/^{13}C]_{solid\ C} \quad (1)$$

Let us assume that there are only minor isotopic differences between the O.R. and volatile fractions and let $[^{12}C/^{13}C]_{O.R.} = [^{12}C/^{13}C]_{vol.} = 100\text{-}115$, $[^{12}C/^{13}C]^{SS} = 89$. Solving Equation (1) we find

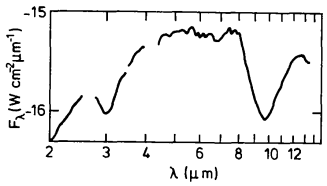
$$[^{12}C/^{13}C]_{solid\ C} = 60\text{-}19$$

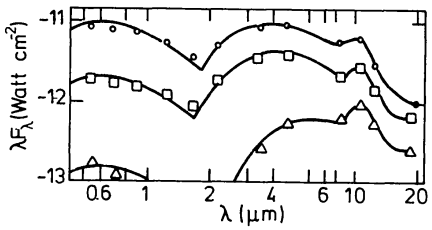
whose mean value is 40.

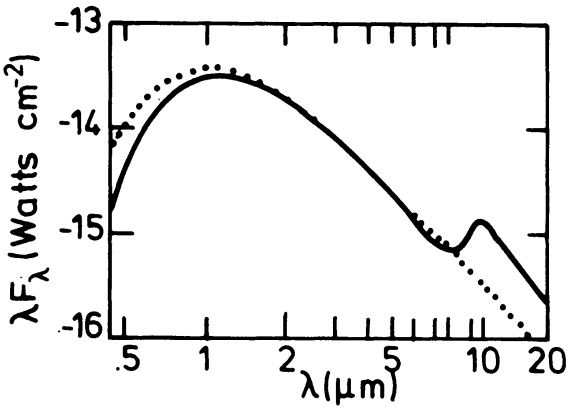
It is interesting that a refractory carbon component in primitive carbonaceous meteorites has been found coincidentally to have an anomalously low $^{12}C/^{13}C$ ratio of ~ 42 (Swart et al., 1983) and it is very tempting to associate this with the solid carbon in the comet as inferred from the interstellar dust. Thus, there is some evidence that comets and carbonaceous meteorites may both have aggregated out of interstellar dust as traced via one of its refractory components. However before this can be taken to imply a physically reliable connection one would have to explain the fact that the relative amount of this carbon in the meteorite is much smaller than that in the interstellar medium. Another question which remains to be studied is whether and to what extent isotopic fractionation has occurred in the yellow stuff.

SILICATES

It has been recognized for some time from the excess 10 μm emission from comet dust that there is a silicate component which resembles that seen in evolved stars and in interstellar space. In Figure 4 some examples are given of the stellar emission spectra (Humphreys et al., 1972) interstellar dust absorption (Willner et al., 1982) and comet dust emission (Ney and Merrill, 1976). We can not, from these observations, automatically conclude that all these silicates are the same. However the interstellar dust evolution scenario gives a physically reasonable series of steps to take the silicates ejected from M supergiants through the interstellar medium and ultimately into the cometesimal aggregate from interstellar dust. We do not have a direct measure of the silicate properties in these three phases, but the spectroscopic evidence suggests that they are all some amorphous and not strictly classifiable material, although a range of sizes and shapes of varying composition of microcrystalline material might appear amorphous. The silicates which we can directly observe spectroscopically (see Figure 4c) or by other means in meteorites and in interplanetary dust particles (IDP's) collected in the earth's atmosphere are generally crystalline rather than amorphous (Fraundorf et al., 1981). Since there are many morphological changes taking silicates from amorphous to crystalline forms which can have occurred both in meteorites - since they were formed 4.5×10^9 years ago - and in IDP's - since their presumed origin from cometary dust occurred as long ago as 10^6 years - the interstellar silicate connection may be taken as a serious possibility. The details of this specific metamorphosis remains to be studied in detail.







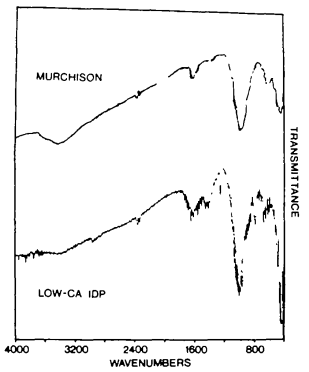


Fig. 4. Evidence for silicates in space: (a) Infrared absorption by dust in front of NGC 2170:IRS 3, a protostellar source (Willner et al. 1982); (b) Emission spectrum normalized at 3.4 μm of α Ori, an M supergiant (Humphreys et al., 1972); (c) Emission spectra of comet West (Ney & Merrill, 1976); (d) Infrared absorption spectra of the Murchison meteorite and an interplanetary dust particle (Fraundorf et al.,1981).

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