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PROPERTIES OF DUST IN DIFFUSE CLOUDS

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Abstract. Our knowledge of the dust in diffuse interstellar clouds is reviewed, and a number of salient problems are identified.

1. INTRODUCTION

Using observational data extending from far-infrared emission to ultraviolet extinction, we are increasingly able to place constraints on the properties of interstellar dust. Nevertheless, the nature of the interstellar grains remains unclear in many respects.

The aims of this review are: to summarize the observational data; to make clear which inferences from the data are robust, and which observational clues remain cryptic; and to highlight problems which demand further attention.

The reader is referred to Mathis (1990) for a more detailed review of extinction studies, to Mathis (1990) and Draine (1994) for summaries of some current grain models, and to the monograph by Whittet (1992) for a general discussion of interstellar dust.

2. WHAT DO WE REALLY KNOW?

Our thinking about interstellar dust is often strongly model-dependent, since we like to have something specific in mind for purposes of discussion. It is therefore useful to begin by reviewing what we *really* know about interstellar dust based on robust, model-independent inferences from observations. Most of our knowledge of interstellar dust pertains to interaction of this dust with electromagnetic radiation: attenuation of light reaching us from stars (interstellar extinction, reddening, and polarization of starlight), scattering of starlight (reflection nebulae), and emission of infrared and far-infrared photons from dust grains. In addition, we have indirect evidence based on interstellar depletions. Interstellar grains found in meteorites offer tantalizing glimpses.

2.1. Interstellar Extinction and the Grain Size Distribution

Interstellar dust was first detected via extinction and reddening, and studies of the wavelength-dependent extinction still provide the most important information constraining the nature of interstellar dust. Figure 1 shows the typical extinction curve for dust in diffuse interstellar clouds, along with examples of unusually steep ($R_V = 2.75$) and flat ($R_V = 4,5$) curves. The curves are based on the parameterization by Cardelli, Clayton & Mathis (1989); we

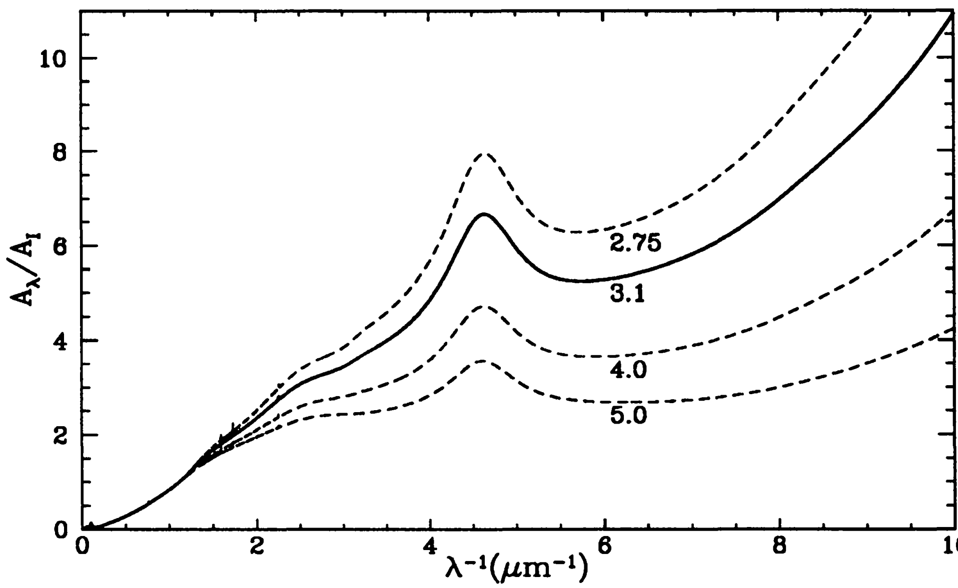

Figure 1. Wavelength-dependent extinction for diffuse interstellar gas, normalized relative to the I band ($0.9\,\mu$m) extinction. Curves are labelled by $R_V \equiv A_V/E(B-V)$; the solid curve ($R_V = 3.1$) is the mean extinction.

have added diffuse interstellar band features and extended the extinction below $\lambda^{-1} < 0.3\,\mu\text{m}^{-1}$. Overall the extinction tends to increase with decreasing wavelength λ down to the shortest wavelengths ($0.1\,\mu$m) for which we have information.

Before proceeding, recall some general results concerning scattering by small homogeneous spheres. Let C_{sca} and C_{abs} be the scattering and absorption cross sections for a grain of radius a. The scattering and absorption "efficiency factors" $Q_{sca} \equiv C_{sca}/\pi a^2$ and $Q_{abs} \equiv C_{abs}/\pi a^2$ depend on the complex refractive index $m(\lambda)$ and on the dimensionless "scattering parameter" $x \equiv 2\pi a/\lambda$. We have the following general results:

- For $x \to 0$, $Q_{abs} \propto x$ and $Q_{sca} \propto x^4$. Thus, if $\mathrm{Im}(m) \neq 0$, $Q_{sca}/Q_{abs} \propto x^3 \to 0$: *very small particles are predominantly absorptive.*
- For $|m-1|x \gg 1$, $Q_{ext} \equiv Q_{abs} + Q_{sca} \approx 2$: thus extinction cross sections tend to be wavelength-independent for $a \gg \lambda/2\pi$.

From the strong wavelength-dependence of the extinction down to $\lambda = 0.1\,\mu$m, we can therefore conclude that:

- The extinction at $\lambda = 0.1\,\mu$m must be dominated by particles with $a \lesssim \lambda/2\pi \approx .02\,\mu$m.

2.2. Scattering

Reflection nebulae clearly demonstrate that interstellar grains are reasonably efficient at scattering light, at least at visible wavelengths. This implies that an appreciable fraction of the extinction at visible wavelengths must be due to scattering. This tells us that:

- The extinction at visible wavelengths ($\lambda \approx 0.6\,\mu$m) must in large part be due to grains with $a \gtrsim \lambda/2\pi \approx 0.1\,\mu$m.

Thus, direct observations plus quite general arguments allow us to conclude that there must be appreciable numbers of interstellar grains with $a \gtrsim 0.1\,\mu$m and with $a \lesssim 0.02\,\mu$m. These conclusions are essentially model-independent.

Quantitative estimates of the grain size distribution are possible once specific assumptions are made concerning the grain composition. Mathis, Rumpl, & Nordsieck (1977) and Kim, Martin & Hendry (1994) derived the grain size distribution assuming the grains to be composed of graphite and silicate. These studies found that for both graphite and silicates:

1. $dn/da \sim a^{-3.5}$ for $0.005 \lesssim a \lesssim 0.2\,\mu$m;
2. $a^4 dn/da$ declines very rapidly for $a \gtrsim 0.3\,\mu$m.

This size distribution, with $\sim 50\%$ of the grain mass in grains with $0.08 \lesssim a \lesssim 0.3\,\mu$m, is fully consistent with the model-independent conclusions described above: the $a \lesssim 0.02\,\mu$m grains are sufficiently numerous to dominate the surface area and far-uv extinction, while the extinction near $\sim 0.6\,\mu$m is primarily due to grains with $a \gtrsim 0.1\,\mu$m.

2.3. Polarization

A remarkable feature of the interstellar extinction in the visible is that it is significantly polarization-dependent: unpolarized light emitted by distant stars arrives at the Earth with a significant polarization due to polarization-dependent attenuation by the intervening interstellar dust. Obviously, this requires that some fraction of the interstellar dust be both nonspherical *and* significantly aligned by some process, presumably involving the interstellar magnetic field. The wavelength dependence of the polarization is very pronounced, peaking near $\lambda \approx 0.55\,\mu$m. The observed wavelength dependence can be understood only if:

- The particles responsible for the polarization near $\lambda = 0.55\,\mu$m have characteristic dimensions $a \approx \lambda/2\pi \approx 0.1\,\mu$m.

Recent work on inferring the degree of grain alignment from observed polarizations (Kim & Martin 1994) confirms that only the grains with $a \gtrsim 0.1\,\mu$m are appreciably aligned.

2.4. Small-Angle Scattering of X-Rays

Interstellar grains can produce significant small-angle scattering of X-rays, resulting in "X-ray halos" in images of X-ray point sources. The observed X-ray halos appear to be approximately consistent with the grain size distribution obtained by fitting the optical-ultraviolet extinction (Predehl et al. 1991).

3. SPECTROSCOPIC EVIDENCE AND GRAIN COMPOSITION

The interstellar extinction law contains several spectral features. Figure 2 shows the mean extinction curve, with the strongest spectral features labelled.

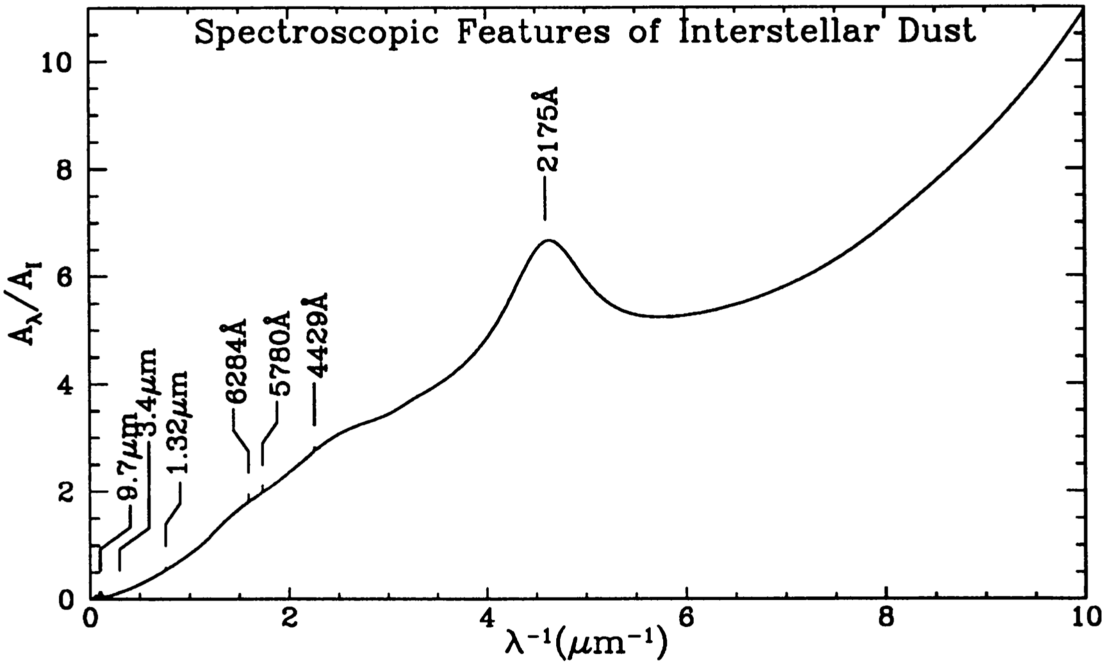

Figure 2. Same as Figure 1, but with the most prominent spectroscopic features labelled.

The spectral features in principle have much to tell as concerning the grain composition; unfortunately, the identification of most of the features remains uncertain.

3.1. The 2175Å Feature

By far the strongest feature is the extinction feature at 2175Å [see the review by Draine (1989)]. It is frustrating that almost 3 decades after its discovery by Stecher (1965), the identity of this feature remains uncertain! The feature is *very* strong – it corresponds to an oscillator strength per H nucleus $\Delta f \approx 9.3 \times 10^{-6}$ – so it must be due to a relatively abundant grain constituent. We can, for example, rule out the possibility that it is due to a simple compound containing Al – the abundance of Al ($\sim 3.6 \times 10^{-6}$ per H) is too small. The carrier of this feature *must* contain one or more elements from {C, Mg, Si, Fe}.

Unfortunately, there is little if any polarization associated with the 2175Å feature (Somerville et al. 1994), so this potential diagnostic (Draine 1988) is unavailable.

A number of identifications for the 2175Å feature have been proposed. Stecher & Donn (1965) pointed out that small particles of graphite [originally suggested as a grain constituent by Cayrel & Schatzman (1954)], would be expected to produce a 2200Å feature. The observed feature would require $\sim$ 15% of the solar carbon abundance (C/H=4.0×10^{-4}).

Identifications other than graphite have been proposed, including:

- ultrasmall particles of amorphous C (Bussoletti et al. 1987);
- "Quenched Carbonaceous Composite"(Sakata et al. 1994);

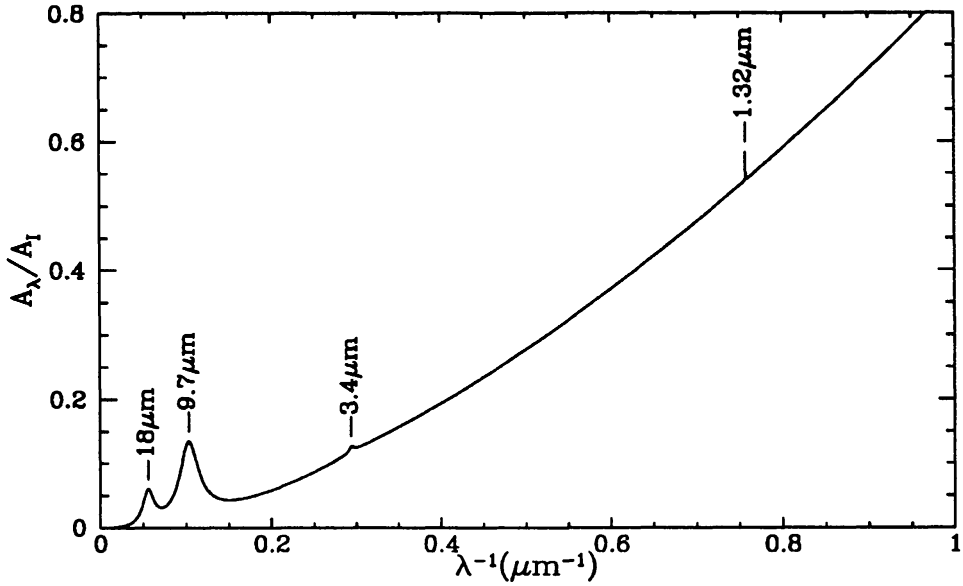

Figure 3. An expanded view of the $\lambda > 1\,\mu$m region. The strong bands at 9.7 μm and 18 μm are almost certainly due to some form of silicate material.

- mixtures of polycyclic aromatic hydrocarbons (Léger et al. 1989).
- OH^- in low-coordination sites on small silicate grains (Steel & Duley 1987).

All of the proposed identifications for the 2175Å feature must contend with the fact that it exhibits considerable *variation in width*, while remaining remarkably *constant in central wavelength* (Fitzpatrick & Massa 1986). This raises difficult problems (see §7.5).

3.2. The Silicate Feature

In my opinion, the only secure identification is that of the 9.7 μm and 18 μm infrared features (see Fig. 3): these are almost surely due to some form of silicate material. The features are observed both in extinction (Roche & Aitken 1985) and in emission from HII regions (Gillett, Forrest et al. 1975), dust shells around newly-formed stars (Gillett, Jones et al. 1975), and stellar winds from oxygen-rich red giants and supergiants (Pégourié & Papoular 1985). Silicates have Si–O stretching and O–Si–O bending modes near 10 and 20 μm respectively; silicates are refractory and are expected to form in near-LTE cooling of gas with cosmic abundances. The observed strength of the silicate feature appears to require that nearly all of the interstellar Si be in silicates (Draine & Lee 1984), together with $\sim$ 16% of the oxygen (assuming 4 O per Si).

3.3. The 3.4 μm Feature

An extinction feature at 3.4 μm (cf. McFadzean et al. 1989) coincides with the wavelength expected for C–H stretching modes in aliphatic hydrocarbons. Unfortunately, it is not possible to identify which hydrocarbon(s) are responsible.

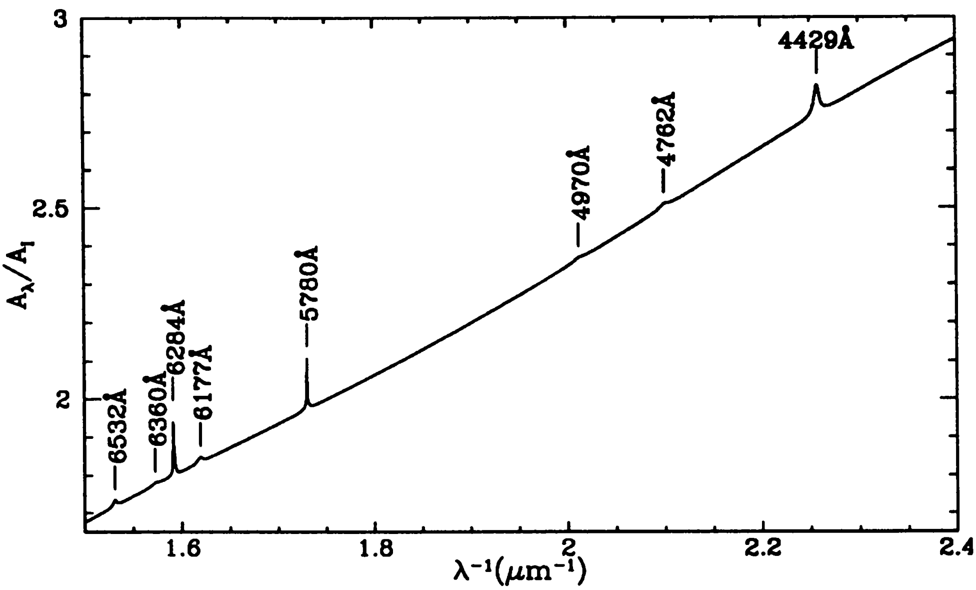

Figure 4. An expanded view of the 1.5 – 2.4 μm^{-1} region, which includes the most prominent DIBs; the strongest DIB is at 4429 Å.

Given the variations in band strength among hydrocarbons, we can only conclude that the carrier incorporates from 2–50% of the cosmic carbon abundance.

3.4. The Diffuse Interstellar Bands

Historically, the first "dust features" observed were the "diffuse interstellar bands", or "DIBs". Traditionally, the 2175Å feature and the silicate features are not termed DIBs. In terms of oscillator strength per H nucleus, the strongest DIB is at 4429Å , but there are many weaker features: Herbig & Leka (1991) analyzed a catalogue of 105 DIBs, while Jenniskens & Désert (1994) catalog ~ 200 DIBs between 3800 and 8680Å. The strongest DIBs are shown in Fig. 4.

In principle, DIBs could be produced by impurities in or on grains, or by large molecules in the gas phase. Many DIB identifications have been proposed. Recent suggestions include: $C_{16}H_{10}^+$ to explain the strong 4429Å band (Salama & Allamandola 1992); C_6H and C_8H for a number of intermediate strength bands (Fulara et al. 1993); and C_{60}^+ to explain two new bands at 9557 and 9632Å (Foing & Ehrenfreund 1994). None of these proposed identifications is, as yet, definitive.

3.5. Important Upper Limits

Dense clouds often show a strong feature at 3.1 μm due to the O–H stretching mode in H_2O ice, but this feature is never seen on paths that pass only through diffuse clouds. The sightline toward VI Cyg No. 12 has $\Delta\tau_{3.1\mu m}/A_V < 0.002$ (Gillett, Jones, et al. 1975); this implies that $\lesssim 0.02\%$ of the solar abundance of oxygen can be in the form of H_2O ice on this path. Ice is *not* a significant constituent of grains in diffuse clouds. [In dark clouds, by contrast, up to ~ 4% of the O may be in H_2O ice (van Dishoeck et al. 1993)].

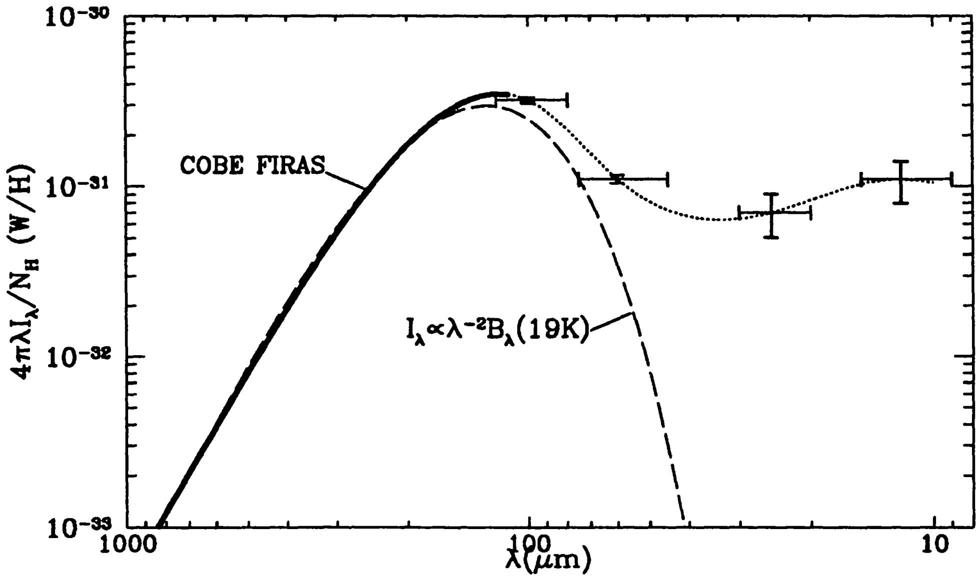

Figure 5. Emission from interstellar grains in diffuse clouds – the so-called "infrared cirrus". The heavy curve is a representation of the *COBE FIRAS* results (Wright et al. 1991); the crosses at 100, 60, 25, and 12 μm are *IRAS* results (Boulanger & Perrault 1988). The broken curve shows the spectrum expected from grains at $T = 19$K with a λ^{-2} emissivity.

An important constraint on interstellar grain composition is provided by nondetection of 11.2 μm absorption by solid SiC; the upper limits on this feature implies that $\lesssim 5\%$ of interstellar Si can be in the form of solid SiC (Whittet, Duley, & Martin 1990).

4. EMISSION FROM DUST GRAINS

4.1. $\lambda > 100\,\mu$m: Grain Temperatures and FIR Emissivities

The bulk of the power radiated by grains in diffuse clouds emerges at $\lambda \gtrsim 100\,\mu$m, and the spectrum of this radiation is indicative of the temperatures of the grains which account for the bulk of the absorption of starlight.

We see that the $\lambda \gtrsim 150\,\mu$m power in Fig. 5 can be reproduced by grains with $Q_{abs} \propto \lambda^{-2}$ in the FIR and temperatures $T \approx 19$K. Thus the grains which absorb the bulk of the starlight must have emissivities which vary approximately as λ^{-2}, and must have emissivities such that starlight can maintain them at temperatures $T \approx 19$K. This is very close to the temperatures expected for conventional graphite and silicate grains suitable for explaining the extinction curve (Draine & Lee 1984). In particular, exotic "fractal" grains with large far-infrared emissivities (Wright 1987) or Fe whiskers (Wickramasinghe & Hoyle 1994) cannot account for more than a small fraction of the total absorption of starlight.

4.2. 10–100 μm Spectrum: Very Small Grains

While "conventional" grains at $T \approx 19$K are able to account for the $\lambda \gtrsim 150\,\mu$m emission, the *IRAS* measurements at 100, 60, 25, and 12 μm (Fig. 5) show that an additional source of emission must be present: grains at temperatures $50 \lesssim T_d \lesssim 250$K. Grains with $a \gtrsim 0.02\,\mu$m attain temperatures $T \approx 19$K where the radiated power balances the starlight heating. However, the heat content of an $a = 0.01\,\mu$m graphite grain at $T = 19$K is only 1.6 eV, so that absorption of a single starlight photon leads to a temperature "spike", followed by gradual cooling: the grain temperature will be a fluctuating function of time. If absorption of a single photon raises the grain temperature substantially above ~ 25K, then the resulting emission at wavelengths $\lambda \lesssim 100\,\mu$m will be enhanced; this appears to be the explanation for the "excess" emission observed in the the *IRAS* 60, 25, and 12 μm bands (Draine & Anderson 1985; Puget, Léger, & Boulanger 1985; Désert, Boulanger, & Puget 1990).

The very small grains radiate most of their energy at $\lambda \approx hc/5kT_{max}$. Thus the excess emission in the 60 μm band should be largely due to grains with $T_{max} = 50$K, and that in the 12 μm band to grains with $T_{max} \approx 250$K. How small must the grains be? Absorption of one 10eV photon can heat an $a = 67$Å graphite grain to $T_{max} = 50$K, or an $a = 15$Å grain (containing ~ 1400 C atoms) to $T_{max} = 250$K.

4.3. 2–12 μm Spectrum: Polycyclic Aromatic Hydrocarbons?

The 2–12 μm emission from diffuse clouds is difficult to measure, but reflection nebulae, planetary nebulae, and HII regions often have broad IR emission features, the strongest appearing at 3.3, 6.2, 7.7, 8.6, and 11.3 μm (Sellgren 1994). Léger & Puget (1984) identified these features as C–H and C–C stretching and bending modes in polycyclic aromatic hydrocarbons (PAHs). Duley & Williams (1988) and Papoular et al. (1989) have argued that these features could be due to luminescence from large grains, but this seems unlikely (Draine 1994).

The 3.3 μm emission feature from the diffuse ISM has been observed by Giard et al. (1994); they find $I(3.3\,\mu\mathrm{m}) \approx 0.0025(\lambda I_\lambda)_{100\,\mu\mathrm{m}}$, or $\sim 0.2\%$ of the total radiated power.

4.4. Red Emission

Spectrophotometry of bright reflection nebulae (e.g., NGC 7023) reveals excess 6000–8000Å light which is attributed to luminescence rather than scattering (Witt & Schild 1988); corresponding emission may be observed in diffuse clouds (Guhathakurta & Cutri 1994). The NGC 7023 emission spectrum resembles the luminescence spectrum of hydrogenated amorphous carbon (HAC) illuminated by ultraviolet light (Furton & Witt 1993), supporting the hypothesis that HAC may be an important constituent of interstellar dust.

5. DIRECT MEASUREMENT

5.1. Interstellar Grains in Meteorites

True interstellar grains have been discovered as inclusions in primitive meteorites; the grains are identified as of interstellar origin by virtue of anomalous isotopic composition. Five distinct types of interstellar grains have been found: see Table 1. Abundances by weight are given for the Orgueil meteorite, a CI carbonaceous chondrite.

Table 1. Interstellar Grains in Meteorites

Composition	diameter (μm)	abundance in Orgueil (ppm)	$^{12}C/^{13}C$ rel. to solar
diamond[a]	~ 0.001	1450	1.04
SiC[b]	$\sim 0.03 - 10$	14	0.02–28
graphite[a]	$0.8 - 7$	6	0.02–80
TiC[b]	$0.007 - 0.021$	$\sim 10^{-5}$	0.7
Al_2O_3[c]	$\gtrsim 1$	0.5	-

[a]Anders & Zinner (1993)
[b]Bernatowicz et al. (1991)
[c]Hutcheon et al (1994)

It must be noted from the outset that the procedures for isolating these grains from the host meteorite are *designed* to destroy the silicate material which constitutes the bulk of the meteorite; it is therefore not surprising that the only interstellar grain material which we are sure is abundant – silicate – does not appear in Table 1.

While the grains in Table 1 were at one time interstellar dust, they were not representative of the interstellar grain population. The very large sizes of the graphite and Al_2O_3 (and many of the SiC) grains makes them atypical, since we know that the interstellar grain population has few grains with diameters $2a \gtrsim 0.6\,\mu$m. The unusual isotopic compositions of the SiC and graphite grains tags them as being formed in outflows from carbon stars; at any instant a small fraction of interstellar grains may share this property, but it seems likely that the bulk of interstellar grains should have isotopic compositions close to the overall composition of the ISM (see §7). The microdiamond grains – most abundant by far of the 5 types in Table 1 – could, perhaps, be a significant grain component (Lewis et al 1989).

5.2. Interplanetary Grains

The local ISM has a density $n_H \approx 0.25$ cm^{-3} and a velocity ~ 20 km s^{-1} relative to the Sun (Lallement et al. 1991). The interstellar ions undergo a collisionless shock at the heliopause, but interstellar grains cross the heliopause and stream through the solar system. The flux of interstellar grains has been measured by the *Ulysses* spacecraft (Grün et al. 1993); the rate of impact of grains with masses $m \gtrsim 4 \times 10^{-15}$g is in good agreement with what is predicted from our estimates (§3) of the interstellar grain size distribution. It would be truly wonderful if an instrument could be devised to collect these grains nondestructively, so that their shapes and compositions could be analyzed!

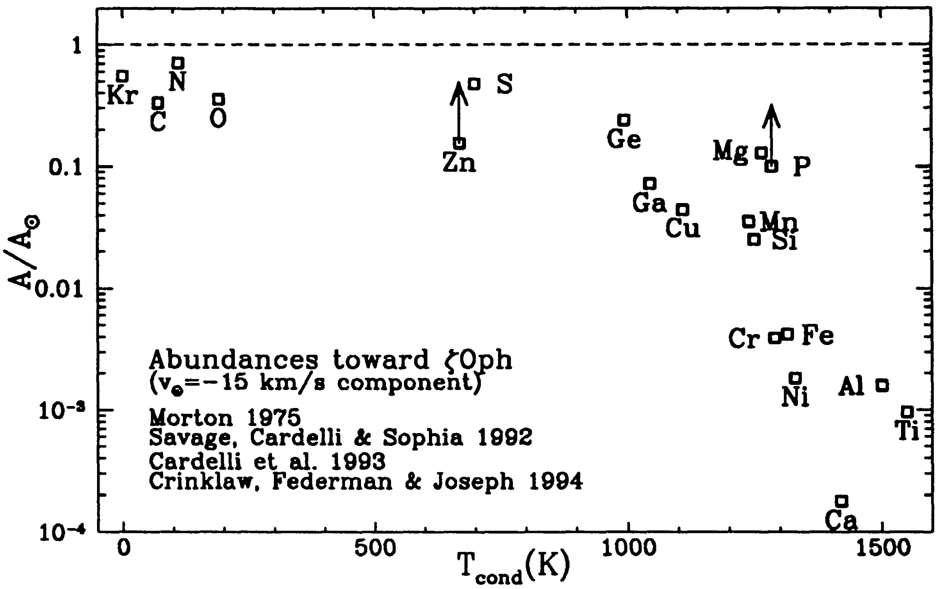

Figure 6. Measured abundances in the $v_\odot = -15\text{km s}^{-1}$ gas toward ζOph, versus "condensation temperature" T_{cond} (see text).

6. INTERSTELLAR DEPLETIONS

Atoms contained in grains are of course absent from the gas phase; therefore measurement of gas-phase abundances using absorption line spectroscopy provides indirect evidence on the composition of interstellar dust.

Field (1974a,b) noted that the observed elemental depletions were strongly correlated with the "condensation temperature" T_{cond}, defined to be the temperature at which, in a cosmic abundance, cooling, near–LTE gas, substantial condensation of that element into some solid form would occur. Figure 6 shows the correlation of depletion with T_{cond}.

Twenty years ago, Field suggested that the observed depletions resulted from two processes: Some condensation "near stars" is responsible for the overall trend of increased depletion with T_{cond}. Additional accretion onto grains in interstellar space produces molecular mantles, which photoprocessing then converts into durable CHON compounds which remain on the grains.

What is the picture 20 years later? It is now clear that condensation of "refractory" elements like Ca, Al, Ti, Fe, and Si does occur in many stellar outflows, including slow winds from cool stars, and the ejecta from SN87a! It is also clear that molecular mantles do form in dense clouds – the 3.1 μm H_2O ice feature makes this clear.

However, we have quantitative difficulties in reconciling theory and observation: the observed large depletions of elements such as Si, Fe, Ti, Al, and Ca appear to require substantial *recondensation of these elements in the ISM!* (see §7.1 below). Such recombination in the ISM occurs far from LTE; the observed correlation of depletion with T_{cond} presumably reflects the correlation of T_{cond} with chemical properties.

The apparent depletion of O in Fig. 6 is difficult to understand, as there seems to be no chemical form in which it could be hidden (see §7.7)!

7. SOME PERPLEXING PROBLEMS...

There are a number of theoretical issues regarding diffuse cloud dust which have proven difficult to understand. Some of these are briefly mentioned below, to remind us that our understanding of interstellar dust is far from complete!

7.1. Observed Depletions: Grain Regrowth in the ISM?

Elements such as Si or Fe are observed to be highly depleted in most diffuse gas. Since grains are destroyed (e.g., by supernova shock waves), and since some stellar outflows (e.g., winds from hot stars) return grain-free material to the ISM, the observed depletions of these elements require that significant condensation onto grains must take place in the interstellar medium. How much depends on estimates of grain destruction rates, but studies of the effects of supernova blastwaves indicate relatively short lifetimes for interstellar grains (see the review by McKee 1989). A number of theoretical studies (see Jones et al. 1994) have independently concluded that sputtering in radiative $v_s \gtrsim 150\,\mathrm{km\,s^{-1}}$ shocks is expected to be effective at eroding grains in the shocked gas, returning much of the grain material to the gas phase. In lower velocity shocks the destruction is less complete, but even in $v_s \approx 20\,\mathrm{km\,s^{-1}}$ shocks we expect a few percent of the grain mass to be vaporized in grain-grain collisions (Jones et al. 1994).

Consideration of rates for grain destruction and gas condensation leads to several conclusions (Draine 1990):

- Most of the grain mass in the interstellar medium was condensed in the interstellar medium, rather than in stellar outflows. Only a small fraction of interstellar dust is really "stardust"!
- Since accretion of metals back onto grains can proceed rapidly only in dense regions, there must be relatively rapid exchange of matter between diffuse gas and dense gas: molecular cloud lifetimes of $\sim 2 \times 10^7\,\mathrm{yr}$ or less are indicated.
- Because ultrasmall grains may be negatively charged even in diffuse clouds, and because they contribute a large amount of surface area, they may potentially play an important role in accretion of metal ions in diffuse clouds.

7.2. Grain "Purity"?

The $10\,\mu$m feature seems to require most of the silicon to be in silicates, and the 2175Å feature may be due to graphite. If most grain mass is actually condensed in the ISM, then it is perhaps surprising to find relatively pure silicates (and perhaps graphite): one would expect impinging C atoms to "stick" to silicate grains, and impinging Mg, Fe, Si atoms to "stick" to graphite grains, thus making it difficult to produce "pure" silicate and graphite. Perhaps the "purity" could be maintained by selective chemisputtering or photodesorption (Draine 1990).

7.3. How is the Observed Grain Size Distribution Produced?

The observed grain size distribution results from a balance between injection from stellar winds, accretion, coagulation, and grain disruption, but the details of this remain unclear. Observed variations in the extinction law are presumably due largely to variations in the grain size distribution.

7.4. Where are PAHs Formed?

Some grain models require a significant fraction of the carbon [~9% in the model of Désert et al. (1990)] to be locked up in PAHs. PAHs containing more than ~ 30 atoms can survive in the UV radiation field (Guhathakurta & Draine 1989) but are still subject to coagulation and chemical attack. The proposed high PAH abundances may require a mechanism to produce them in the ISM (in addition to injection via outflows from carbon stars).

7.5. What is the Carrier of the 2175Å Feature?

Fitzpatrick & Massa (1986) found constancy of the central wavelength of the 2175Å feature even as the width varies considerably from one sightline to another. This imposes difficult constraints on the carrier of the 2175Å feature. Adding ice coatings, or varying the size and shape distributions, can cause changes in the profile width, but these are invariably accompanied by unacceptable shifts in the central wavelength (Draine & Malhotra 1993). With these effects evidently incapable of accounting for the observed variations in profile width, we are forced to conclude that the absorbing material itself must undergo alteration: either the entire grain is somehow chemically altered, or the grain surface is modified (by chemical alteration or accretion), but in either case it is necessary to make the ad-hoc assumption that the altered or accreted material contributes a broadened feature but with the same central wavelength as the material producing the narrower feature (Mathis 1994) This explanation would be much more attractive if we had some laboratory examples showing such broadening!

7.6. How Does Grain Alignment Take Place?

The processes leading to the observed grain alignment are still unclear. It now seems apparent that superthermal rotation (Purcell 1979) must be important in diffuse clouds, but it is still not certain that paramagnetic relaxation (Davis & Greenstein 1951) is the dominant aligning mechanism; gas-grain streaming has recently received renewed attention (Lazarian 1994; Roberge et al. 1994). The fact that the very small grains are not aligned also requires explanation. Mathis (1986) has proposed a model in which large grains are are more aligned because they are more likely to contain superparamagnetic inclusions. However, perhaps other phenomena play a role.

7.7. Where is the Missing Oxygen?

As discussed in §6, the gas phase abundance of O toward ζOph and other stars appears to be only about 50% of the solar value. The usual view is that the oxygen has been depleted into grains, but what chemical form could it be in? Normal oxides (e.g. $MgFeSiO_4$, or $MgO+FeO+SiO_2$) can only tie up about 16% of the O. H_2O, OH, CO, and CO_2 appear to be unimportant, based on spectroscopy of diffuse and dark clouds. Where is the O hiding? Or was the solar nebula 4.5Gyr ago oxygen-rich relative to today's interstellar medium?

8. SUMMARY

The only "facts" we are really confident of are:

- Grains in diffuse clouds have sizes of up to $\sim 0.3\,\mu$m, and extending down to $0.02\,\mu$m or below.
- The size distribution has most of the mass in large grains, and most of the area in small grains.
- An appreciable fraction of the grain mass consists of silicate material.
- An appreciable fraction of the $a \gtrsim 0.1\,\mu$m grains are nonspherical and aligned.
- The smaller grains are either more spherical or less aligned than the larger grains.
- Most of the starlight absorption is by grains which are heated to $T \approx 19$K and which have emissivities varying approximately as λ^{-2}.
- There is a population of very small grains or large molecules which are excited by starlight and which radiate at $3.3\,\mu$m, and into the 12, 25 and $60\,\mu$m IRAS bands.

Much more work is needed to decipher existing spectroscopic information (the 2175Å feature, the DIBs, the IR emission features), and to address various open questions regarding grain composition, evolution, alignment, etc.

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