Pre-stellar interstellar dust

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PRE-STELLAR INTERSTELLAR DUST*

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(Received 27 June, 1978)

Abstract. Before we can properly build a theory for the origin of the solar system we must know what interstellar gas and dust look like in the pre-stellar stage. In this paper we have concentrated on the dust. We arrive at a description of this pre-stellar dust on which the limiting criteria are developed out of evolution from average dust properties. We identify two populations of dust grains: large core-mantle grains and very small bare particles. The cores are presumed to be silicate of size $\sim 0.05\ \mu$m while the mantles consist of a size distribution of accreted thicknesses of C, N, O molecules and radicals which have been photoprocessed and an outer layer of molecules (mostly CO) and other species accreted in the later stages of cloud contraction. Most of the mantles must contain stored energy, some perhaps with enough to blow off the mantle if sufficiently disturbed. The maximum mean size of the core-mantle particles is $\sim 0.21\ \mu$m. The bare particles have not yet been positively identified but are $\sim 0.005\ \mu$m in size and outnumber the core-mantle particles by $\sim$ 3000–4000 while the remaining hydrogen in the cloud is $\sim 10^{12}$ times more abundant than the core-mantle grains. Physical arguments are presented to explain the narrow size distribution of these two types of particles.

1. Introduction

Before we can properly build a theory for the origin of the solar system we must know what interstellar gas and dust look like in this pre-stellar stage. It is on the dust that the principal attention of this paper will be directed.

The observational knowledge we have of the dust is almost entirely what it looks like only before and after star formation (with *maybe* a little information through I.R. emission during star formation). The problem is how to connect these two phases through the star birth phase. The difference between before and after are not very great for the regions not too close to the star where the dust can be entirely or partially evaporated. What actually goes into the stars is totally destroyed. What remains either goes directly or indirectly to form planets and comets. Of these objects only those which are formed and remain cold are direct descendants of the primordial dust.

Because the dust contains all, or almost all, of the elements heavier than hydrogen (excluding helium) in the last stages of cloud contraction preceeding the protostellar system, the initial chemical composition of the star and its planets must be governed by the evolution of this dust and must depend on how the dust plays a physical role in this condensation phase. Since the dust has evolved out of the dust as we see it in the interstellar medium this will be the starting point in our development of the subject. We shall carry this evolution up to that point at which grain-grain coalescence may become important. The comets are a very likely candidate of this direct agglomeration of the

* Paper presented at the Conference on Protostars and Planets, held at the Planetary Science Institute, University of Arizona, Tucson, Arizona, between January 3 and 7, 1978.

The Moon and the Planets **20** (1979) 15–48. 0165–0807/79/0201–0015$05.10

interstellar dust and any knowledge we can get studying and connecting these two would provide an important link in the solar system formation process.

The dust left over in the cloud out of which the star and planets formed remains in the stellar neighborhood for some time after birth. As a matter of fact, even if the newly formed solar system has a residual velocity of 1–2 km s^{-1} relative to the gas from which it formed, it is likely to continue to pass through the cloud complex regions of high gas and dust density for some millions of years (each parsec of cloud passage at 1 km s^{-1} takes 10^6 yr). During this time, a planet like the Earth would be likely to collect enough dust to provide a layer 100 μm thick over its entire surface (assuming a local cloud density of $n_H = 10^4 \text{ cm}^{-3}$ and distance of 1 pc). It is interesting to speculate that should the Earth have since passed through such a cloud, the average dust density would be such that the light scattered by the Sun could be as much as 1000 times brighter than the zodiacal light as we know it today so that the earth would seem to be in twilight.

Since there exist in the literature a number of interstellar dust models which are demonstrably incorrect in the light of the best available observations we shall in the next section provide an observational and theoretical framework for a basic grain model which appears to provide the proper basis leading toward the prestellar conditions of interest here. The physical and chemical properties of the grains – size, shape, surface characteristics, chemical composition, optical absorption and emission – may be derived from this model and applied to such problems as the way in which grains may coalesce to form larger aggregates in the very high density phase.

2. Interstellar Dust Model

2.1. Summary of Observations

In this section we summarize the principal observational properties of the dust from which a self-consistent model of the interstellar grains and their evolution may be deduced.

(a) The shape of the wavelength dependence of extinction, $\Delta m(\lambda)$, is fairly uniform. Deviations from the average occur in dark clouds, near newly formed stars and other regions of physical variability. From the first property we may deduce a mean particle size by comparing $\Delta m(\lambda)$ with the calculated extinction vs wavelength curves for small particles.

Grain materials may be classified as dielectrics or metals. Dielectrics have small values of m'' in the visual but substantial values of m'' in the ultraviolet. Metals (graphite, iron, magnetite) have substantial (and wavelength dependent) values of m'' in the visual.

As seen in Figures 1 and 2, the observed extinction saturates at about $\lambda^{-1} \simeq 5\,\mu^{-1}$ (ignoring for the moment the $4.6\,\mu^{-1}$ extra "hump") before *again* rising beyond $\lambda^{-1} \simeq 6\,\mu^{-1}$.

It is a well known property that once the extinction saturates for a given particle size it *can no longer* rise. We must therefore assume that there are two basically different particle sizes in interstellar space. We call these the classical particles and the very small particles. First consider the classical particles and then the bare ones. We note that the

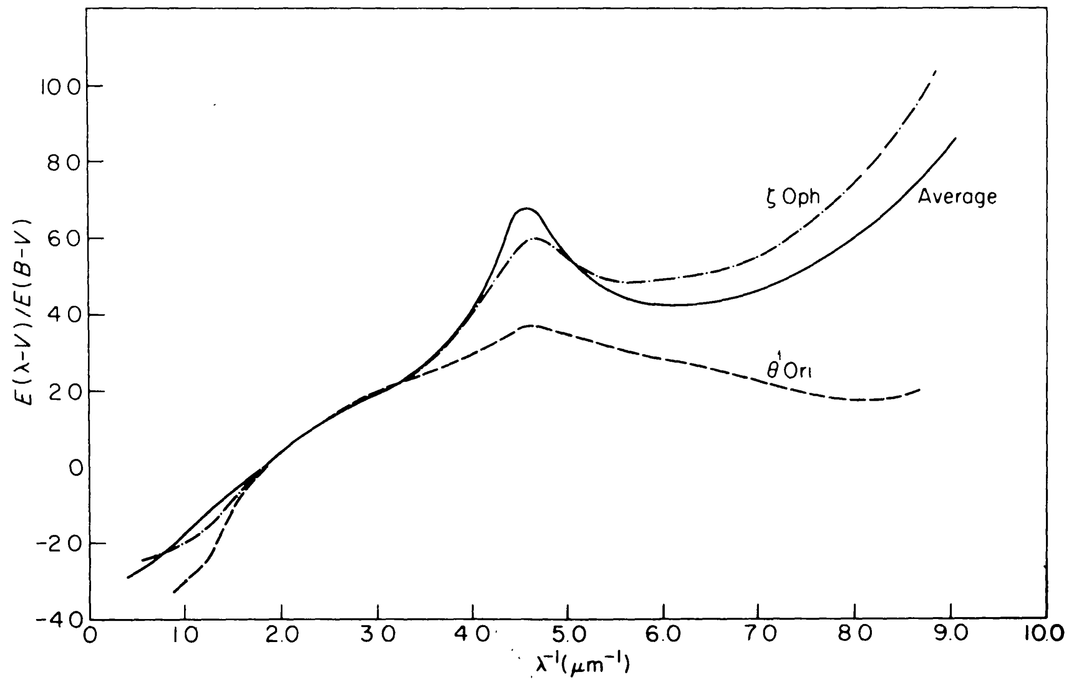


Fig. 1. Observed (normalized) wavelength dependence of extinction from the infrared to the far ultraviolet. The very exceptional star θ' Orionis is shown for comparison. (From Bless and Savage, 1972).

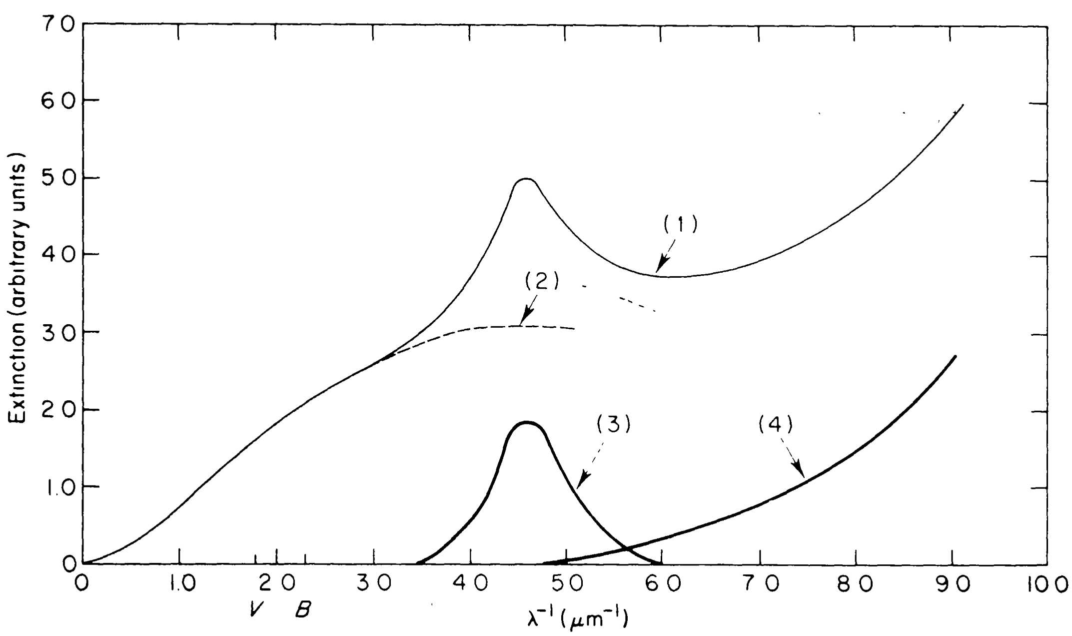


Fig. 2. Schematic extinction curve. The mean extinction curve (1) is arbitrarily divided into portions to which the major contributions are made by classical sized particles (2) and by very small particles (3) and (4).

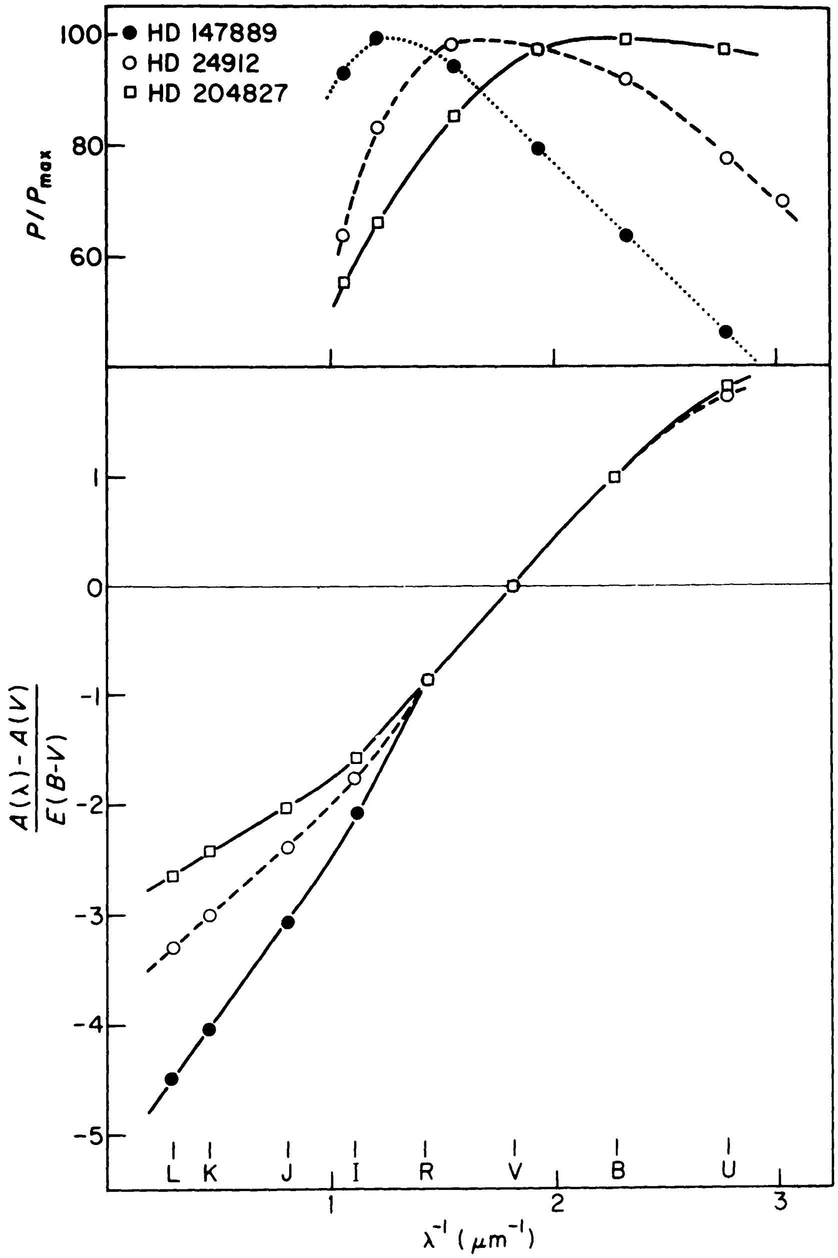


Fig. 3 (a). Observations of the correlation of variations in the wave-length dependence of extinction and polarization (From Serkowski, Gehrels and Wiśniewskć, 1969).

particles producing the $4.6\,\mu^{-1}$ hump must be quite small ($\leqslant 0.02\,\mu$m) but they may constitute only a fraction of all the bare particles.

For dielectric spheres (see Figure 7) the saturation occurs at around $\rho = (4\pi a/\lambda)(m' - 1) \simeq 4$. Inserting the observed saturation value of $\lambda^{-1} = 5\,\mu^{-1}$ into the equation of ρ and using $m' = 1.33$ (ices) and $m' = 1.66$ (silicates) we find respectively $a_{\text{ice}}^{(\text{class})} \simeq 0.19\,\mu$ and $a_{\text{sil}}^{(\text{class})} \simeq 0.095\,\mu$ as representative classical (dielectric) particle sizes. For metals we

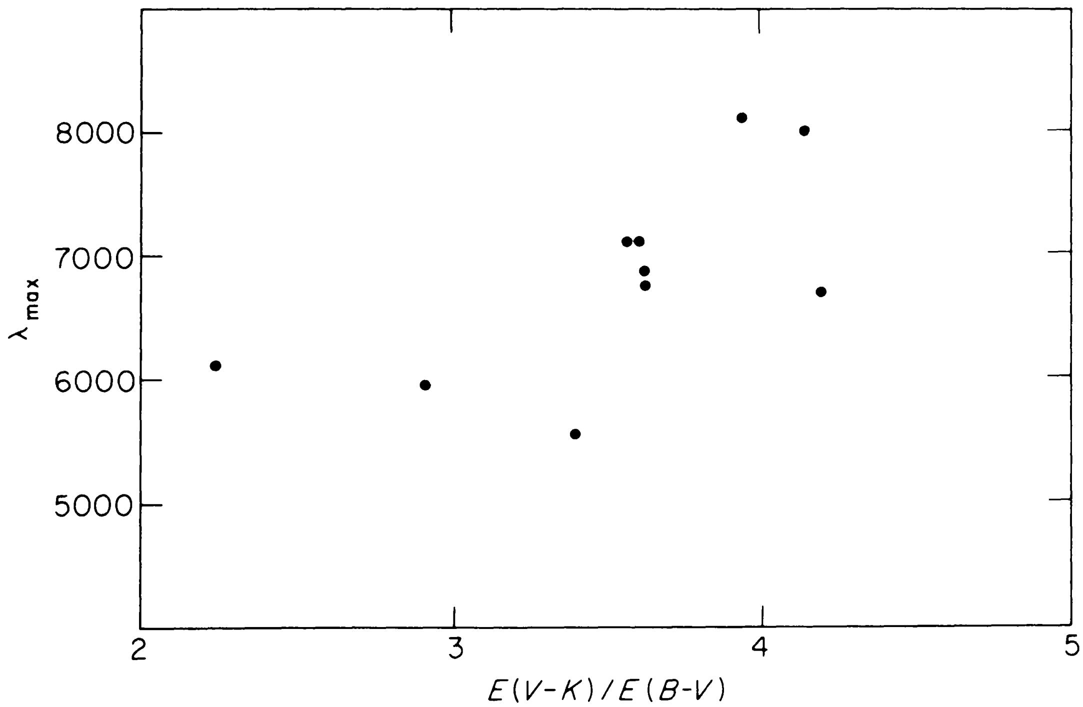


Fig. 3(b). The value of the maximum of the polarization vs the total to selective extinction as given approximately by $E(V-K)/E(B-V)$. Observation in ρ Oph. (From Carrasco, Strom and Strom, 1973).

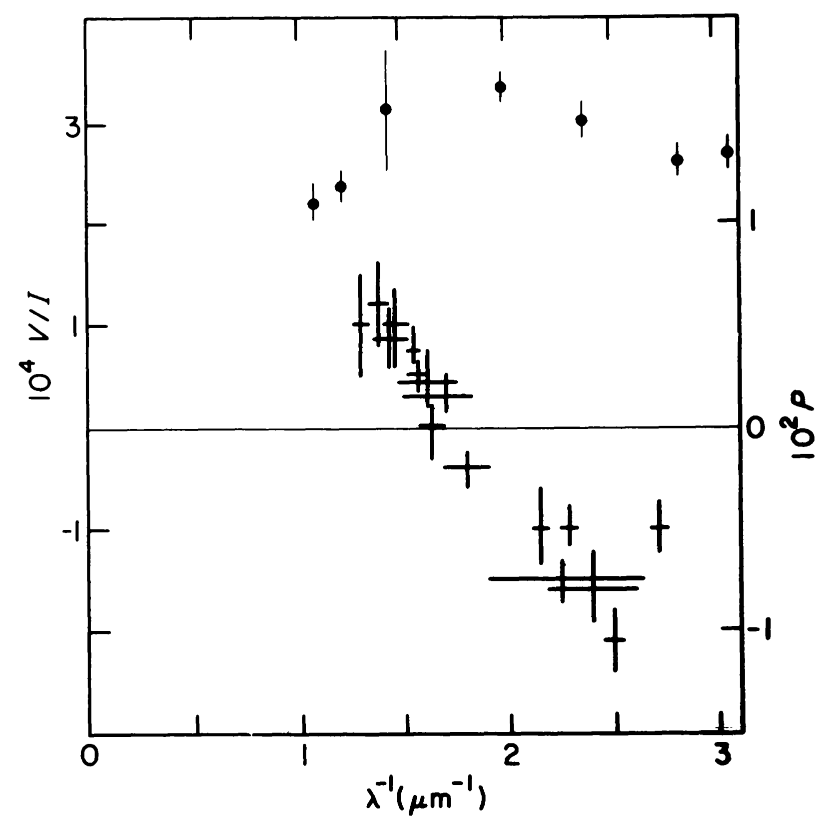


Fig. 4. Observations of linear and circular polarization for the star σ Scorpii (From Martin, 1974).

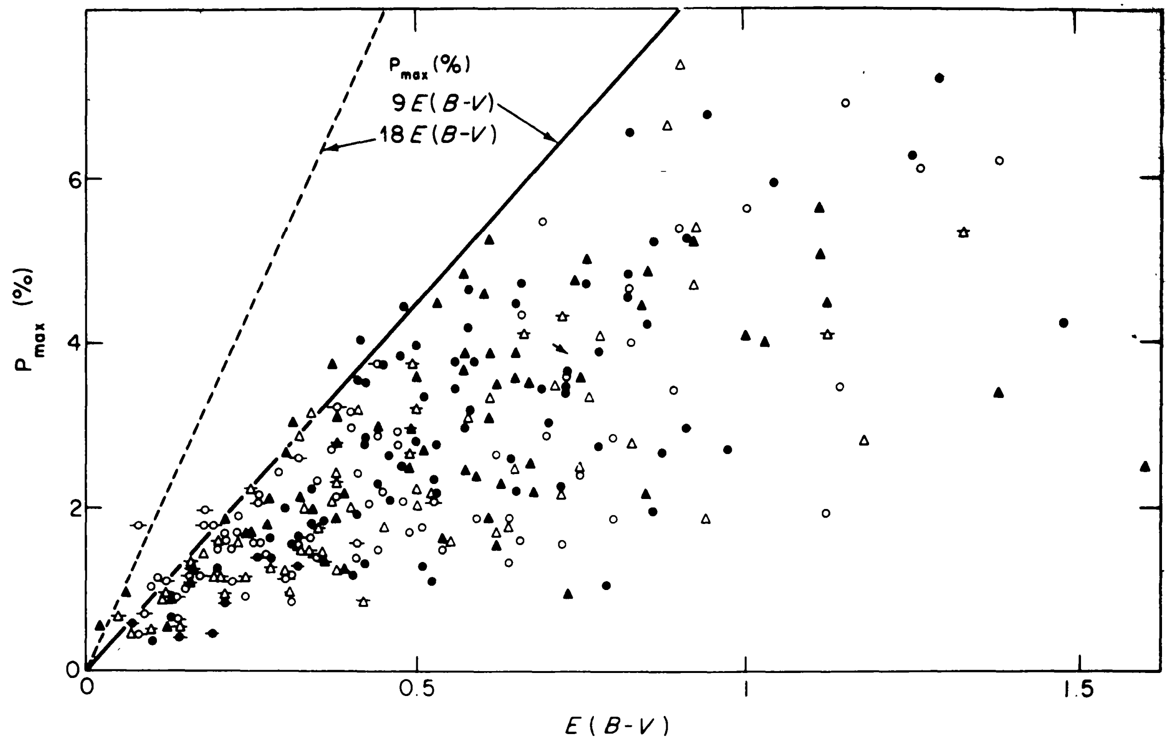


Fig. 5. Ratio of maximum polarization to color excess $E(B-V)$. (From Serkowski, Mathewson and Ford, 1975). It is to be noted that P_{max} occurs at different wavelengths for different stars and therefore an inferred value of the ratio of polarization (at the visual wavelength) to the extinction at the same wavelength must take this into account.

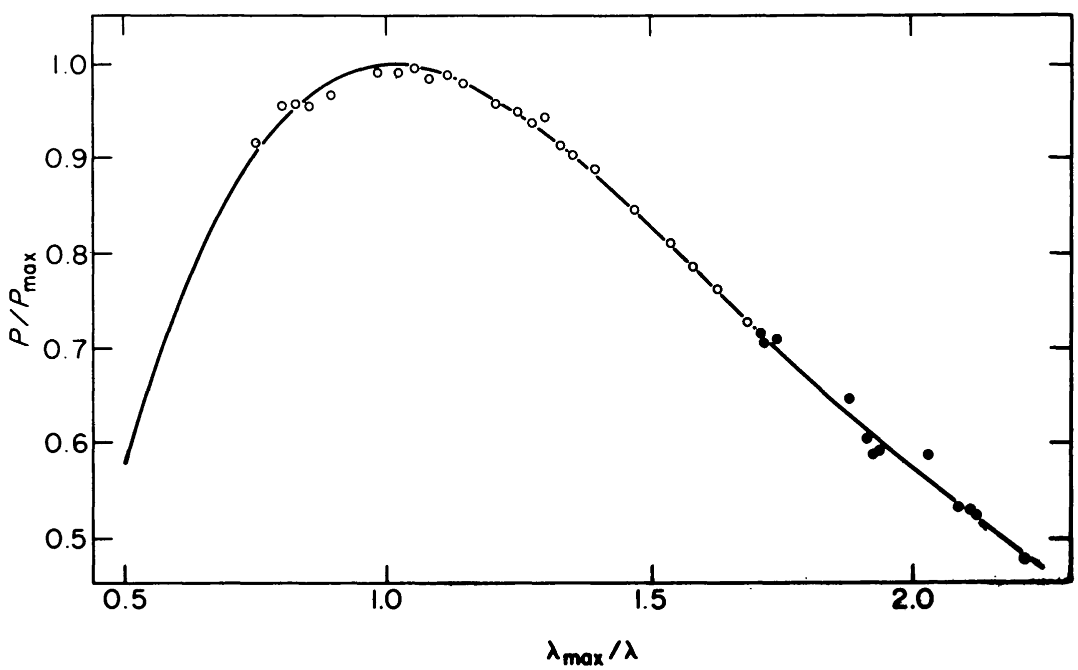


Fig. 6. "Uniform" wavelength dependence of interstellar linear polarization: P/P_{max} vs λ_{max}/λ. Each open circle is based on 20 stars while each dot represents the observations of an individual star with a particular filter. (From Serkowski, Matthewson and Ford, 1975).

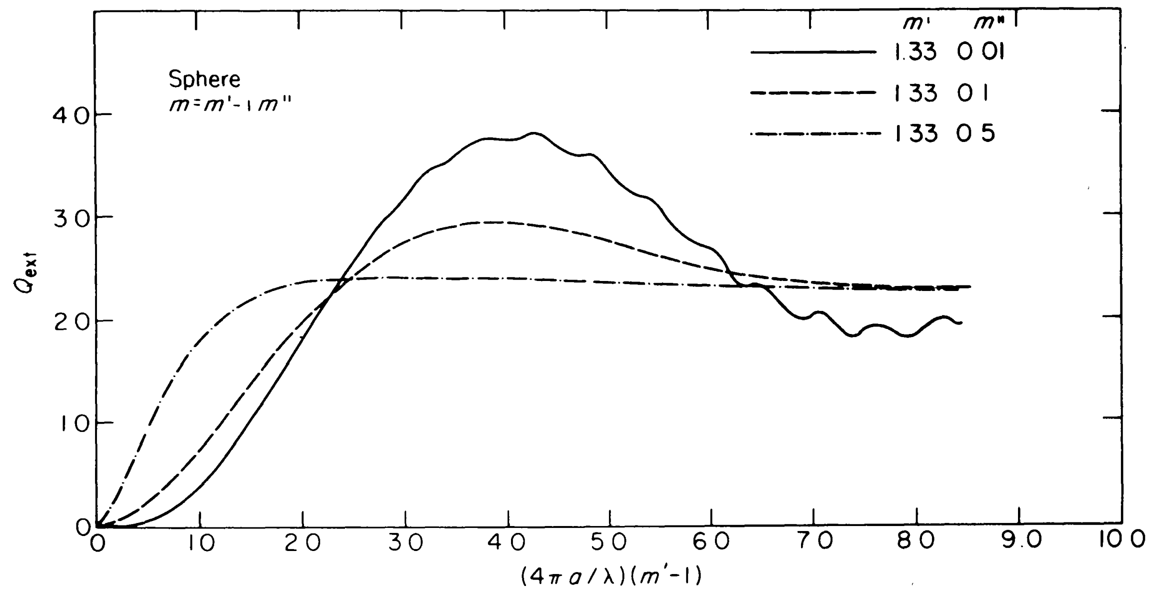


Fig. 7. Extinction efficiencies for spheres as a function of absorptivity. The curves for $m = 1.33-0.01i$ and $m = 1.33-0.1i$ are characteristic of dielectric particles. The curve for $m'' = 0.5$ is almost like that for a metal.

use the saturation value of $x = 2\pi a/\lambda = 1.5$ to correspond to $\lambda^{-1} \simeq 5\,\mu\text{m}^{-1}$ to give $a_{\text{metal}}^{(\text{class})} \simeq 0.05\,\mu$m. More exact calculations and use of size distributions lead to very similar results.

In the far ultraviolet, all particles, whether dielectric or metallic, have large m'' and therefore act similarly. Since the far ultraviolet part of the extinction is still rising with upward curvature at $\lambda^{-1} \simeq 10\,\mu\text{m}^{-1}$ we see from Figures 8(a) and (b) that this must correspond to $2\pi a/\lambda \simeq 0.5$–$0.75$ leading to particles with characteristic radii $a_b \simeq 0.01\,\mu$m; i.e. about 1/20 as large as the classical particles.

(b) The mean wavelength dependence of polarization has a maximum at about $\lambda = 0.545\,\mu$m (Serkowski *et al.*, 1975). If we compare this result with the calculated polarization for aligned dielectric (ice-like) cylinders by using $\lambda = 0.5\,\mu$m to correspond to the (smoothed) maximum (in Figures 9(a) or (b) at $2\pi a/\lambda \simeq 2$ we find $a \simeq 0.16\,\mu$m. Since this is reasonably close to the value of size deduced from extinction it is inferred that polarization and extinction are produced by the same particles.

(c) The variations in the polarization shape appear to be well correlated with variations in the shape of the extinction curve (Figure 3(a)). If we typify a polarization curve by λ_{max} the value of the wavelength at maximum polarization, and the extinction curve by $R = A(V)/E(B-V)$, the ratio of total to selective extinction, we find a correlation as shown in Figure 3(b). Since increasing R and λ_{max} both indicate increasing particle size it is natural to associate the variations with varying accretion of oxygen, carbon and nitrogen atoms and molecules from the interstellar gas. This effect is further studied in Section 4.

(d) The wavelength dependence of circular polarization and its correlation with the

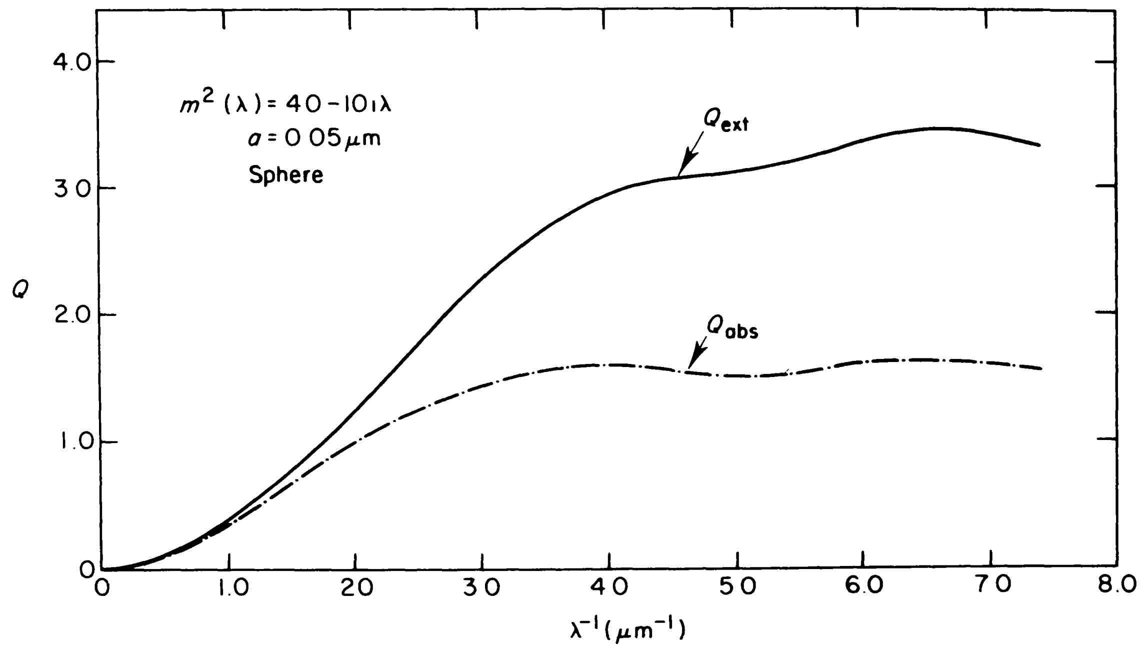


Fig. 8(a). Extinction and absorption efficiencies for a spherical particle of radius $a = 0.05\ \mu$m with graphite-like index of refraction $m^2 = 4 - 10i\lambda$. Both the extinction and absorption curves "saturate" at about $x = 2\pi a/\lambda = 1$.

shapes of both linear polarization (see Figure 4) and extinction are a strong indication that the particles producing all three vary in size together and have an approximately constant index of refraction in the range $1 < \lambda^{-1} < 3\ \mu\text{m}^{-1}$ i.e., are dielectrics like ices (Greenberg, 1978b).

(e) The uniformity of the polarization as shown by plotting p/p_{max} vs $\lambda_{\text{max}}/\lambda$. (Figure 6) again indicates that the particles are ices. Since, for dielectric grains, the polarization is a function of $2\pi a/\lambda$ alone (as shown in Figures 9(a) and (b)) an increase in mean particle size, resulting from growth by accretion in the interstellar medium, produces a corresponding shift of the polarization towards longer wavelength. Metallic particles (graphite, iron, magnetite) of varying size would produce differently shaped polarization curves (not normalizable in the above sense) because the index of refraction varies with wavelength and since p is a function of $m(\lambda)$ as well as of $2\pi a/\lambda$, the invariance is destroyed.

(f) The generally observed maximum ratio of polarization to extinction $p/\Delta m \lesssim 0.03$ (see Figure 5) shows that even with imperfect alignment the particles must be substantially nonspherical. If the particles were in perfect spinning alignment, we would expect to observe a dependence of the extinction curve on the direction of viewing with respect to (magnetic) alignment direction (Greenberg and Meltzer, 1960). Since this effect has not been seen it implies the kind of reduction produced by incomplete alignment (Greenberg, 1968).

(g) The correlation of gas and dust in clouds, in the disk of a spiral galaxy, in the inner

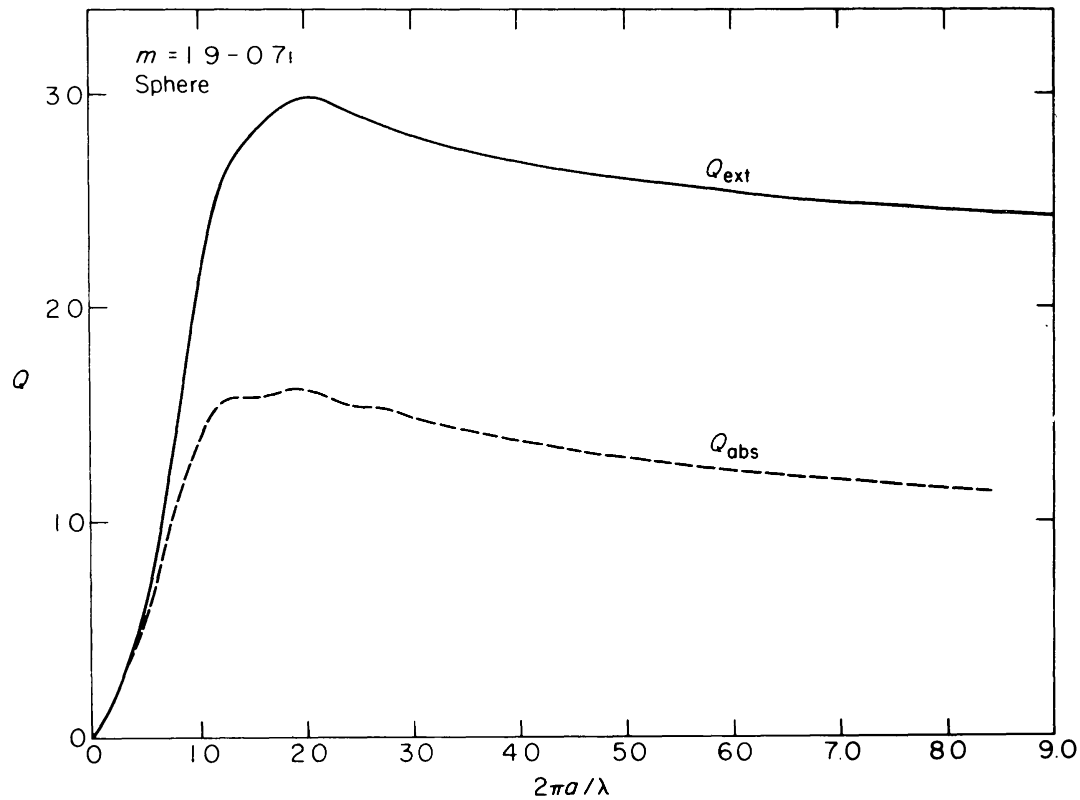


Fig. 8(b). Extinction and absorption efficiencies for a silicate-type grain with index of refraction characteristic of its far ultraviolet values: $m = 1.9–0.7i$. Note similarity of dielectric grains in the far ultraviolet to metallic grains in the visual.

edges of spiral arms etc. shows that they are generally well mixed. The value of the correlation constant, $A(V)/N_H = 0.7 \times 10^{-21}\,\mathrm{cm}^2$ (Morton 1974), where N_H is the column density of hydrogen in all forms for the same line of sight as the extinction, shows how much area the grains must have relative to the hydrogen density. Combining this area with size leads to the total dust volume. Accepting the concept of cosmic abundance of the elements then limits the choice of grain models.

Suppose all the interstellar dust is in the form of spheres of a fixed characteristic radius $\bar{a}$. For mass estimates this is acceptable (Greenberg and Hong, 1975). The visual extinction per unit length is

$$\Delta m(V) = A(V) = n_d \pi \bar{a}^{-2} Q(V), \tag{1}$$

where n_d = number of dust particles per unit volume and $Q(V)$ is the extinction efficiency factor which is $\simeq 1$.

The mass density of grains is

$$\rho_d = n_d \tfrac{4}{3}\pi \bar{a}^3 s = \tfrac{4}{3} A(V) s \bar{a}/Q(V), \tag{2}$$

where s = grain material specific density.

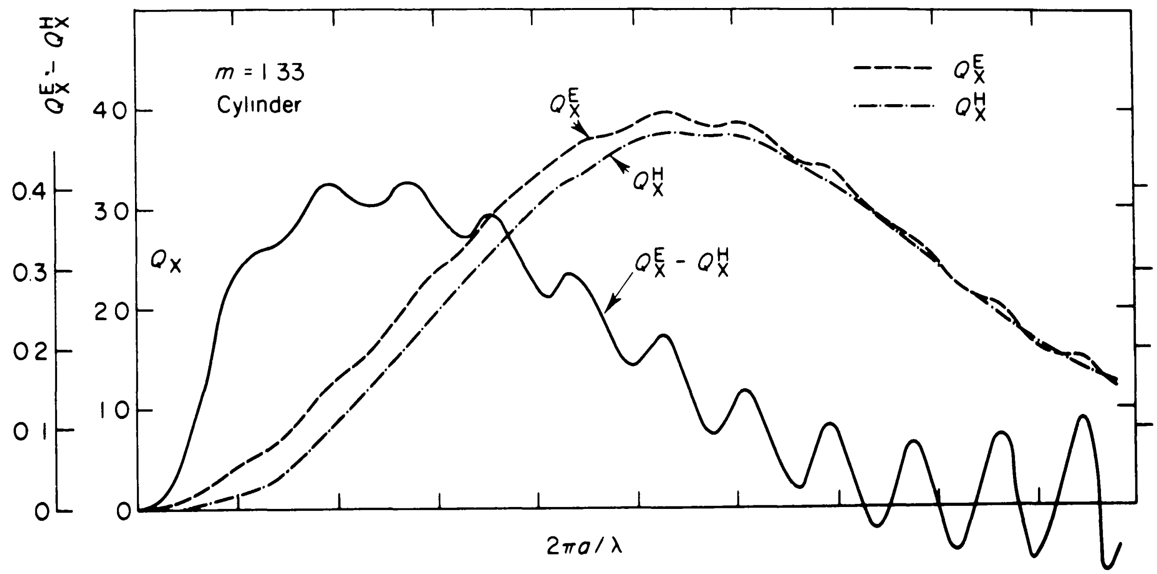


Fig. 9(a). Extinction efficiencies for perfectly aligned circular cylinders with index of refraction $m = 1.33$. Q^E and Q^H are for the electric and magnetic vector of the incident radiation parallel respectively to the cylinder axis. The solid curve (with ordinate to the left) is the difference or polarization curve.

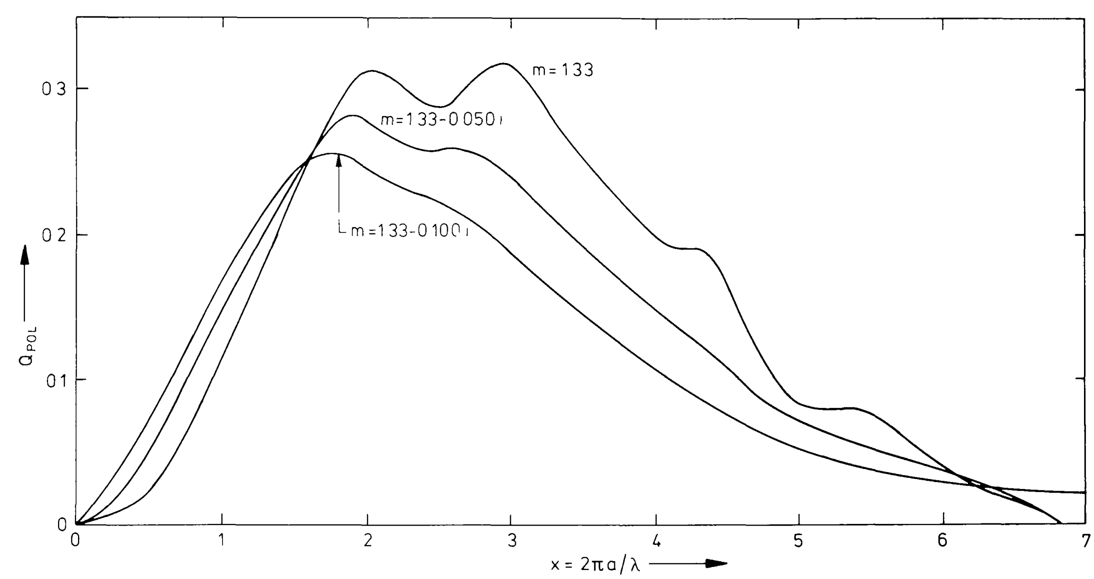


Fig. 9(b). Polarization efficiency factors as a function of $x = 2\pi a/\lambda$ for perfectly aligned spinning cylinders with three different values of the imaginary part of the index of refraction.

Using $A(V) = 0.7 \times 10^{-21} N_{\mathrm{H}}\ \mathrm{cm}^2$ in Equation (2) we get

$$\frac{\rho_d}{n_{\mathrm{H}}} = \frac{4}{3}\frac{\bar{a}}{Q(V)}(0.7 \times 10^{-21})\bar{s}. \qquad (3)$$

But ρ_d is simply the number density of molecules of the grain material times the molecular weight $n_M M n_H$, so that

$$n_M/n_H = \frac{4}{3}\frac{\bar{a}s}{Q(V)}\frac{(0.7\times 10^{-21})}{Mm_H}, \quad (4)$$

where m_H = mass of hydrogen and M = molecular weight of the grain material. Equation (4) gives the *required* number of molecules in the dust relative to hydrogen and it must be less than that given from cosmic abundance in order to be acceptable for a given grain model.

If grains were made of pure H_2O of radius $a = 0.2\,\mu$, Equation (4) would give us

$$n_O/n_H = 5\times 10^{-4} < \text{C.A.}$$

On the other hand, $0.1\,\mu$ radius grains of olivine, Mg_2SiO_4 as a representative silicate give $n_{Si}/n_H = 6\times$ C.A. which means that more Si is required than is available. Therefore, even though we have spectroscopic evidence at $\sim 10\,\mu$m (the Si–O stretch) for some sort of silicates in the interstellar medium they cannot provide a major contribution to the extinction. They can, however, be the nuclei on which O, C, N, etc. accrete.

2.2. Average Grain Model

The basic form of the classical sized grains suggested by the observations is a core-mantle structure with the core consisting of a silicate material and the mantle of a generalized material consisting of complex combinations of O, C, N and H. The more refractory cores are probably ejecta from cool evolved stars. The mantles are accreted by the cores in interstellar clouds and subsequently modified by the interstellar ultraviolet radiation to become a heterogeneous mixture of complex molecules which is substantially more refractory than the ices consisting of water, methane and ammonia. Using a cylindrical model with size distribution (see justification in Section 4) for mantles a_m on a single core size a_c

$$n(a_m) = \exp\left[-5\left(\frac{a_m - a_c}{a_i}\right)^3\right], \quad (5)$$

and indices of refraction "characteristic" of silicates and ices one arrives at mean classical and bare particle dimensions

$$\left.\begin{aligned} a_i &= 0.2\,\mu \\ a_c &= 0.05\,\mu \end{aligned}\right\} \Rightarrow \bar{a}_m = 0.12\,\mu \quad (6)$$

bare $a_b = 0.005\,\mu$ (assumed to be silicate; see later). These sizes produce

$$\frac{A(V)}{E(B-V)} = 3.$$

The mean space density of such particles is (see Greenberg and Hong, 1974; Hong, 1975):

$$n_{c-m} = 9.5e^{-1}\times 10^{-13}\,n_H,$$

$$n_b = 4.6 \times 10^3 e n_{c-m}, \tag{7}$$

where e is the elongation of the classical particles.

It is interesting to note that the amount of silicate material in the cores is somewhat greater (by about a factor of two) than that which can be produced by M stars unless it is concentrated to the galatic plane relative to the M star distribution (see Section 4).

Using the above model for the dust and applying it to the observation of ζ Oph we find that the total number of accountable atoms of O, C and N along the line of sight as either atoms + ions (Morton, 1974) or in dust is only about 50% of those predicted by cosmic abundance. Since the most abundant molecule, CO, supplies at most the order of an additional 20% to C, 10% to O and nothing to N, there is implied a substantial gas fraction in undetected molecules – probably mostly quite complex. This sea of condensible gaseous material is actually required to produce the growth of grains as we see them in dense clouds relative to the average.

A star for which extinction, linear and circular polarization are all observed is σ Sco. The model representing this is given by (Hong, 1975; Greenberg, 1978b)

$$\begin{aligned} a_i &= 0.26\,\mu \\ a_c &= 0.05\,\mu \qquad \Rightarrow \bar{a}_m = 0.15\,\mu. \\ a_b &= 0.005\,\mu \end{aligned}$$

The comparisons between observations and theory for σ Sco are shown to be rather good in Figure 10 where we have had to use slightly larger than average classical particles.

3. Chemical Evolution of Grains

The chemical evolution of grains – more specifically core-mantle grains – consists of a combination of various independent processes:

(a) Formation of cores

(b) Accretion of atoms and molecules from the interstellar medium

(c) Photochemical processing of the mantle materials

(d) Destruction processes.

The formation of the cores is discussed by Donn (1978). The accretion of atoms and molecules on the cold surfaces of the cores (which subsequently become core-mantle particles) is a well established phenomenon. With surfaces whose temperatures are in the 10–20 K range the sticking probability of most of the abundant atoms or molecules is of the order of unity (Stickney, 1970). Even hydrogen atoms may be presumed to have a sticking probability of better than 0.1 to 0.2 and probably higher. Thus as a bare core is initially exposed to the interstellar medium the growth of its mantle occurs at a rate given by the collision rate of the major condensible species in the gas; namely, atoms of oxygen, carbon, and nitrogen and possibly CO. This growth rate may be estimated as (Greenberg, 1978b).

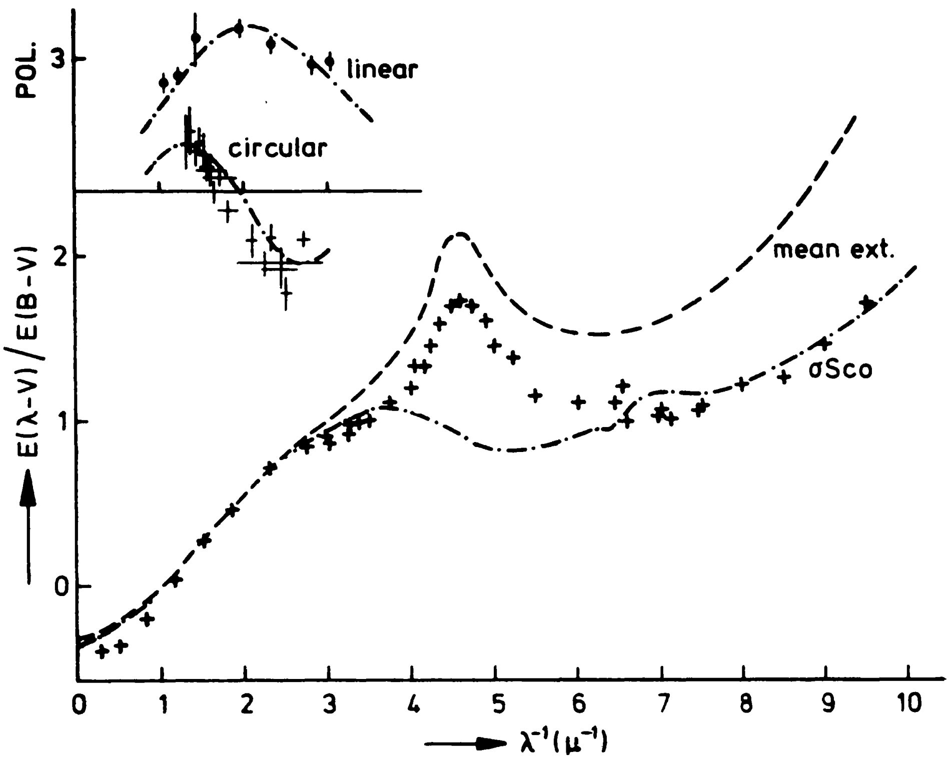


Fig. 10. Extinction, linear polarization, and circular polarization calculated from a bimodal grain model and compared with the observations of these quantities for the star σSco. (From Hong, 1975).

$$\frac{da_m}{dt} = 3.43 \times 10^{-23} n_{\mathrm{H}} T^{1/2} \mathrm{cm\,s}^{-1}, \tag{8}$$

where n_{H} is the number density of hydrogen in all forms and it is assumed that the condensibles (mostly O, C and N) are moving with a velocity given by the kinetic temperature T. At this rate the mantle thickness will grow from zero to the interstellar average of about 0.07 μm in 4×10^{14} s (about 10^7 yr) in a cloud whose mean density is $n_{\mathrm{H}} = 50\,\mathrm{cm}^{-3}$. In the next section I will further discuss this in relation to the ultimate growth of grains in dense clouds and also in relation to the production of steady state size distribution.

In addition to growth of grains by collisional accretion there will be interaction in the grains produced by the ultraviolet photons in the interstellar medium. Although observational and theoretical evidence leads to a model for dust grains which consist to a major extent of a composition of oxygen, carbon and nitrogen, the strength of the 3.07 μm band of H_2O ice, where observed, implies that only a small part of the grains can consist of ices of H_2O, or CH_4 and NH_3 in the classical sense (van de Hulst, 1949). This is not at all surprising when we consider the fact that the grains are continually being subjected to ultraviolet radiation in space. Except in the deep interiors of the darkest clouds the ultraviolet photons are sufficiently numerous to modify substantially the internal molecular composition of the mantles of the grains by photo-chemical reactions. The experimental

TABLE I

Some bond dissociation energies (Calvert and Pitts, 1966)

Molecule/Radical	Bond	Bond Dissociation Energy (eV)
N≡N		9.8
C≡O		11.4
H–C≡H	–C≡C–	9.97
H–C≡N	–C≡N	9.71
O=O		5.16
O=C=O		5.51
$H_2C{=}O$	C=O	7.59
$H_2C{=}O$	H–C	3.82
$H\dot{C}{=}O$	$\dot{C}$=	0.82
H–C≡N	H–C≡	5.62
H–C≡C–H	H–C≡	5.42
H–C≡C	H–C≡	5.42
NH_3	N–H	4.47
H_2O	O–H	5.16
H–O	O–H	4.42
CH_4	C–H	4.51
$\cdot CH_3$	C–H	4.6

basis for this theory is in its infancy but a few quantitative arguments based on analogous chemical problems show the extent of this photo-processing and its likely consequences (Greenberg, 1976).

3.1. Free Radicals and Complex Molecules in Interstellar Grains

When a sufficiently high energy photon is absorbed by a grain it may break a chemical bond; for example (see Table I)

$$H_2O + h\nu \rightarrow OH + H, \quad NH_3 + h\nu \rightarrow NH_2 + H.$$

The OH, NH_2, and other molecules with unsaturated bonds are called free radicals and have the property of being extremely reactive with each other. However, because the grains are extremely cold, these radicals are inhibited from migrating, so much so that we have ideal conditions for trapping a substantial number of these free radicals. There exists a rich literature on the production and trapping of radicals in various mixtures, but studies of substances as complicated as the interstellar ices are only now under way.

As more and more radicals are created and trapped there must come a time when their density exceeds a value at which the probability for reactions between adjacent radicals is unity. Actually even when the density is less than this value there is a high probability of establishing a chain reaction in the grain (Jackson, 1959a, b; and Section 3.2). This critical density is of the order of 1%. If the photochemical processing is to be important, the time required to achieve this density must be smaller than the grain lifecycle of the order of 10^7 yr.

The number of photons with wavelength less than some threshold λ_t (for producing a free radical) impinging on a grain of radius a per unit time is

$$\frac{dN_{\text{u.v.}}}{dt} = (\pi a^2/h) \int_{912\,\text{Å}}^{\lambda_t} U_\lambda \lambda d\lambda, \tag{9}$$

where U_λ is the energy density.

If we approximate the Habing (1968) radiation field by letting $U_\lambda = 40 \times 10^{-18}$ erg cm^{-3} Å^{-1} throughout the ultraviolet, we may simply integrate Equation (3.1.1) to obtain

$$\frac{dN_{\text{u.v.}}}{dt} = 30\pi a^2 (\lambda_t^2 - 912^2), \tag{10}$$

where λ_t is in Ångström. Thus for $\lambda_t \simeq 2000$ Å the rate of u.v. photons impinging on a 0.12 μm size grain is

$$\frac{dN_{\text{u.v.}}}{dt} = 5 \times 10^{-2}\,\text{s}^{-1}. \tag{11}$$

Let the net efficiency for free-radical production be ϵ; then the time required to achieve the critical number density is

$$\tau_c = n_c V_d / \epsilon (dN_{\text{u.v.}}/dt) = (n_c/M)(M/\epsilon)(dN_{\text{u.v.}}/dt), \tag{12}$$

where V_d = the volume of the grain.

The value of ϵ for interstellar grain material is impossible to estimate with any precision. The 10% efficiency of free-radical production in methane by 10 eV photons is probably much greater than the value of ϵ we should use. However, even allowing for an underestimate of ϵ by as much as a factor of 10^2, i.e. letting $\epsilon = 10^{-3}$ we obtain

$$\tau \leqslant 10 \left[\mu m_{\text{H}} \frac{dN_{\text{u.v.}}}{dt}\right]^{-1} \frac{4}{3}\pi a^3 = 5 \times 10^{10}\,\text{s} = 1.7 \times 10^3\,\text{yr}, \tag{13}$$

where we have assumed $n_c/M \simeq 0.01$ and where we have approximated the mean molecular weight by $\bar{\mu} = 17$. We see that the critical free-radical creation time is well within the limits prescribed by the grain lifetime.

The fact that the critical density for chain reactions is achieved by no means guarantees that a chain reaction will take place. For particles below a critical size the chain reaction reaches the surface before it can go to completion.

The critical size derived by Jackson (1959a, b) is proportional to $(D\tau_{MR})^{1/2}$, where D is the diffusion constant and τ_{MR} is the lifetime for mobile radicals. As applied to the nitrogen system this leads to the order of 10^4 molecule layers for $n_c = 0.1\%$ or 10^3 layers for $n_c = 1\%$. The latter combination implies, for average molecular size of 2 Å, a minimum grain diameter of about 2×10^{-5} cm. Although this is within the range of average interstellar grain sizes we hasten to point out that there are enough uncertainties in its derivation to require much further experimental study before it may be considered conclusive. Among other things we have entirely ignored surface effects.

Assuming a complete chain reaction, what happens to the grain depends on the total energy released. Let the energy released per radical-radical recombination be E. Then the total energy released per molecule in the material is

$$H = \tfrac{1}{2}(n_c/M)E.$$

For $(n_c/M) = 0.01$ and $E = 5$ eV, $H = 0.025$ eV. The binding energy for an organic crystal is about 2 k cal/mol (Kittel, 1956) which is equivalent to about 0.1 eV/molecule. On estimating the break-up energy of the grain this quantity may be reduced by a substantial factor to account for the fact that the total number of molecules is generally reduced in the process of the chain reaction. Whether or not the average new molecule is five times larger than the original small ones (H_2O, etc.) the grain will evaporate by an explosive process (Greenberg, 1976). This is a complicated process to treat theoretically, but experimentally it has been shown that under some conditions very large molecules can be created in solid water, methane, ammonia mixtures (Greenberg *et al.*, 1972) so that there is a strong presumption that it must take place in an interstellar grain.

One should expect spectroscopic evidence for the existence of radical and molecular species in interstellar grains. Among the decay modes of excited vibrational states of a molecule in a low temperature solid, like the grain mantle, are those in which the radiation in the infrared is not completely coupled to the acoustic phonons and therefore may appear as infrared fluorescence. The emission spectrum associated with the planetary nebula NGC 7027 has lines which have been tentatively identified with molecules and radicals which may be expected to exist in grain mantles (Allamandola and Norman, 1978). An experimental program along the lines of that discussed in the next section (3.2) is currently being set up in our Laboratory Astrophysics group to study just this kind of fluorescence in irradiated analog grain mantle materials.

From the fact that the critical free-radical creation time is so short we could expect that the build-up and reaction sequence would occur frequently during the grain life and that there is a possibiltiy of the grain having a steady-state or mean chemical composition.

Once the number density of frozen radicals and the critical size are reached, the probility for triggering a chain reaction is expected to become appreciable. In the case of the interstellar grains we must follow their history as well as the static requirements. During the course of the growth of a grain in an intermediate-density cloud, the grain is subjected to the normal interstellar ultraviolet flux and therefore acquires free radicals in its mantle at the same time as it grows. During this stage, the grain temperature is of the order of 10 K. The number of grains with mantles greater than the critical size will increase during cloud contraction. As the cloud density increases, the ultraviolet flux decreases and the rate of formation of free radicals decreases. However, even here this rate of formation appears to remain substantial relative to the growth rate. Let the collision rate of heavy atoms dN_{HA}/dt be $\sim 10^{-3}$ times that of hydrogen; then

$$\frac{dN_{HA}}{dt} = 4.5 \times 10^{-8} n_H \, s^{-1} \tag{14}$$

for a size 0.12 μm.

For comparison with Equation (14) the ultraviolet photon collision rate inside a cloud is that given in Equation (10) reduced by some attenuation factor. We estimate the effective ultraviolet optical depth as being about three times the visual extinction. The visual extinction is obtained from the correlation factor $n_H R/E(B-V) = 4.2 \times 10^{21}\,\mathrm{cm}^{-2}$ (Morton, 1974), where R is the distance inside the cloud. The attenuation factor is then $\exp(-\tau_{u.v.})$ where $\tau_{u.v.} \sim 2 n_H R \times 10^{-21}$. The heavy atom and ultraviolet collision rates are then equal at the centre of a spherical cloud of radius R and uniform density n_H when

$$\exp(-2 n_H R \times 10^{-21}) = 0.9 \times 10^{-6} n_H \tag{15}$$

For $R = 1$ pc the solution to Equation (15) is $n_H = 10^3\,\mathrm{cm}^{-3}$. For $R = 0.1$ pc, one obtains $n_H = 0.8 \times 10^4\,\mathrm{cm}^{-3}$. Thus, it is only in the very latest stages of cloud contraction that the photolysis may be negligible.

We then picture the ulitmate core-mantle grain (see next section) before star formation as consisting of a core surrounded by a mantle comprising perhaps two or more layers, with the innermost layer having undergone substantially complete photoprocessing and the outermost layer consisting of material accreted from the remaining molecules and atoms in the densest regions of the cloud where photoprocessing may be neglected.

3.2. Laboratory Analog of Photoprocessing of Interstellar Grains

In the Laboratory Astrophysics group at Leiden University we are currently studying the photochemistry of analog interstellar materials at temperatures down to about 10 K. The scientific staff are L. Allamandola, F. Baas, W. Hagen and C. van de Bult. The basic equipment consists of: (1) a closed system helium cryostat with a cold finger on which may be deposited thin ($< 10\,\mu$m) samples of various gas mixtures of simple molecules containing oxygen, carbon and nitrogen; (2) a Fourier Transform Infrared spectrometer (Digilab FTS 15) to study the absorption spectrum of the sample; (3) a quadrupole mass spectrometer (mass range 1–300 a.m.u.) to study the molecular weights of the molecules evaporated off the cold finger; (4) a set of ultraviolet lamps and windows as sources of the production of the photolyzing photons; (5) a gas handling system for mixing and depositing various molecular mixtures: (6) a visual and vacuum ultraviolet monochrometer and phototube to measure the light output of the sample when it is warmed; (7) various temperature and pressure measuring and control devices. A set of photos of the lab are shown in Figure 11. A detailed description of the laboratory and its operation will be published elsewhere. All I will do here is to describe as illustrative the results of one of the experiments which was first performed in our laboratory. A deposit of NH_3 and CO was first put on the cold finger in the cryostat. The infrared spectrum of this layer was then recorded. The ultraviolet photons from a hydrogen lamp with a MgF

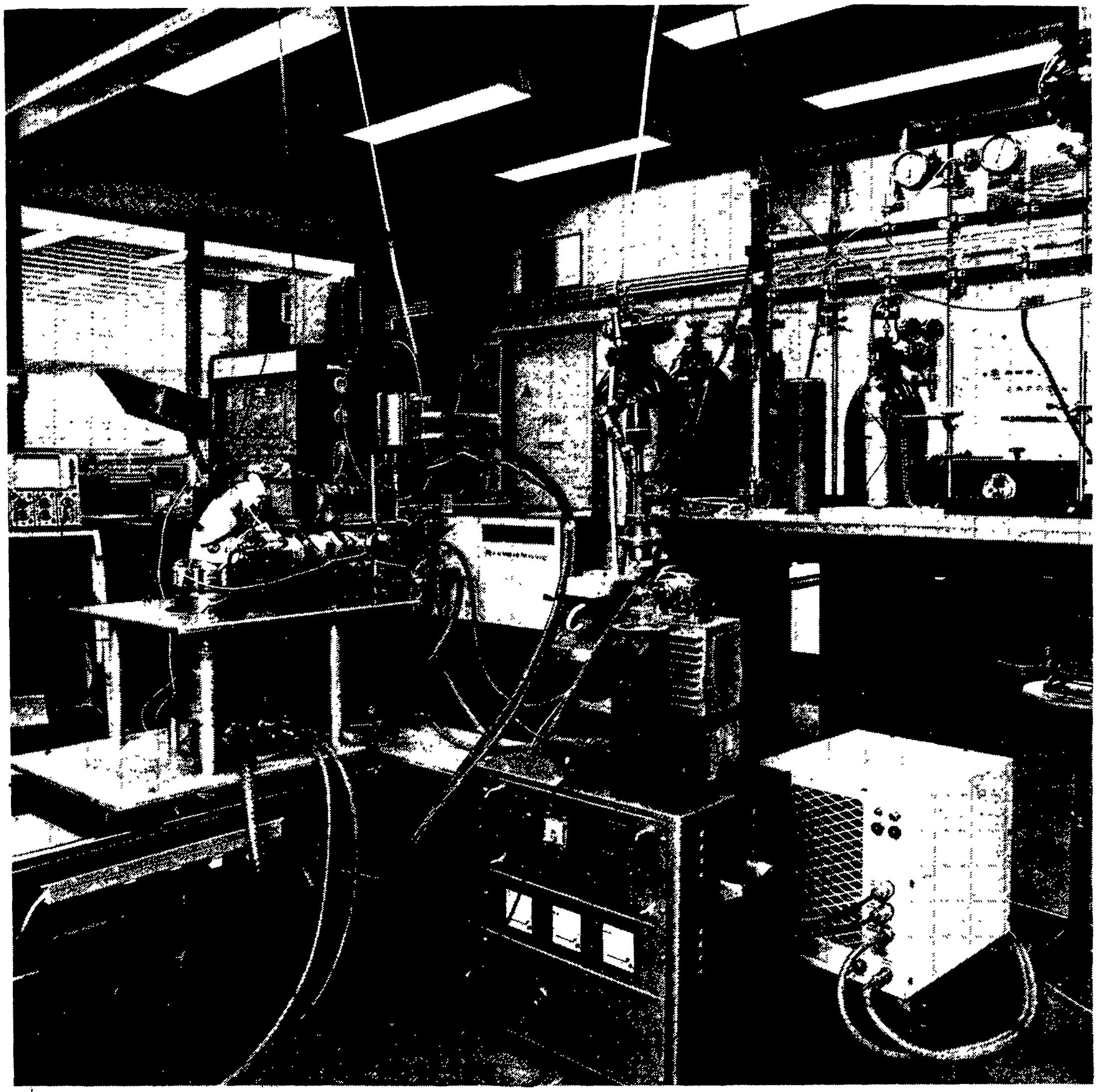


Fig. 11(a).

window were then used to photolyze the sample for 2 hr. The infrared spectrum was recorded. In Fig 12 is shown the absorption spectrum of the irradiated material with positive identification of the newly created radicals and molecules as listed in Table II. There are probably more complicated radicals and molecules but in insufficient number to have been readily detected.

When the irradiated sample was allowed to warm up there appeared a greenish-blue fluorescence which continued for some time at about 25 K. This fluorescence subsequently died down and upon continued heating another fluorescence appeared at about 30–35 K. The sample was then heated slowly to about 45 K at which time a flash of light appeared. This experiment has been performed four times with varying temperature histories of the post-irradiated samples. The samples were either cooled back to 10 K between fluorescence or allowed to warm up continuously to the 45 K. In each case the

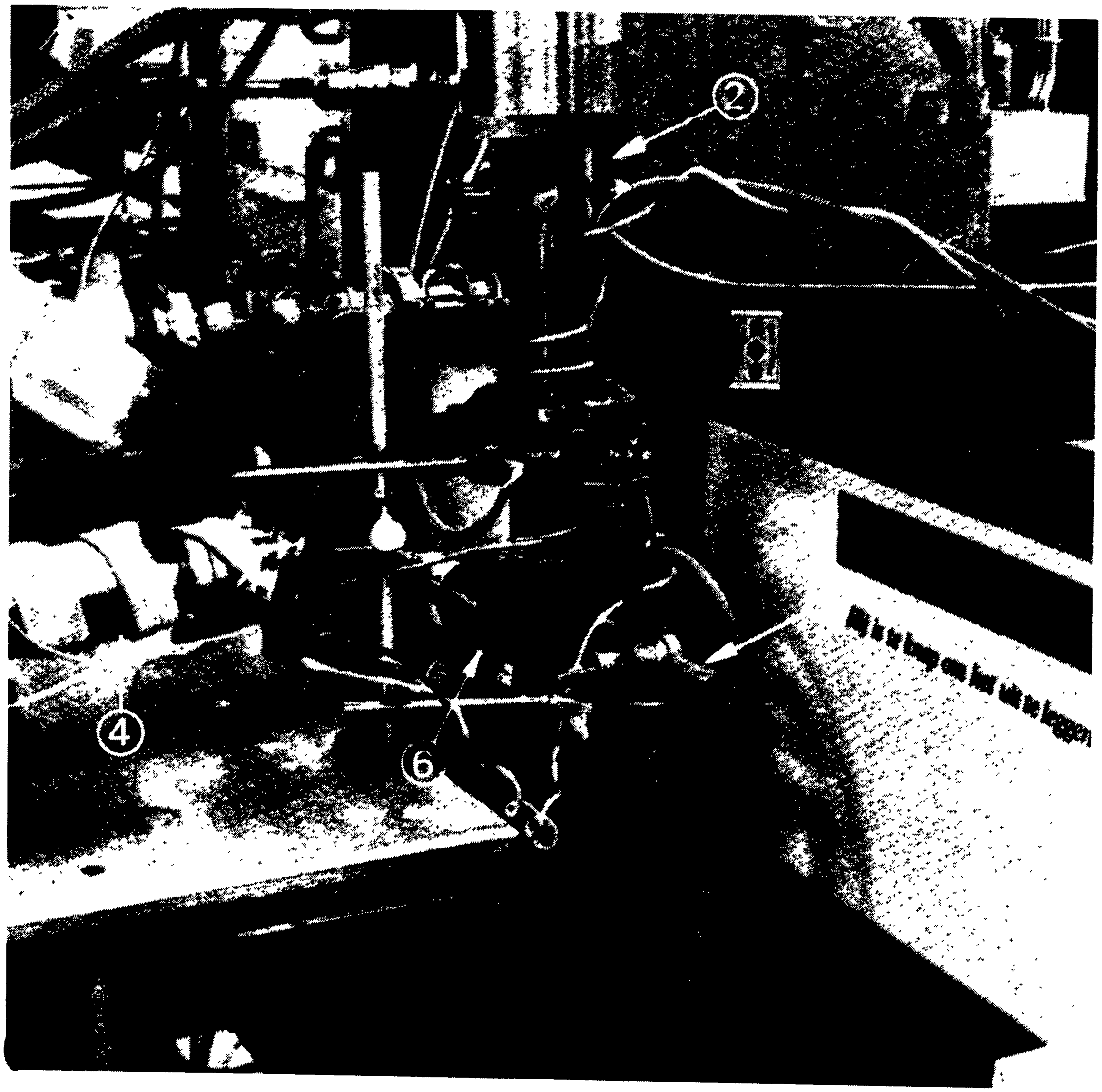


Fig. 11(b).

flash of light was accompanied by a sharp pressure rise. We believe this to be presumptive evidence of the kind of explosive process which can lead to large molecule formation and ejection into the interstellar medium by interstellar grains which are participating in the star formation process and which have been heated by the gas kinetic temperature or by grain-grain collisions in the contracting cloud or by a protostellar source of energy.

Should either the stored energy of the grains be too small or the chain reaction not go to completion the recombined radicals and molecules which remain within the grain will be of the larger or polymerized variety. Consequently the residual mantle on the dust will tend to be substantially more refractory than the classical ices consisting of the relatively volatile substances H_2O, CH_4 and NH_3.

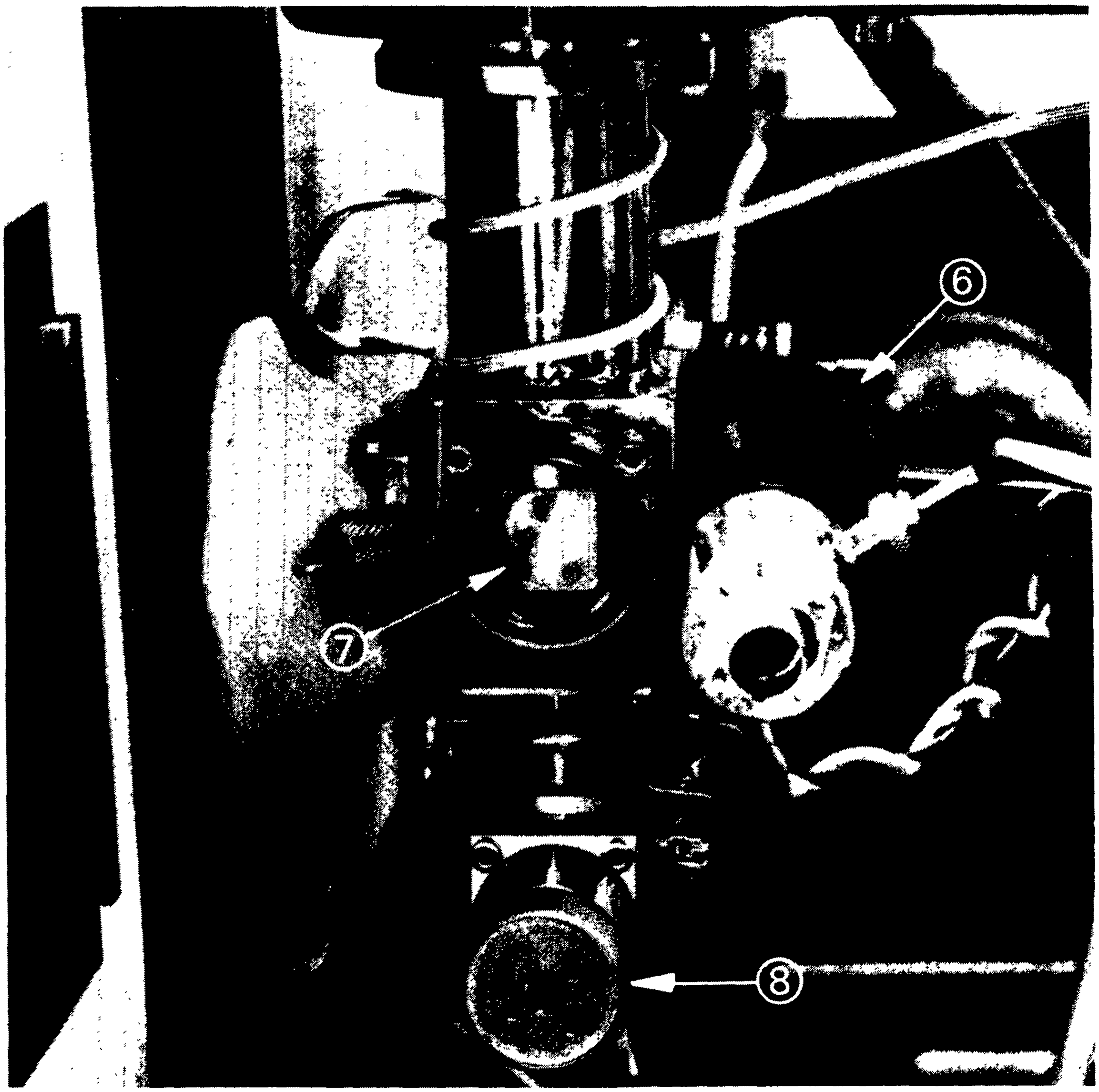


Fig. 11(c).

Fig. 11(a–c). The laboratory for study of effects of photoprocessing on analog interstellar ices. (1) Gas handling apparatus. (2) Closed cycle helium cryostat. (3) Ultraviolet light source. (4) Mass spectrometer. (5) Fourier Transform infrared spectrometer. (6) Photomultiplier for observing fluorescence. (7) Cold finger with solid film deposit. Note inference rings. (8) Inlet valve to mass spectrometer.

4. Evolution of Grains

(a) *Accretion and Maximum Size*

Clouds with densities $\geqslant 10^3 \text{cm}^{-3}$ whether dark or H II regions (not too close to the exciting star) have *observationally* implied larger than average dimensions for the classical sized particles. On the other hand, the extinction (wavelength dependence in the far ultraviolet) by the very small particles, appears to imply that their sizes (but not numbers) are relatively constant. The differences in the relative extinction contributions by the classical and bare particles in the far ultraviolet seems to be easily accounted for by a

TABLE II
Identified molecules and radicals in photolyzed sample of NH_3 + CO (1 ÷ 100) plus trace H_2O, CO_2

Molecule/Radical	Frequency (cm^{-1})
HCO (Formyl)	2488, 1860, 1090
NH_2	1499, (1506), (3213)
H_2CO (Formaldehyde)	2865, 2796, 1737, 1506, (1499)
HOCO	(1830)
CO_2	2348, 660
HNCO	2263, 815, 810 592
NCO	1963
$HCONH_2$	3529, 1726, (1265)

Unassigned new features
2040, 1890, 1876, 1855, 1794, 1719, 1506, 1199, 1105
(Milligan and Jacox, J. Chem, Phys. 1965, **43,** 4487; 1971, **54,** 927.)

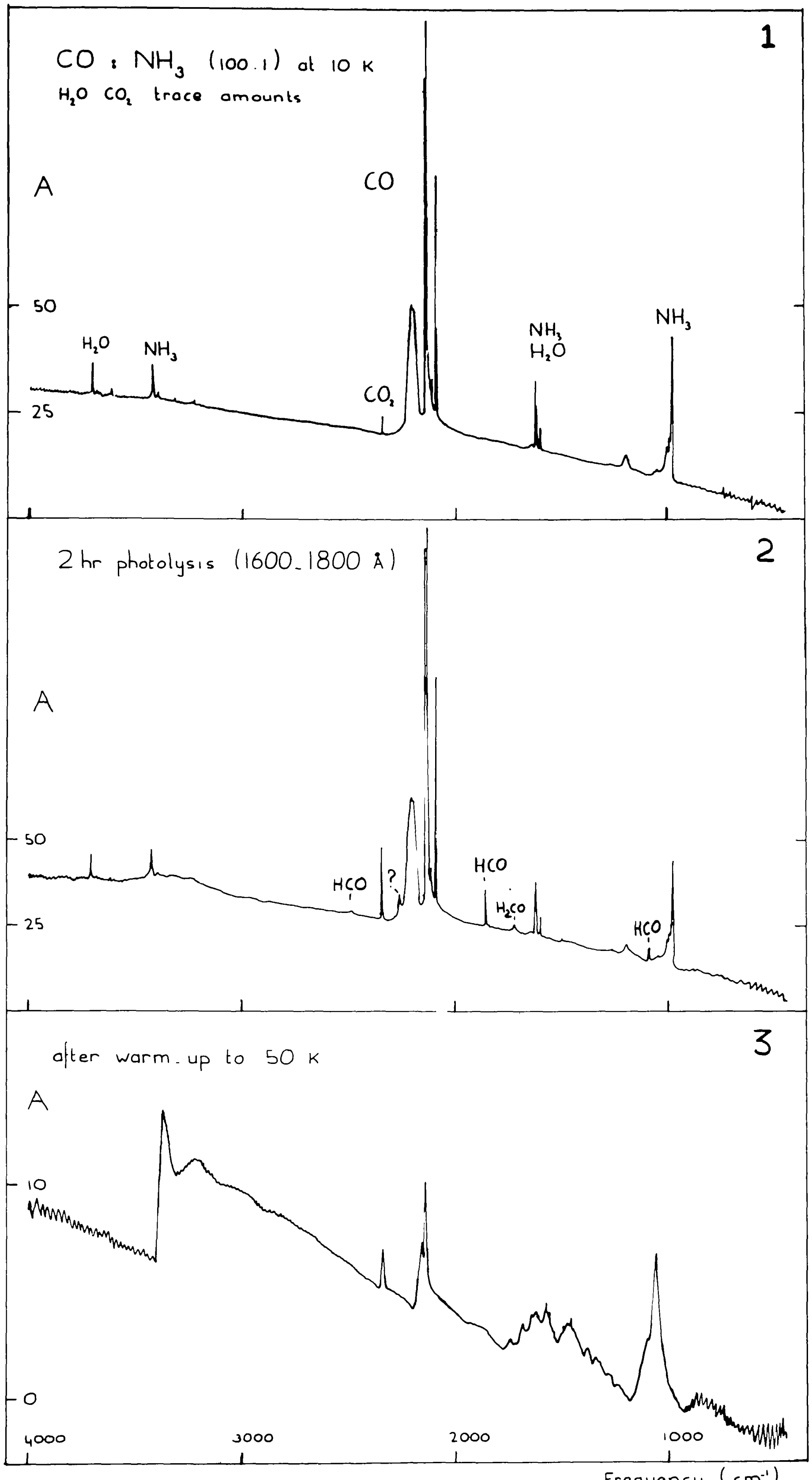
combination of varying sizes of the larger particles with relative separation of the bare particles due to the radiation pressure differential between the two in the presence of strongly ultraviolet emitting stars.

For example, θ' Orionis has a wavelength dependence of extinction which bends over at a longer wavelength than average (see Figure 1), thus implying larger than average classical sized particles. At the same time the far ultraviolet extinction is substantially reduced relative to the visual extinction. If the classical sized particles are only 1.5 times larger than average in front of θ' Orionis we can already account for a factor of ~ 2 in this ratio relative to the average. Suppose, in addition, the bare particles have been pushed outward from the star so that they fill a sphere of radius $R + \Delta R$ while the core-mantle particles occupy a sphere of radius R. (In addition to this separation we may expect that *both* classical sized and bare particles are excluded from a region close to the star but this small hole can be neglected in making the relative comparisons). Because of the relative redistribution of the bare particles and core-mantle particles, the line of sight number density ratio is changed from

$$\frac{n_b}{n_{cm}}\frac{R}{R} \quad \text{to} \quad \frac{n_b'}{n_{cm}}\frac{(R+\Delta R)-\Delta R}{R},$$

where

$$\frac{n_b'}{n_b} = \frac{R^3}{(R+\Delta R)^3-(\Delta R)^3},$$


CO : NH3 (100:1) at 10 K
H2O CO2 trace amounts
1
A
CO
50
25
H2O
NH3
CO2
NH3
H2O
NH3
2 hr photolysis (1600–1800 Å)
2
A
50
25
HCO
?
HCO
H2CO
HCO
after warm-up to 50 K
3
A
10
0
4000
3000
2000
1000
Frequency (cm-1)

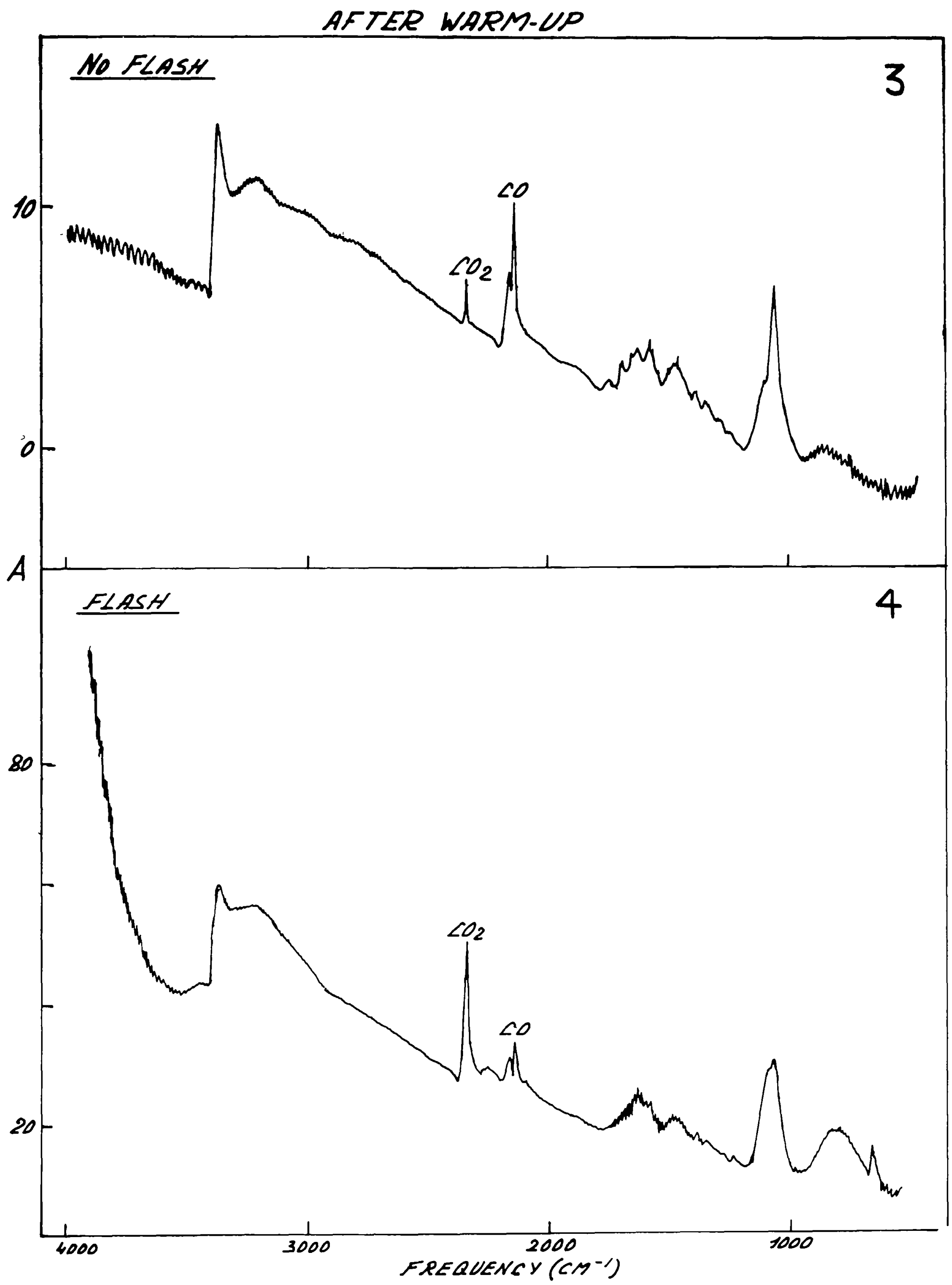


Fig. 12. Infrared absorption spectra of a mixture of NH_3 and CO deposited as a thin film on a cold (10 K) finger of a cryostat and subsequently irradiated by ultraviolet radiation from a hydrogen lamp. Uppermost spectrum is before irradiation. Second spectrum is result after 2 hr of photolysis (note new peaks appearing). Third spectrum is what remains after irradiation stopped and sample is warmed slowly to ~ 50 K (note disappearance of CO). Fourth spectrum for similar sample after flash.

Thus a shift of only 20% in $R(\Delta R/R = 0.20)$ produces an "effective" line-of-sight reduction in the number of bare particels by a factor of 1.7 (Greenberg and Hong, 1974). This factor combined with the factor due to larger classical particles can account for a reduction of the "apparent" UV extinction (as commonly normalized) by as much as 1/3.

In the ρ Oph cloud the visual extinction and polarization can be explained by grains whose size implies very close to total depletion of the available condensible atoms O, C and N. It is notable that the heavy atom depletion observed in σ Sco is greater than average, consistent with the fact that the grain mantles have to be thicker than average to produce the observed wavelength dependences of extinction and linear and circular polarization. At $T_d = 10\,\mathrm{K}$ the sticking coefficient for all atoms and molecules, including CO, which has a high vapor pressure above $T = 30\,\mathrm{K}$, should be very close to unity. Photodesorption on the classical particles is a minor effect because energy is readily absorbed in the bulk of the grain. The time scale for accretion of condensible species from a cloud (*not* the grain growth time) may be shown to be $\tau_{ac} < 2.6 \times 10^8/n_\mathrm{H}$ yr. By comparison the Jeans time (free fall) is $\tau_{ff} = 4 \times 10^7/n_\mathrm{H}^{1/2}$ yr which is already longer than τ_{ac} at a density $n_\mathrm{H} = 10^4\,\mathrm{cm}^{-3}$ (see Greenberg, 1977). The maximum mean mantle dimension consistent with cosmic abundance is $\bar{a}_m = 0.21\,\mu\mathrm{m}$.

On the bare particles, desorption by various mechanisms is growth limiting. When a photon is absorbed the absorption occurs either at the surface or within the grain. If the specific heat of the grain material is low (low concentration of imperfections) each photon induces a temperature spike to $T = 30$–$100\,\mathrm{K}$ which, in most regions, occurs much more frequently than the atom or molecule collision, thus preventing sticking. If there is a high concentration of impurities the specific heat is raised and the temperature spikes are damped. However, in this case, it may be shown that for very small particles with $a < 0.01\,\mu\mathrm{m}$ the number of surface imperfections equals the number of volume imperfections so that ultraviolet produced phonons are likely to be absorbed on the surface and shake off any existing physisorbed species (Greenberg, 1978c). A non-irradiative way of inhibiting growth on the very small particles is that the energy released when atoms or molecules combine on their surfaces is sufficient to detach the accreted material, whereas on the larger grains this energy is readily dissipated within the grain. The possibility that the very small particles are themselves pieces of mantle like material which has broken off of the core-mantle grains and are therefore chemically similar to the particles proposed by Platt (1956) and discussed more recently by Greenberg (1974), and by Adriesse and de Vries (1974) is not to be excluded. The observational evidence for lack of bare particle growth is rather good as can be seen from the following.

Let us suppose that, entering the phase of cloud condensation at $t = 0$, we have a bimodal size distribution consisting of (i) $0.05\,\mu\mathrm{m}$ silicate cores plus modified ice mantle particles characterised by $a_i = 0.20\,\mu\mathrm{m}$ ($\bar{a}_m = 0.12\,\mu\mathrm{m}$) and (ii) a large number (several thousand times the number of core-mantle particles) of bare silicate particles of radius $a_b = 0.005\,\mu\mathrm{m}$. Comparison with the observed average interstellar extinction shows that qualitatively this combination produces a good fit in the 0–3.5 $\mu\mathrm{m}^{-1}$ range and in the far ultraviolet $\lambda^{-1} \geqslant 6\,\mu\mathrm{m}^{-1}$ (ignoring the detailed structure which is, after all, dependent on

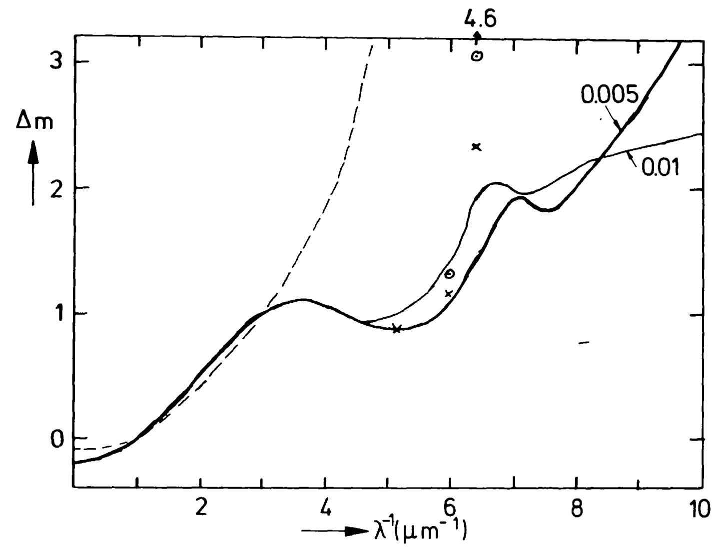


Fig. 13. The solid lines are normalised $\Delta m(3)-\Delta m(1) = 1$ theoretical extinction curves by the combinations of $a_c = 0.06\,\mu$m, $a_i = 0.20\,\mu$m core-mantle particle with either 0.005 or 0.01 μm bare particles at time $t = 0$. The number ratios of 0.005 and 0.01 μm bare particles to the core mantle particle are, respectively, 1500 and 300. The dashed curve is the combined extinction curve produced when the core mantle and 0.01 μm bare particles are at time $t = \tau$ corresponding to mantle increments of 0.02 μm. The crosses (X) and dotted circles (⊙) are for the combination of 0.005 μm bare and core mantle particles at $t = \tau/10$ and $t = \tau/4$, respectively. (From Greenberg and Hong, 1974).

the detailed optical properties of the material chosen). The region between $\lambda^{-1} = 4\,\mu\text{m}^{-1}$ and $\lambda^{-1} = 6\,\mu\text{m}^{-1}$ will probably be filled in by any irregularities in the surface of the core mantle particle (Greenberg *et al.*, 1971).

After some time $t = \tau$ in a dark cloud the grains have grown to larger sizes. If we were to let the core-mantle and the bare particles grow equally, we would very shortly reach a condition in which the far ultraviolet extinction would even more greatly exceed the visual extinction than in normal regions. For example, a mantle increase of only 0.002 μm increases the value of $\Delta m(8\,\mu\text{m}^{-1})$ by a factor of two relative to the visual. If this were to occur, the dark clouds would be exceedingly dark in the ultraviolet, but this does not appear to be the case. The time scale for a growth of 0.002 μm, assumed linear with time and for a constant hydrogen density of $n_\text{H} = 10^4\,\text{cm}^{-3}$, is about 2500 years, which is short compared with the lifetime of the cloud.

Once the cloud becomes so well shielded as to significantly reduce the ultraviolet photon flux, we might expect the bare particle mantle growth in the interior to increase very rapidly. This leads to increased shielding, because of the increased ultraviolet to visual extinction ratio, and produces a tremendous amplification of the normal shielding process.

The problem is clearly demonstrated in Figure 13 which shows that even such very small increments as 0.002 μm and 0.005 μm on the 0.005 μm bare particles drastically increases the ultraviolet extinction. This would make the cloud completely opaque to ultraviolet radiation, and consequently very cold. If the very small particles are ordinarily inhibited from accretion by temperature fluctuations from ultraviolet photon absorptions (Greenberg and Hong, 1974), the extreme reduction in ultraviolet radiation would lead to a rapid increase in the bare particle accretion processes, which would then lead to a run-away depletion of the interstellar condensible material on the bare particles at the expense of the core-mantle particles. This possibility may be checked by examining the wavelength dependence of extinction in very dark clouds, and the current evidence in the ρ Ophiuchi cloud (Carrasco *et al.,* 1973) indicates that this effect does not occur. Further, if both kinds of particles accrete at the same rate, the extra volume of condensed material on the core-mantle particles is, for Δa much less than a_m, proportional to $a_m^2 \Delta a$ and that on the bare particles is, for Δa much less than a_b, proportional to $a_b^2 \Delta a$. For $\bar{a}_m = 0.12\,\mu$m, $a_b = 0.005\,\mu$m and $n_b/n_{\bar{\text{cm}}} = 1500$, the ratio of extra volume on the bare particles to that on the core-mantle ones is 3.72 and approaches the limiting value 1500 as Δa increases. Therefore, if the bare particles should accrete at the same rate as the core-mantle particles, the bare particles will quickly use up most of the condensable material and leave little material available for the core-mantle particles. Hence, the core-mantle particles would never become large enough to produce the kind of extinction and polarization characteristic of larger than normal grains as observed in the dark clouds, eg. the ρ Opiuchi cloud.

The very small particles must therefore not be able to accrete material in dense clouds even when the cloud becomes opaque. One should not forget that the total accreted material in the gas is perhaps only a factor of five (Greenberg and Hong, 1974) greater than that which is already in the original mantles corresponding to $a_i = 0.20\,\mu$m. Therefore, the maximum effective grain mantle radius may increase from about $0.12\,\mu$m to only about $0.21\,\mu$m, no matter how long a time we allow; i.e. a total additional mantle growth of only $0.09\,\mu$m is permissible with the particular parameters chosen. It is not likely that any significant difference should be found between grain models of the same general core-mantle type considered here. If the grains grow to this maximum size, an extrapolation of the relation $\lambda_{p_{max}}^{-1} \bar{a}_m \simeq 0.26$ leads to the possibility that the wavelength at maximum polarization may be shifted at most to about 8000 Å, or possible a little higher. If observations of the maximum of *interstellar* polarization are found ever to be significantly greater than this value, it may be that the growth of grains in dense clouds should be re-investigated, or that we are seeing evidence of grain-grain coalescence.

Presuming the accretion of grains in dark clouds to follow the above path, we may anticipate that the grains in regions of new star formation will initially have mantle thickness greater than twice those of normal grains. Thus the fact that the wavelength dependence of both extinction and of polarization in the Trapezium region (Breger, 1974) indicates substantially larger than normal grains is not too surprising since the additional thickness required is substantially less than the maximum possible. However, the values are approaching the limiting value and indicate an almost complete depletion of the available heavy elements, in agreement with the suggestion in that paper. Thus we have indirect evidence that the starting point for grains in H II regions may indeed approach the limiting possibilities in size.

We are thus led to the following ranges and limitations for interstellar particles

classical sized
no mantles: $\bar{a}_m = a_c \simeq 0.05\,\mu : R \ll 3$
maximum mantles: $\bar{a}_m \simeq 0.21\,\mu : R > 3$

bare
$a_b \simeq 0.005\,\mu$ (if silicates or mantle pieces)
$a_b \simeq 0.02\,\mu$ (if graphite) (not discussed in detail here).

For $a_b \simeq 0.005\,\mu$ (silicates):

$$\frac{n_b}{n_{c-m}} \simeq 4000e: \text{average}; \quad \simeq 3000e: \text{near hot star} \qquad e = \text{elongation of classical particles}$$

with the proviso that the total cloud integrals

$$\int n_{c-m}\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z \sim \int n_b\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z$$

i.e. the *total* number of particles *relative* to each other is constant except, of course, *very* near hot stars where both core and bares may evaporate.

The cores and bare particles (of whatever type) are resistant to disruption except at temperatures > 1000 K. The mantle material of modified ices is substantially more refractory than simple ices. It is relatively resistant to sputtering because of larger sized molecules and has an evaporation temperature in the 300–400 K range rather than the 100 K for H_2O, CH_4, NH_3 type ices

(b) *Steady State Interstellar Particle Size Distribution*

The striking degree of uniformity in extinction and polarization curves is a strong indication that the dust particles have generally reached a steady state in their average size distribution. More than 30 years ago Oort and van de Hulst (1946) derived a distribution by following a model for growth and destruction processes. Greenberg (1966) derived a size distribution of the form exp $(-\alpha^3 a^3)$ which results from a simple area dependent particle destruction process. This distribution was used for a large variety of calculations (see, for example, Greenberg 1968) but its justification in terms of observations has only recently been semi-quantitatively substantiated (Hong and Greenberg, 1978). It has been shown empirically that among a variety of one parameter size distributions, a distribution with characteristics similar to $\exp(-\alpha^3 a^3)$ best yields the most commonly observed combination of the key features of the interstellar extinction and polarization; namely, the ratio of total to selective extinction, $R = A(V)/E(B-V) \simeq 3$ and the maximum polarization wavelength, $\lambda_{\max} \simeq 5500$ Å.

Consider the following four types of size distributions:

$$\text{exponential}; n(a) \propto \exp(-\alpha a), \qquad (16a)$$

$$\text{Gaussian}; n(a) \propto \exp(-\alpha^2 a^2), \qquad (61b)$$

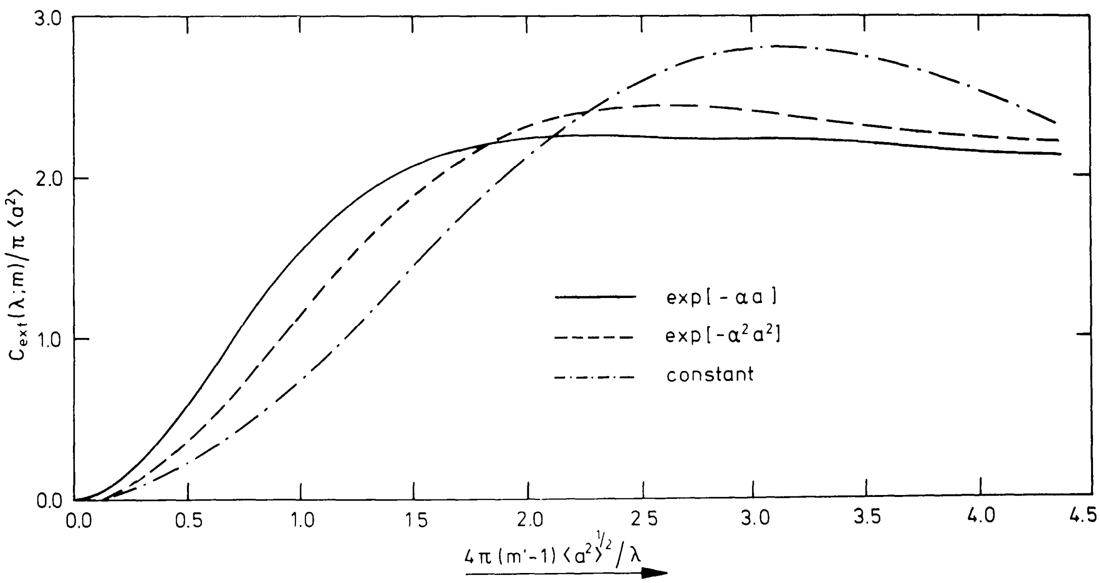


Fig. 14. Extinction curves for three different size distributions.

$$\text{constant}; n(a) = \text{constant for } \alpha a \leqslant 1$$

$$= 0 \qquad \alpha a > 1 \tag{16c}$$

$$\text{single size}; n(a) = \delta(a - a_0). \tag{16d}$$

The first three of these constitute a family of successively flatter distributions with sharper cut-offs and for each there exists a physical basis depending on the nature of the grain destruction probability function (Greenberg, 1968).

The wavelength dependence of extinction resulting from an ensemble of particles is

$$C_{\text{ext}}(\lambda; m) = \int 4\pi a^2 n(a) C_{\text{ext}}(\lambda, a; m) da, \tag{17}$$

where m is a given index of refraction.

For analytical convenience we may represent the essential aspects of the extinction cross-section for dielectric spheres by the eikonal approximation (van de Hulst, 1957, 1946; Montroll and Greenberg, 1954)

$$C_{\text{ext}}(\lambda, a; m) = 4\pi a^2 Re\{\tfrac{1}{2} + (i\eta)^{-1}\exp(-i\eta) + (i\eta)^{-2}[\exp(i\eta - 1)]\} \tag{18}$$

where $\eta = 4\pi a(m-1)/\lambda$ is a dimensionless parameter characterizing the particle size in terms of the phase shift experienced by a ray passing through the center of the particle. In the following, m will be assumed to be pure (or almost pure) real (no absorption). From the average geometrical cross section of the particles, $\pi\langle a^2\rangle$, we define a mean particle size by $\bar{\eta} = 4\pi(m-1)(\langle a^2\rangle)^{1/2}/\lambda$ which is different for each kind of distribution. The extinction curves resulting from inserting Equation (18) into Equation (17) for each size distribution in Equations (16a–16d) are shown in Figure 14 as normalized to the geometrical cross section.

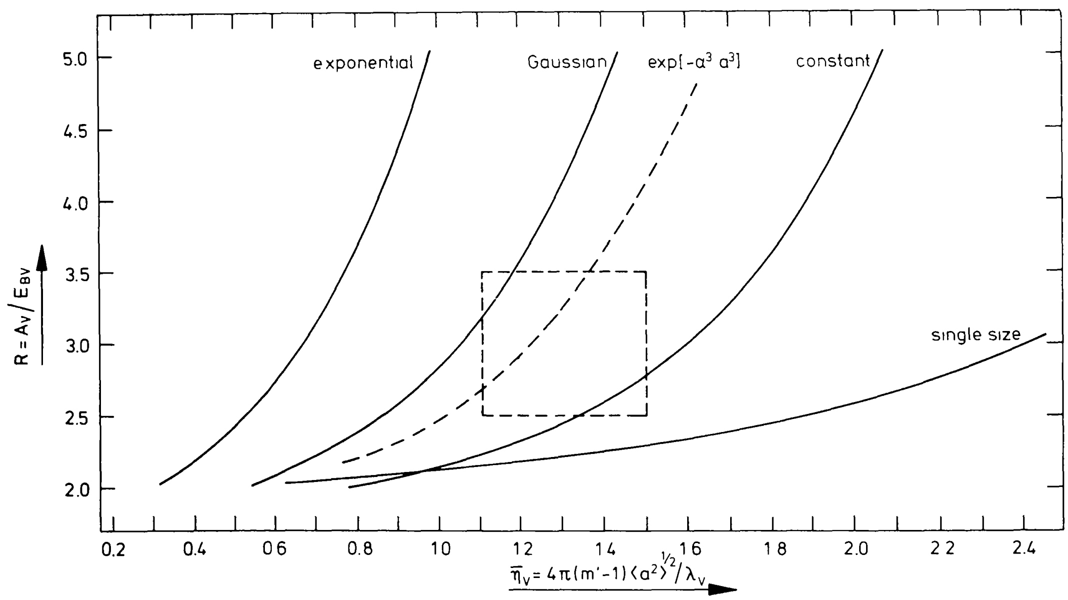


Fig. 15. Total to selective extinction ratio is shown as a function of $\hat{\eta}_V = 4\pi(m-1)\sqrt{\langle a^2\rangle}/\lambda_V$ for various size distributions. The rectangular box represents the average interstellar medium.

For each of the curves in Figure 14 we find the ratio of total to selective extinction from

$$R = A(V)/E(B-V) = Q_{\text{ext}}(\bar{\eta}_V)/[Q_{\text{ext}}(\bar{\eta}_B) - Q_{\text{ext}}(\bar{\eta}_V)] \tag{19}$$

In Figure 15 we see how the value of R is a different function of $\bar{\eta}$ for each size distribution. However, any size distribution may be made acceptable by an appropriate selection of the mean size. Thus, from consideration of R (extinction) alone, it is impossible to select a best size distribution as was already noted by van de Hulst (1949) and Shah (1966).

Just as R describes the shape of the extinction curve, the wavelength at maximum polarization, λ_{max}, characterizes the polarization for a given star (Serkowski, 1973). Serkowski, Mathewson and Ford (1975; also see the review by Coyne, 1974) give 0.545 μm as the median value of λ_{max} from observations of about 350 stars. They also note a good correlation between λ_{max} and R. Considering only average grain characteristics, a size distribution is considered acceptable by requiring that $R \simeq 3$ and $\lambda_{\text{max}} \simeq$ 0.545 result from the same mean particle size.

The polarization efficiency factor, $Q_{\text{POL}} = \bar{Q}^E_{\text{ext}} - \bar{Q}^H_{\text{ext}}$, is plotted in Figure 9(b) for perfectly aligned spinning infinite cylinders of which the real part of the index of refraction is $m' = 1.33$. For the case of $m'' = 0.005$ the maximum polarization occurs at $x = 1.9$. The assumption of small but finite value for m'' is consistent with the albedo being less than 1 (Lillie and Witt, 1973; van de Hulst and de Jong, 1969) in the visible portion of the spectrum. Thus, the observed maximum polarization wavelength $\lambda_{\text{max}}(\simeq \lambda_V)$ and $x_{\text{max}} \simeq 1.9$ correspond to $\eta_V \simeq 1.3$ for an absorbing "ice type" material.

Contributions by smaller particles in a given size distribution are relatively more important to the polarization than to the extinction (see for example Figure 85 in Greenberg, 1968). In other words for a given size distribution the mean size averaged over extinction efficiency, $\langle a^2 n(a) Q_{\text{ext}}(a)\rangle / \langle n(a) Q_{\text{ext}}(a)\rangle$, is generally larger than the mean size averaged over polarization, $\langle a^2 n(a) Q_{\text{POL}}(a)\rangle / \langle n(a) Q_{\text{POL}}(a)\rangle$. A consequence of this is that the value of $\bar{\eta}_V$ corresponding to $x_{\max}$ for an extended size distribution will be somewhat larger than the value 1.3 derived for a single particle size.

On the other hand, the maximum polarization is shifted toward smaller x values as the alignment axis is tilted from being perpendicular to the line of sight. Wobbling of interstellar grains due to incomplete alignment in interstellar space also produces this effect, even when the mean alignment axis is perpendicular to the line of sight. In general, then, $x_{\max}$ for partially aligned particles is slightly smaller than that for perfectly aligned particles. This effect compensates in part for the increase in $\bar{\eta}_V$ due to the use of a distribution of sizes rather than a single size.

In order to allow for all possible uncertainties in the effects of grain optical properties and size distributions the polarization maximum criterion is described loosely by

$$1.1 \leqslant \eta_V \leqslant 1.5. \tag{20}$$

For similar reasons the theoretical value of R is allowed to be in the range $2.5 \leqslant R \leqslant 3.5$. An acceptable size distribution of interstellar grains should be such that it pass through the rectangular box marked on the R vs $\bar{\eta}_V$ diagram (Figure 15). We see that this condition – as broad as it is – leads to the conclusion that the interstellar particle size distribution is fairly flat with a limiting cut-off faster than that given by a Gaussian distribution. The dashed curve in Figure 15 resulting from a numberical integration of Equation (17) for the $\exp[-\alpha^3 a^3]$ distribution, falls well within the limit rectangle.

Since the $\exp[-\alpha^3 a^3]$ distribution is clearly favoured it is useful to recall its physical justification even though it may not be completely realistic. The differential equation for grain growth and destruction is

$$\dot{a}\frac{dn(a)}{da} + D(a)n(a) = 0, \tag{21}$$

where $n(a)da$ is the number of particles between radius a and $a + da$, $\dot{a}$ is the rate of growth (assumed constant) by accretion of mostly C, N and O atoms and molecules from the interstellar medium, and $D(a)$ is the probability per unit time that a particle of size a is destroyed. With the assumption that $D(a)$ is proportional to the grain area, $D(a) = Ka^2$, we obtain the solution

$$n(a) = n_0 \exp(-\alpha^3 a^3),$$

where $\alpha^3 = K/3\dot{a}$.

Many destructive processes, including grain destruction in cloud collisions, can proceed with a probability proportional to a^2. Various estimates (see the recent review by Salpeter, 1977; Oort and van de Hulst, 1946; and Greenberg, 1968) of time-scales involved in collisional destruction indicate that these are short enough for interstellar grains to attain a steady state size distribution.

The value of α^3 implied by our standard core-mantle model (Equations (5) and (6)) is $\alpha^3 = 5/(0.2)^3 = 625\,\mu\text{m}^{-3}$. Combining this with the time average value of $\dot{a}$ (Equation (8) with n_H replaced by $\langle n_H \rangle$ and $T = 100\,\text{K}$) one obtains $K = 3\dot{a}\alpha^3 = 2 \times 10^{-7} \langle n_H \rangle$. The destruction probability per unit time for the mantle of a grain with radius $a = 0.2\,\mu\text{m}$ is then $D = Ka^2 = 0.08 \langle n_H \rangle$ per 10^7 yr. If we use a mean hydrogen density of $1\,\text{cm}^{-3}$, which is consistent with the mean hydrogen density in the galaxy, we find that about one grain in ten loses its mantle each 10^7 yr. A more detailed treatment of this problem taking grain-grain collisions in the final stages of cloud contraction into account is in progress. The idea being developed is that collisions at velocities of the order of $0.1\,\text{km s}^{-1}$ (greater than 100 times Brownian motion grain velocities) are sufficient to bring the grains up to a temperature $T_d \sim 50\,\text{K}$ at which chemical chain reactions have been detected in the laboratory. The sources of such velocities in regions of new star formation could be turbulence, radiation pressure or ambipolar diffusion.

(c) *Total Destruction of Core-Mantle Grains*

It may be presumed that all of those grains which finally become part of a new star must have been totally evaporated. This sets a lower limit on the total destruction rate because at least some of those grains which are near to the new star after it formed will also be evaporated. An estimate of this core loss rate depends on the star formation rate.

Let us assume that approximately 1/50 of the interstellar medium in the solar neighbourhood is processed into the new stars each 10^8 yr (Oort, 1974). Thus the *current* loss rate for silicate cores is such that, barring replenishment, they would all be lost in 5×10^9 yr. In order to have a steady state density for the silicate cores we would have to resupply them at this same rate. One obvious source is via mass loss from cool stars (see Donn, 1978; also see Salpeter 1977), since it is from such stars that we may expect solid particles to be substantial portions of the ejected material consisting of Si, Mg, Fe. Thus, of the total mass returned by stars to the interstellar medium one should perhaps look only at that observed from *M* stars which are seen to contain silicate dust (seen from infrared excess at $\sim 10\,\mu\text{m}$). The very difficult problem is to fold in the mass loss per star with the local number density of such stars. *If* we let there be $\sim 10^{-5}$ such stars per pc^3 and let each such star lose $\sim 10^{-8} M_\odot\,\text{yr}^{-1}$ we arrive at a value of the order of $dM/dt \sim 2.5 \times 10^{-3} M_\odot\,\text{pc}^{-3}\,\text{yr}^{-1}$ given by Pottasch (1970). Using this value we may show that, for the assumption that all the metallic atoms form solid particles, the rate of formation of silicate cores is 1/10 the rate of destruction; i.e. the current replenishment rate requires a time of 5×10^{10} yr to resupply the cores (Greenberg, 1978b). Although this tells us that the cores are presently diminishing in number, there are enough uncertainties in either the star formation rate or the solid particle mass loss rate to reverse this conclusion. It is my feeling that the latter is more susceptible to change. One reasonable way of increasing the "effective" core production rate is to assume that the galactic thickness distribution of *M* stars is greater by a factor of about 10 than that of the dust (which is a disk population material) and that the solid ejecta from the *M* stars are brought down by some means (gravitation) to the plane in times less than $\sim 10^9$ yr.

5. Summary

There are both observational and theoretical grounds for indicating the variability of interstellar dust. Its concentration variations are clear from photographs of our own and other galaxies. The physical environment of dust varies from the cold (20 K) dark clouds with little penetrating radiation to the 10,000K H II regions around hot young stars with high fluxes of ultraviolet radiation. And between the time of collapse of the dark clouds and the coming into existence of the H II region there is the birth of stars out of the gas and dust of the interstellar medium. Not all of the stars formed are the hot ones but all of them are mixtures of gas and dust. The conclusion one is led to from the apparent fact that the dust before and after star birth has very similar characteristics is that most of it follows a continuous sequence between the before and after stage. This has been the basis for arriving at a description of the pre-stellar dust on which the limiting criteria are developed out of evolution from average dust properties.

A simple picture emerges of two populations of dust grains: (1) core-mantle grains and (2) very small bare particles. The cores are presumed to be a silicate (unidentified, and possibly a mixture of oxides of Mg, Si and Fe) of size $\sim 0.05\ \mu$m. The mantles consist of a size distribution of accreted thicknesses of O, C, N molecules and radicals which have been photoprocessed and an outer layer of molecules (mostly CO) and other species accreted in the later stages ($n_H \gtrsim 10^5\ cm^{-3}$) of cloud contraction. Most of the mantles must contain stored energy, some with perhaps enough to blow off the mantle if sufficiently disturbed. The maximum *mean* size of the core particles is $\sim 0.21\ \mu$m. The bare particles have not been positively identified yet. But if they have classical scattering properties and are $\sim 0.005\ \mu$m in size, they outnumber the core-mantle particles by $\sim$ 3000–4000. The remaining hydrogen in the cloud, assuming no relative separation of gas and dust has taken place, is $\sim 10^{12}$ more abundant than the core-mantle grains.

It is interesting to speculate on the nature of cometary material if it accretes directly out of the dust. The bulk of the comet chemical composition would then consist of the mantle material of the core-mantle particles which is made of molecules and radicals with a range of complexity containing various combinations of oxygen, carbon and nitrogen. Embedded in this matrix are the cores (silicate) and the very small bare particles each with a total relative volume of the order of 1/50. The stored radicals in the cometary matrix material could provide the source of energy needed for the eruptions which have been known to occur as comets are warmed up in approaching the Sun.

Acknowledgements

I thank L.J. Allamandola and W. Hagen for checking and discussing the section on the laboratory experiments, and C. van de Bult for helping prepare some figures and tables.

I also would like to thank C. Norman for some helpful discussions and S. S. Hong for his various contributions to this paper.

References

Allamandola, J. L. and Norman, C. A.: 1978, *Astron. Astrophys.* **63**, L23.

Andriesse, C. D. and de Vries, J., 1974. *Astron. Astrophys.* **30**, 51.

Bless, R. C. and Savage, B. D.: 1972, *Astrophys. J.* **171**, 293–308.

Breger, M., 1974.: in *Planets, Stars and Nebulae studied with Photopolarimetry*, Ed. by T. Gehrels, The Univ. of Arizona Press, Tucson, Arizona, p. 946.

Calvert, J. G. and Pitts, J. N., Jr.: 1966, *Photochemistry*, John Wiley and Sons.

Carrasco, L., Strom, S. E., and Strom, K. M.: 1973, *Astrophys. J.* **182**, 95.

Coyne, G. V., 1974.: in *Planets, Stars and Nebulae studied with Photopolarimetory, Ed. by T. Gehrels,* The University of Arizona Press, Tucson, Arizona, p. 895.

Donn, B.: 1978, in *Protostars and Planets,* T. Gehrels Ed., The Univ. of Arizona Press, Tucson, Arizona.

Greenberg, J. M.: 1966, in Proc of IAU Symp. No. 24: *Spectral Classification and Multicolor Photometry,* Eds. K. Lodén, L. O. Lodén and U. Sinnerstadt, p. 291.

Greenberg, J. M.: 1968, *Stars and Stellar Systems,* 7, Chapter 6, Eds. Barbara M. Middlehurst and Lawrence H. Aller (Univ. of Chicago Press), p. 221.

Greenberg, J. M. and Meltzer, A. S.: 1960, *Astrophys. J.* **132**, 667.

Greenberg, J. M., Wang, R. T., and Bangs, L.: 1971, *Nature Phys. Sci.* **230**, 110.

Greenberg, J. M., Yencha, A. J., Corbett, J. W., and Frisch, H. L.: 1972, Mémoires de la Societé Royale des Sciences de Liège, 63 série, tome III, pp. 425–436.

Greenberg, J. M.: 1974, Astrophys. J. Lett. 189, L81.

Greenberg, J. M. and Hong, S. S.: 1974, *H II Regions and the Galatic Center.* Eslab. Symp. No. 8, Frascati, Ed. A. F. Moorwood, ESRO SP-105, p. 153.

Greenberg, J. M. and Hong, S. S.: 1975, *The Dusty Universe*, Eds. G. B. Field and A. G. W. Cameron (N. Watson Academic Publications), p. 132.

Greenberg, J. M.: 1976, *Astrophys. Space Sci.* **39**, 9.

Greenberg, J. H.: 1977, "Comets, Asteroids, Meteorites", Ed. A. H. Delsemme, (Univ. of Toledo), 491.

Greenberg, J. M.: 1978b, *Cosmic Dust,* Chapter 4, Ed. by A. J. M. McDonnel (Wiley, London), p. 187.

Greenberg, J. M.: 1978c, Paper presented at Liège Astrophysical Symposium on Small Molecules, June, 1977.

Habing, H. J.: 1968, *Bull. Astron. Inst. Neth.* **19**, 421.

Hong, S. S.: 1975, *Unified Model of Interstellar Grains,* Ph.D. Thesis, State Univ. of New York at Albany.

Hong, S. S. and Greenberg, J. M.: 1978, *Astron. Astrophys.* in press.

van de Hulst, H. C.: 1946, *Rech. Astr. Obs. Utrecht* **11**, part 1.

van de Hulst, H. C.: 1949, *Rech. Astr. Obs. Utrecht* **11**, part 2.

van de Hulst, H. C.: 1957, *Light Scattering by Small Particles* (New York: Wiley).

van de Hulst, H. C. and de Jong, T.: 1969, *Physica* **41**, 151.

Jackson, J. L.: 1959a, *J. Chem. Phys.* **31**, 154.

Jackson, J. L.: 1959b, *J. Chem. Phys.* **31**, 722.

Kittel, C.: 1956, *Introduction to Solid State Physics,* John Wiley and Sons, New York.

Lillie, C. F. and Witt, A. N,: 1973, in Proc. of IAU Symp. No. 52: *Interstellar Dust and Related Topics,* Eds. J. M. Greenberg and H. C. van de Hulst (Dordrecht: Reidel), p. 115.

Martin, P.: 1974, *Astrophys. J.* **187**, 461.

Milligan, D. E. and Jacox, M. E.: 1965, *J. Chem. Phys.* **43**, 4487.

Milligan, D. E. and Jacox, M. E.: 1971, *J. Chem. Phys.* **54**, 927.

Montroll, E. W. and Greenberg, J. M.: 1954, *Proc. Symposia Applied Math., Ann. Math. Soc.* **5**, 103.

Morton, D. C.: 1974, *Astrophys. J.* **193**, L35.

Oort, J. H.: 1974, *Recent Radio Studies of Bright Galaxies,* IAU Symp. No. 58. Ed. by J. R. Shakeshaft, 375.

Oort, H. H. and van de Hulst, H. C.: 1946, *B.A.N.* **10**, 187.

Pottasch, S. R.: 1970, *Interstellar Gas Dynamics*, Proc. IAU Symp. No. 39, Ed. by H. J. Habing (Dordrecht: Reidel), p. 272.

Platt, J. R.: 1956, *Astrophys. J.* **123**, 486.

Salpeter, E. E.: 1977, *Ann. Rev. Astron. Astrophys.* **15**, 267.

Serkowski, K., Gehrels, T., and Wiśniewski, W.: 1969, *Astron. J.* **74**, 89.

Serkowski, K.: 1978, in Proc of IAU Symp. No. 52: *Interstellar Dust and Related Topics*, Eds. J. M. Greenberg and H. C. van de Hulst (Dordrecht: Reidel), p. 145.

Serkowski, K., Mathewson, D. S., and Ford, V. L.: 1975, *Astrophys. J.* **196**, 261.

Shah, G. A.: 1966, Ph.D. Theses, R.P.I.

Stickney, R. E.: 1970, *Rarefied Gas Dynamics*, Supp. 3, v. 2 (Academic Press, New York), p. 468.