SOME ASPECTS OF INTERSTELLAR GRAINS

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INTRODUCTION:

The observations of extinction and polarization during the past few decades and recent far infrared absorption and emission features from some astronomical objects have firmly established the importance of the interstellar dust grains. They can influence the stellar, galactic and intergalactic distance scale if their effects of dimming starlight are not taken into account. They are important in making appropriate correction to the observed magnitudes of the stars so as to derive intrinsic luminosities of the stars. They can considerably change the spectral energy distribution of the stars and without due corrections the spectral class and type assigned to some stars may be misleading. They are also thought to play an important role in the evolution of the stars—especially in the early stage of evolution. The origin and formation of the Solar System has intimate connection to the processes of condensation of solid grains from interstellar cloud containing ionized as well as neutral gas. The grains occur in interplanetary space too. This is revealed by the study of zodiacal light produced by scattering of sunlight by electrons and/or grains. The grains are also associated with comets, meteorites, planetary and circumstellar atmospheres and cosmology. Krishna Swamy (1974) has discussed some advances in our knowledge of interstellar matter in an earlier article in this Bulletin. We wish to make special references to the review articles by Aannestad and Purcell (1973) on interstellar grains and Stein (1975) on recent revelations of infrared astronomy. Here we shall consider some selected items on grains.

HIGHLIGHTS OF OBSERVATIONS:

Since the pioneering work of Trumpler (1930), Stebbins and Whitford (1943, 1945) and Whiteoak (1966), efforts have mainly been directed to the observations of visual extinction and polarization of starlight and recently, of the infrared and ultraviolet continua, from various celestial objects. The observations from space-borne equipments started with the rocket experiments by Boggess and Borgmann (1964) and by Stecher (1965, 1969). More recently, the satellite observations in the far UV wavelength region (Bless and Savage 1972; Nandy et al. 1975) are further important contributions. The interstellar linear polarization was purely an accidental discovery (Hall 1949, 1958; Hiltner 1949, 1956 a, b). The observations including its wavelength dependence so far are mainly from the ground based astronomy (Gehrels 1960, 1973, 1974; Coyne and Gehrels 1967; Mathewson and Ford 1970; Serkowski, Gehrels and Wisniewski 1969; Klare et al. 1972; Coyne, Gehrels and Serkowski 1974; Serkowski, Mathewson and Ford 1975). Recently Martin et al. (1972), following prediction by van de Hulst (1957), have also reported interstellar circular polarization in the direction of the Crab nebula.

(a) **Extinction**: —The current picture of extinction is based on many observations (see, for example, Johnson 1968; Stecher 1965; Bless and Savage 1972; York et al. 1973; Peytremann and Davis 1974; Nandy et al. 1975).

The average extinction curve is shown in Figure 1. It can be conveniently divided into four parts; (I) IR region, $\lambda \gtrsim 1\,\mu$ (II) visual region, $1\,\mu \gtrsim \lambda \gtrsim 0.333\mu$ (III) UV region $0.333\,\mu \gtrsim \lambda \gtrsim 0{\cdot}166\,\mu$ and (IV) Far UV region $\lambda < 0.166\mu$.

In region I, the infrared extinction is small and varies from star to star. The region II, the classical visual extinction, shows very nearly λ^{-1} dependence. There is suspected knee or kink at $\lambda^{-1} \backsim 2.3\mu^{-1}$. The knee may be real and may be caused by the broad band absorption wings of the unidentified diffuse bands at 4430Å (Herbig 1966; Walker 1966). However, Harris (1969) obtained high resolution observations which show λ4430 band and the knee as separate features. A distribution of grain sizes has been discussed by Hayes et al. (1973) to explain the knee. The question of existence and origin of the knee remains unanswered so far.

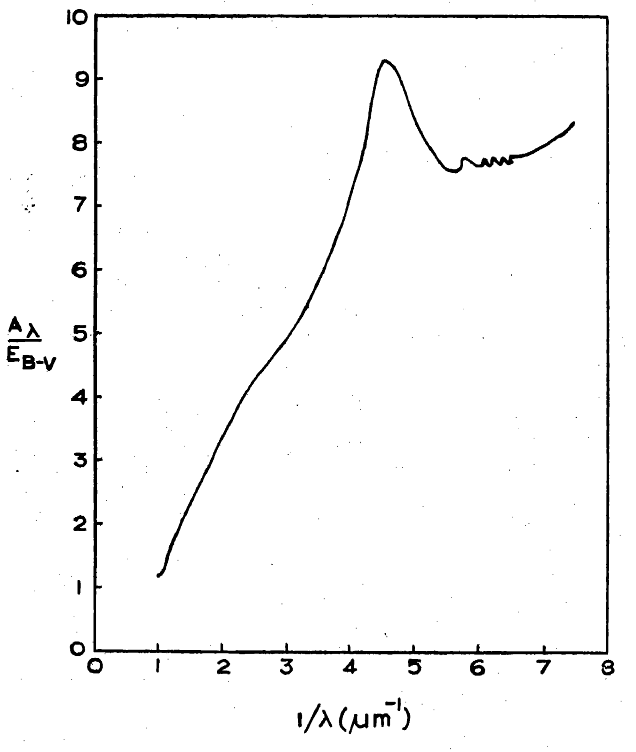

Fig. 1 The mean interstellar extinction per unit (B-V) colour excess plotted from Table 3 of Nandy et al. (1975). The mean equivalent width of the band at $\lambda \simeq 2180$Å is 130Å per Kpc.

In region III, the noteworthy feature is the extinction hump at $\lambda^{-1} \simeq 4.6\ \mu^{-1}$ (2175Å). The height and position of the peak within the hump may vary slightly from star to star. The most plausible explanation for hump is the extinction caused by small graphite grains.

The far UV extinction in region IV immediately after the hump, continues to dip with a shallow minimum in the wavelength range $5.5\mu^{-1}$ to $7.5\mu^{-1}$ The minimum value appears to shift towards the shorter wavelength side for stars with smaller extinction. Around $\lambda^{-1} = 7\mu^{-1}$ the extinction again rises with conspicuous sharp gradient and there is no hope of its declining very soon even after $10\mu^{-1}$. Curiously, as shown by Savage (1972), whenever the hump for certain stars is detectable, the difference in extinction at $\lambda = 2175$Å and 3500Å is empirically correlated with the usual visual colour excess E(B-V) by the relation E(2175-3500) $\simeq$ 5E(B-V). The absence of such correlation with the hump may be taken to mean that differnt types of grains with regard to size and/or composition may be involved in producing the extinction in the visual and far UV regions. The far UV observations (Nandy et al. 1975) obtained from the TD1 satellite have revealed that the mean extinction curve derived individually for three widely separated galactic regions do not show longitude dependence. The absorption band, the hump near λ 2200, has been found to be well correlated with the visual colour excess E(B-V) and the equivalent width per Kpc is 130Å ± 10Å. Nandy et al. conclude that separate sets of species of interstellar grains are responsible for the general extinction and the λ 2200 hump.

(b) Infrared Observations:— Some of the differences in the extinction in the IR may reflect the intrinsic properties of the stars. They may also be caused by the material in the circumstellar envelopes through either emission or absorption. The much sought for absorption band at$\sim$3.1μ due to interstellar ice grains was reported by Danielson et al. (1965) and Knacke et al. (1969 a, b) by obtaining spectra of highly reddened supergiant stars. Their conclusion speaks of the presence of interstellar ice dust not more than about 10 percent. This may be an underestimate if the circumstellar grains also cause part of the observed extinction. Hence further detailed observations, especially for stars with moderate reddening are necessary. Gillett and Forrest (1973) have obtained the IR absorption spectrum of the Becklin-Neugebauer star in the Orion constellation. This starlight suffers visual extinction in excess of 70 magnitudes. The Becklin-Neugebauer star, like NML Cygni, shows a prominent absorption band at 3.1μ due to ice. There is an absorption feature in the wavelength region 8 to 12μ. Such a feature is also observed in the direction towards the galactic centre.

The interstellar IR absorption features near $\lambda = 10\mu$ and 20μ (Knacke et al. 1969b; Hackwell et al. 1970) are thought to be caused by various forms of silicate grains. According to Woolf (1973) the silicate material on the basis of 9.7μ feature may be roughly 6-20 time the interstellar ice in conformity with the observations of Knacke et al. (1969a). The new infrared observations by Hagen, Simon and Dyck (1975) have shown excess IR flux around 33μ from several cool stars. This may be due to thermal emission from silicate grains as predicted by Krishna Swamy (1971). Further high resolution far infrared observations including polarization are required to assess the silicate dust hypothesis vis-á-vis other compositions proposed for interstellar grains.

(c) **Polarization** :—In general, the interstellar linear polarization is correlated with other phenomena relating to the dust grains such as interstellar absorption, the intensity of the λ4430 band, the intensity of interstellar lines, etc. The correlation is not one to one, however. For a star to exhibit polarization, for example, interstellar extinction is a necessary but not a sufficient condition. The latter is related to various factors like alignment of the non-spherical and/or anisotropic grains with a net asymmetry when integrated along the line of sight. Polarization is found in the radiation of all types of stars, single and multiple, early spectral type and late, main sequence and supergiant, intrinsic variable and nonvariable etc. The maximum polarization is found along and near the galactic plane for stars suffering large extinction. Further, the plane of vibration of the electric vector i.e. plane of polarization, is associated with the plane of the Galaxy. A relationship exists between the observed polarization and visual obscuration by dust clouds. The degree of polarization P is defined by $P = (I_{max} - I_{min}) / (I_{max} + I_{min})$ where I_{max} and I_{min} are the maximum and minimum intensities measured when the polaroid filter rotates in the path of starlight. In magnitude, the polarization is given as $\Delta m_p = 2.172P$. The maximum value of P, as reported by Mathewson and Ford and by Klare et al., is about 7 percent. Of the 1800 stars observed by Mathewson and Ford, 120 stars show $P > 0.01$ and only 33 stars exhibit $P > 0.02$; the average of P is hardly a few percent. The observational ratio of polarization Δm_p and extinction Δm both in units of magnitudes, reaches a maximum of $\simeq$ 0.065 and on the average $\Delta m_p / \Delta m \simeq 0.03$. This ratio is an indicator of the polarizing ability of the interstellar grains. It implies that the extinction efficiencies of the grains for two orthogonal states of polarization of the incident light differ by several percent at the most. The difference can be far greater if a component consisting of very large and/or spherical grains is involved in diluting the net polarization.

Gehrels (1960) who discovered the wavelength depedence of polarization for the first time, fitted the observations with the theoretical models of very elongated grains based on scattering by infinite cylinder at normal incidence. The grains may have many other aspects like orientation, anisotropy, mixture of single and composite particles, variation of sizes, shapes, chemical composition and solid state structures. Some of these factors are considered in the recent literature including empty exercises but so far there is no unique model of grains that can satisfy all the observational criteria (cf. Davis and Greenstein 1951; Jones and Spitzer 1967; Greenberg 1968; Purcell and Spitzer 1971; Cugnon 1971).

The wavelength dependence of polarization may also exhibit some structure depending on the nature of the grains. Such an attempt by Mavko et al. (1974) has led to the detection of hitherto unknown structures, viz. the hump at 4000Å and a broad depression between 4200Å and 5200Å, in the polarization curve of the famous star HD 183143. The study of such structures in extinction and polarization curves may help in sorting out the conflicting claims on various models of the grains.

The linear polarization discussed above is caused by linear dichroic properties of the interstellar medium, which as a whole convert a plane polarized light into a circular polarized component in certain favourable circumstances. An essential condition for the production of the circular polarization envisages interstellar medium to be birefringent also, i.e. two orthogonal states of polarized waves travel at different velocities within the medium. The interstellar circular polarization detected from several celestial sources (Martin et al. 1972; Michalsky et al. 1974) is of the order of ± 1 percent or less. An interesting feature of the change of sign of polarization (from right circular to left circular) may carry an imprint of the grain type. The sign, in general, is positive in the visual and blue and negative in the infrared wavelength region as indicated by observations. The linear and circular polarization observations should be extended in the far UV and far IR.

The plot of interstellar linear polarization (P) versus inverse wavelength $(1 / \lambda)$ for each star, normalized with respect to maximum polarization (P_{max}) and corresponding wave number $(1 / \lambda_{max})$, respectively, i.e. (P / P_{max}) vs. $(\lambda_{max} / \lambda)$, results in an unusual well defined representation (Serkowski 1971, 1973). Coyne et al. (1974) have shown that the observations in the wavelength range 0.22 to 2.2μ for all stars with 1 percent $\lesssim P \lesssim 10$ percent and with $0.45\mu \lesssim \lambda_{max} \lesssim 1.0\mu$, fit to a single curve as shown in Figure 2. This curve has been shown to correspond to the empirical formula

$$\left(\frac{P}{P_{max}} \right) = \mathrm{Exp} \left[- 1.15 \, ln^2 \; (\lambda_{max} / \lambda) \right] . \quad (1)$$

They have also matched this curve with some of the theoretically calculated models (Shah 1967; Greenberg 1968) for aligned spinning grains. These models refer to the dielectric dust grains oriented according to Davis-Greenstein mechanism (Davis and Greenstein 1951) of paramagnetic relaxation. They also incorporate further modifications introduced by Jones and Spitzer (1967) who have taken into account the effects of the thermal fluctuations in the magnetization within the grains. The OAO-2 observations by Lillie and Witt (1973) have shown the evidence for the differences in the composition and size distribution of the grains. The theoretical models must include such factors.

The unidentified diffuse interstellar bands (cf. York 1971; Bromage and Nandy 1973; Herbig 1967) pose another challenging problem. Having failed to identify them with any atomic or molecular species, investigators have turned attention to interstellar grains to seek the origin of these bands. So far no attempt has been successful. The fine structure of the polarization within the band presumably produced by the grain impurities was studied by Greenberg and Stoeckly (1970, 1971), Wickramasinghe and Nandy (1971), and by Kelly (1971). There are some disputing claims regarding the polarization within bands (see, for example, Wampler 1966; Nandy and Seddon 1970; A'Hearn 1972). The most favoured band for this study has been the strongest one at λ4430.

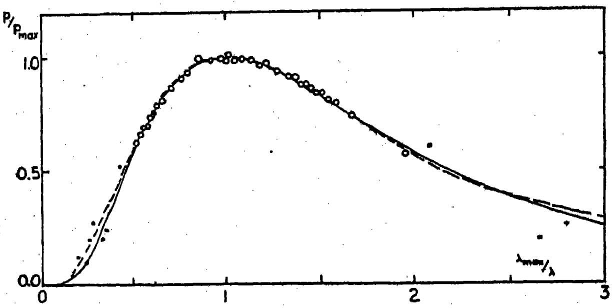

Fig. 2 Normalized wavelength dependence of interstellar polarization. The solid line is Serkowski's empirical formula (1), the dashed line is a theoretical curve for dielectric cylinders of constant elongation, with Oort-Van de Hulst type size distribution, oriented according to theory by Jones and Spitzer (1967). The orientation parameter of Wobbling cylinder is ξ=0.1 to 0.4 (Shah 1967, Fig. 50 and Greenberg 1968 Fig. 95). The circles and squares represent observations by Dyck (1974), Gehrels (1974) and Zellner (1973).

Source : Coyne et al. (1974).

A detailed analysis of the extinction observations in the wavelength range 3400-11000Å by Hayes et al. (1973) has shown a broad band structure of several 100Å width. This may also be associated with the interstellar grains. Although a correlation of the equivalent widths of some interstellar diffuse features with the colour excess is one of the strongest reasons for believing their origin in the grains, various other mechanisms have been suggested. For example, pure electronic transition model (Wickramasinghe and Nandy 1971), preionization of H^- and O^- (Rudkjobing 1969a, b, 1970; Ingemann-Hilberg and Rudkjobing 1970; Fano 1961), impurities within the solid grains (Greenberg and Stoeckly 1970) among other suggestions may be mentioned. The question of identification of the diffuse bands still remains open.

THEORIES OF ELECTROMAGNETIC SCATTERING :

In order to understand the nature of the dust grains, one needs to construct theoretical models which can reproduce at least some of the observational features. The theories of scattering of electromagnetic radiation by particles having various shapes, structure, composition and orientation have been the starting point. The auxiliary physical constants such as conductivity, complex dielectric constant, absorptivity, susceptibility etc. are mostly chosen to be representative of bulk materials with isotropic and homogeneous properties. For real situation in space, as in interstellar clouds or circumstellar envelopes, the conditions may create wide range of complications so that the assumed properties of the grain models may have limited relevance. As pointed out by Greenberg (1973), somewhat more subtle physical phenomena are involved if the particles are sufficiently small that bulk optical properties are no longer applicable.

The simplest and most widely axploited theory of scattering for reproducing observed interstellar extinction is that of Mie (1908) and Debye (1909). This theory is applicable to isotropic and homogenous spheres with smooth surface (cf van de Hulst 1957). A variety of computations based on Mie theory of scattering, using distribution of radii, mixture of grains etc., are found in the literature each claiming a best fit from time to time. However, combination of homogeneous spherical particles and Mie theory cannot reproduce simultaneously the observed polarization of star light. Alternatively, in the next step one has to assume some sort of anisotropic optical properties and/or nonsphericity of the scatterers. The simplest nonspherical particles which can be dealt with rigorously are in the form of circular cylinders. The pertinent theory of scattering refers to infinite cylinders (cf. Lind and Greenberg 1966). It offers a good scope of studying interstellar grains because the cross-sections and efficiencies for absorption and extinction are defined in terms of unit length of the cylinders. The analog experiments on microwave scattering (cf. Greenberg et al. 1961, 1963) have shown that the calculated scattering cross sections for infinite circular cylinder agree well with the measurements on corresponding realistic finite cylinders.

The interstellar grains may consist of composite particles consisting of core and accreted mantle. The core and mantle can have different indices of refraction including their wavelength dependence. This adds little complication in rigorous solution of the boundary value problem. Fortunately, the exact theories of scattering do exist for concentric spheres (Güttler 1952) and for coaxial concentric circular cylinders (Shah 1970) at oblique incidence.

There are no comprehensive exact theories available for other configurations. Some approximations for small values of the ratio of circumference to wavelenghth are possible in the case of spheroids and discs (van de Hulst 1957). In addition to the shape effect one has to consider the anisotropy and surface roughness of the grains. Very little analytical work has been attempted along these lines either theoretically or experimentally. Greenberg's microwave analog scattering experiments have been useful in assessing certain scattering properties of spherical and nonspherical particles with smooth or rough surfaces. In such analog experiments, the size and wavelength are scaled up by keeping their ratio constant. The refractive index, which is the function of complex dielectric constant, complex magnetic permeability, conductivity and wavelength does not figure in scaling. Nor is it easily amenable to do so. The theory of the complex refractive index involves microscopic considerations (cf. Stone 1963) leading to relations in terms of macroscopically measurable parameters. In solids and liquids the constituent atoms and molecules are in intimate contact and interact strongly in a way characteristic to each wavelength domain. Therefore, one wonders if the refractive and dispersive properties of a material valid in one wavelength domain can be transplanted into another domain by analog considerations. One can also ask whether scaled models can allow one to study some subtle features in the interstellar extinction, polarization, albedo, etc., resulting from

> (i) wavelength dependent indices of refraction of certain important materials, (ii) the modifications of refractive index effected by the interaction of the grains with the radiation fields and corpuscles in space. Hence we suggest that the laboratory experimentation on real particles and fields be carried out possibly under actual astronomical conditions.

Some effects of surface roughness on cylindrical particles studied by microwave scattering experiment (Greenberg et al. 1971) have been correctly interpreted by Shah and Vardya (1972). It has been found that the surface roughness can give significantly though not drastically different results as compared to equivalent smooth particles. Further assessment on the effects of surface roughness on electromagnetic scattering using variety of shapes and orientation would be desirable.

As an illustration of scattering by nonspherical particles from theoretical viewpoint we wish to mention a novel attempt by Purcell and Pennypacker (1973). They describe a method of calculating extinction, absorption and scattering cross sections for dielectric grains of arbitrary shape with dimensions comparable to or smaller than the wavelength of the incident radiation. The scatterer is modeled by an arrary of N ($\simeq$ 100) polarizable elements located in a simple cubic lattice. The polarizability of each element is such that the bulk dielectric constant of the grain material would be mimicked on application of Clausius-Mossotti relation to such an unbounded array. The cross sections for five different grain shapes and three different complex refractive indices have been tabulated. The authors claim that discrepancy between the calculated and exact cross sections is not more than 5 percent. for $(a/\lambda) \leqslant 1$, but it may reach upto 20 percent for $(a/\lambda) = 2$ in some cases. Here a and λ are size of the particle and wavelength of the incident light, respectively. However, the test of accuracy in case of nonspherical particles should be made with reference to the scattering cross sections and related quantities obtained from analog or real experiments.

ALIGNMENT OF GRAINS:

The orientation of the scattering particles can significantly modify the state of polarization as well as the scattering cross sections and related parameters. Under the conditions prevailing in interstellar space grain can rotate with spinning rate about 5×10^5 radians per second in HI regions and 6×10^6 rad/sec in H II regions. The grains initially rotating with short axis not parallel to the external magnetic field would experience periodic changes in magnetization of each volume element. Energy from the external magnetic field is lost to such elements by paramagnetic absorption which may be thought to arise from internal friction impeding the alignment of the microscopic dipoles within the grain. The cumulative effects of the torques involved in this process urge the angular momentum vector of the grain to slowly drift toward the B-field. In the net effect, this process leads the alignment of the short axis of the grain parallel to the B-field. This mechanism (DG) was proposed by Davis and Greenstein (1951) and by Davis (1958). Further modification, incorporating the effects of thermal fluctuations of magnetization within the grains has been given by Jones and Spitzer (1967). It has been pointed out that a difference between gas and grain temperatures is essential for alignment. These thermal effects result in grains wobbling about the average spin vector. The above theories were used by Greenberg and Shah (1966), Shah (1967) and Greenberg (1969) for constructing models of interstellar extinction and polarization. Estimates of interstellar magnetic fields can also be made from these models. Purcell (1969) and Purcell and Spitzer (1971) have considered DG mechanism for nonspherical particles in a Monte Carlo method. They conclude that adequate alignment of paramagnetic particles would require an interstellar magnetic field strength somewhat higher than had been commonly thought. In yet another attempt, Cugnon (1971) has solved a Fokker-Planck equation, as in Jones and Spitzer's treatment, taking into account collisions with gas atoms and magnet interactions in order to obtain the angular statistical distribution of the axes of the grains in the form of cylinders, prolate and oblate spheroids and nearly spheres. His approximations suggest minimum magnetic field requirement to be 2ϒ. Still lower requirement can be achieved by following the procedures described by Greenberg (1969) and by Shah (1972).

Greenberg (1969) has considered the optical properties of some nonspherical particles with reasonable values of the magnetic properties and orientation parameter. The scattering properties of the graphite flake core plus dirty ice mantle obtained from microwave analog experiment have also been included. The maximum observed ratio of polarization to extinction ($\Delta m_p / \Delta m$) has been taken as a criterion to distinguish between the models based on dirty ice and graphite grains having various shapes. It has been concluded that the magnetic field strength, required to produce the moderate or maximum observed value of ($\Delta mp / \Delta m$), is greater than ~ 0.5 ϒ for all grain models considered. The core-mantle grains seem to require a larger magnetic field than the dirty ice grains.

Another method of estimating the orientation parameter (ξ) and the resulting galactic magnetic field consistent with the observed moderate values of $\Delta m_p / \Delta m$ as well as the ratio of total visual to selective extinction (R) has been given by Shah (1972). It is assumed that the grains, cylindrical in shape, consist of a pair of distinct effective sizes (a_1, a_2) with corresponding different number densities (n_1, n_2). In this scheme also, the galactic magnetic field requirement as low as 0.6ϒ can be achieved by choosing $a_1 = 0.11\mu$ and $a_2 = 0.22\mu$ with $n_1 / n_2 \lesssim 40$ for dirty ice material. A suitable range of orientation parameter, satisfying both the observed quantities, R and $\Delta m_p / \Delta m$, has been found to be $0.4 \lesssim \xi \lesssim 0.8$.

Some difficulties in assessing the orientation theories must be pointed out. The dissipative torques in DG mechanism which opposes the rotation of a paramagnetic crystal about an axis transceverse to a uniform magnetic field is proportional to B^2 and to χ'', the imaginary part of the magnetic susceptibility. The magnetic susceptibility is a measure of magnetization that can be introduced in a specimen put in an external magnetic field. It is one of the most important parameters because it plays vital role in the grain alignment. Unless its exact value is known, the estimates of interstellar B-field from the observed polarization data would be in error. The theory and experiment show that for paramagnetic grain material, in the low frequency limit,

$$\chi'' \gtrsim K \left(\frac{\omega g}{Tg}\right)$$

where $K \simeq 10^{-12}$

ω_g = spin rate of the grain,

and T_g = temperature of the grain.

According to Jones and Spitzer (1967), Purcell and Greenberg (1969) this value of K gives a lower bound for dielectric interstellar grains. It is approximately independent of the composition of the grains or the concentration of paramagnetic ions. The upper limit on the value of K for paramagnetic substances is $\simeq 2 \times 10^{-12}$ if dipole-dipole interactions are predominant. The alignment of the paramagnetic grains treated by most of the workers has created a problem of stronger interstellar magnetic field requirement as compared to evidence from radio astronomical data (Verschuur 1969, Jokipii and Lerche 1969, Manchester 1972). However, an approximate treatment by Shah (1972) has led to field requirement some what lower than usually cited value of 1ϒ. An alternative to reduce the magnetic field requirement is to consider "super-paramagnetism" suggested by Jones and Spitzer (1967). The basic idea here is to consider an aggregation of ferromagnetic iron atoms or molecules, say Fe_3O_4 or ϒ Fe_2O_3, into many magnetically ordered lumps. Thus, to use analogy of Jones and Spitzer, some of the grains might be viewed as a sort of "raisin pudding" of ferromagnetic domains in an otherwise nonmagnetic matrix of grain material. The isolated cluster of iron atoms distributed within the body of the grain can produce comparatively giant magnetic moments. With hardly 1 percent of Fe concentration, one can expect the value of K to go up by several orders of magnitude larger than 10^{-12}. This would remove the difficulty mentioned above at least for dielectric grains.

The magnetic properties of graphite are complicated by the fact that (1) there are present simultaneously the diamagnetism produced by the orbital electron motions in the basal planes (i.e. directions of high conductivity) and the paramagnetic spin part (2) the magnetic properties are anisotropic. Some estimates of χ'' are available but quantitatively reliable data are lacking. Aannestad and Purcell (1973) have indicated that there is no known mechanism other than ordinary electronic paramagnetism that could magnetically align graphite flakes. Furthermore, Cugnon (1971) has shown that the resulting alignment and polarization direction in case of graphite grains are not consistent with observations.

LABORATORY EXPERIMENTS ON INTERSTELLAR GRAINS :

In spite of a number of models of the grains, the identification of the grains has intrigued the astronomers for the past four decades. It is very likely that the grains consisting of variety of compositions, sizes, shapes, structures and surface conditions co-exist. One of the chief physical properties of the grains is the wavelength dependent complex dielectric constant or refractive index. The optical properties of some materials, discussed in the literature, are available for ice (Field et al. 1967; Irvine and Pollack 1968; Ray 1972; Browell and Anderson 1975) graphite (Phillip and Taft 1962 Friedemann and Schmidt 1966), and silicates (Huffman and Stapp 1971, 1973; Dorschner 1968, 1971; Pollack et al. 1973). Unfortunately, the measured values of the optical constants vary with the author. Sometimes only the real part of index of refraction is measured although the imaginary part is equally important. No one knows how far they represent the actual situation occurring in interstellar space. For example, why should there be only one kind of silicate material ? Meteorite studies reveal many kinds of silicates and metallic oxides. Indeed, Cameron (1973) has suggested that meteorite collections in our museums may be very valuable for research on interstellar grains. At present it is difficult to specify the nature of the grains in various celestial sources simply from highly idealized models and observations. Therefore attempts must also be made to supplement observational data with laboratory studies of particulate material of terrestrial as well as extra-terrestrial origin under various physical conditions. In what follows we summarize some relevant experimental results.

A recent work by Zaikowski et al. (1975) and Zaikowski and Knacke (1975) compares the infrared spectra of carbonaceous chondrites, Cold Bokkeweld Murray and Orgueil with phyllosilicate minerals and interstellar absorption features near 10μ (Gillett and Forrest 1973). It has been suggested that similar minerals are present in primitive meteorites and the interstellar dust. It is possible that hydrous silicate phases occur in the interstellar grains. As in meteorites, phyllosilicates may form directly (Arrhenius and Alfvén 1971; Kerridge 1971) or result from the alteration of high temperature condensates (e.g. Olivine, Pyroxene) if equilibrated with water (Larimer and Anders 1967). Evidently clues to the formation mechanisms of interstellar dust may be found in the laboratory studies.

The technique developed by Dorfeld and Hudson (1973) permits laboratory simulation of graphite condensation in the envelopes of cool, late type stars. Processes in the stellar envelope were simulated by allowing hydrogen-carbon mixtures of typical circumstellar composition and temperature to expand into vacuum. Then the condensation products which result from subsequent cooling and supersaturation were examined by mass spectroscopy using molecular beam techniques. The results implied that envelope expansions near M giants contribute at most 10^{-2} of the observed interstellar grain density. The complete carbon condensation into graphite can occur for the case of pulsating N stars. It may be recalled that the possibility of graphite formation was originally suggested by Cayrel and Schatzman (1954) and subsequently studied in detail by Hoyle and Wickramasinghe (1962), Donn et al. (1968), Kamijo (1969) and Fix (1969).

In an electron microscopic study of the grains of iron, carbon, silicon carbide and silica produced by striking an electric arc in argon environment, Lefévre (1970) found that the sizes of the grains range from about 100Å to 2000 Å. Only for silica one obtains beautiful spherica shapes in association with chain like structures. The elongated and mosaic structures and complex shapes are found for carbon, silicon and silicon carbide. The calculated extinction based on the Mie theory for spheres and infinite cylinders (polarization vector perpendicular to axis) has been shown to agree with experimental results in the wavelength range 3600-7000Å; the appropriate particle radii being 400Å for iron and for carbon spheres. The author concludes that the van der Waal interactions can be very efficient during encounters between interstellar grains either within a single cloud or during cloud-cloud collision. The sticking of the grains in chain-like structures observed in experiments can provide elongated grains. Therefore, one must be cautious in using smooth spherical grains only. The experimental extinction by silicon carbide obtained by Lefévre show some bands which nearly coincide with the unidentified band centered at λ4430, λ5780, and λ5797 and λ6614. But it has not been possible to say conclusively if these bands are due to grains of silicon carbide.

Laboratory experiments at Dudley Observatory have been developed to study the electromagnetic scattering by particles of arbitrary indices of refraction and smooth shapes including single homogeneous sphere, concentric spheres, single homogeneous and co-axial circular cylinders, and spherioids. Greenberg and Yencha (1973) have begun study of radiative effects in low temperature solid mixtures representative of the usual ice grains. They are also studying the chemical composition of dust and the possibility of formation of complex organic molecules as a result of triggering explosive chemical reaction in a grain consisting of free radicals frozen in a matrix of photolyzed dirty ice material. Greenberg and Yencha have mentioned that the presence of free radicals within the grains can have important effect of providing exotic optical properties. It is believed that the grains play a critical role in the formation of interstellar molecules. The exact mechanism of molecule formation on the surface of the grains is so far not clear.

Formation of molecules and growth of grains including the mantles, may be intimately related problems. Certain diatomic radicals and simple molecules can form in gas phase in certain special regions of the intestellar clouds by radiative association and charge exchange reactions (cf. Solomon and Klemperer 1972). However, complex molecules with four or more atoms cannot form in gas phase unless one brings in the role played by dust grains. One can think of catalytical and possibly photo-catalytical reactions. The laboratory experiments based on these ideas have been performed by Breuer (1969, 1973), and Moesta et al. (1969). They introduced gases like H_2, D_2, N_2O_2, CO, NH_3, CH_4 and CD_4 in the reaction system. These gases were allowed to be absorbed on metallic films or foils. The absorbed layer was then irradiated by an exploding wire light source or by resonance lamps.

The experimental results show that by irradiating simple gases adsorbed at the surface of a solid, rather variety of complex organic molecules can be formed. The measured cross sections for formation and desorption of molecules like CN, HCN, H_2CO, CH_3CN, HNCO, $HCONH_2$ and HC_3N show that photocatalytic reactions are important for formation of molecules. Since these experiments were performed at room temperature, application to conditions prevailing in interstellar space is risky. Furthermore, experiments using nonmetallic substrate as well as a reaction system, which may enable one to study both the formation of molecules and growth of grains at very low temperatures, are desirable.

Silicates have often been mentioned in the literature as a possible circumstellar shell material (see, for example, Gillett and Forrest 1973). The equilibrium calculations for condensation in the early solar nebula show certain silicates to be an important phase (Grossman and Larimer 1974). According to Woolf (1973) an average observed ratio of visual to infrared 10μ extinction is 50:1. Thus it is necessary to determine whether the same particles are responsible for extinction in the visual as well as IR. Day, Steyer and Huffman (1974) have given quantitatively measured extinction by small spherical particles of amorphous SiO_2, quartz, almandine and olivine. A comparison with Mie calculations has been made. They find that silicates have little effect in producing the extinction in the visual region of the general interstellar extinction curve. The measurements of extinction by small olivine (forsterite) spheres by Day (1975) do not show sharp spikes predicted by Mie theory. It may be noted that Mie theory applies to spheres with homogeneous distribution of the material within and smooth surface of a sphere. In practice, however, these spheres of olivine though virtually perfect are highly crystalline. Also, the optical constants of small submicron particles may not have the same values as those of bulk materials. The good agreement as obtained by Day, can be expected for positions of major resonance peaks and integrated absorption and scattering cross sections. Similar experiments on various material with nonshperical shapes as well would be valuable in delineating some properties of the interstellar grains.

The sticking coefficients are experimentally found to vary by orders of magnitude between different gases, substrates and crystal planes. The mechanism of energy transfer in gas-to-surface collisions is still a matter of speculation. The results on the measurement of angular dependence of sticking coefficients on tungsten by Stembruchel and Schmidt (1974) amply demonstrate the significance of the accommodation coefficient on the angle of incidence. This area needs to be studied carefully in laboratory experiments in relation to the formation of molecules on small interstellar grains. Until recently the only molecules thought to exist in interstellar space were CH, CH^+, CN and NaH (McKellar 1941; Adams 1949). These were discovered on the basis of optical astronomy. In the past several years, many more molecules have been discovered from studies of radioastronomical observations. Sagan (1972) has discussed the various mechanisms proposed for synthesis of interstellar molecules. A feasible method for their production is the recombination of atoms on the surface of the grains. Watson and Salpeter (1972) examined this process by using primarily photodesorption to eject molecules formed on the grain surfaces. Duley (1973) suggests that small grains, due to the absorption of single photons, experience large temperature fluctuations. It has been stated that in all but the densest clouds average grain temperature T_g in the usual 5-10 K range are of little statistical significance because of large fluctuations produced by absorption of photons of energy in the range 1-10 eV from the ambient radiation field. The grains exposed to such a field will on the average spend roughly 10 percent of the time at an elevated temperature T far above their average value T_g. This effect may introduce an additional complication in the calculations of molecule formation on grain surfaces. However, the dense dust clouds are likely to have more favourable conditions for the formation of molecules and the probability of the contribution due to phenomena of photodesorption and temperature fluctuations seem to be low. Allen and Robinson (1975) have proposed another mechanism of the ejection of molecules from the surface of the grains with sizes $\lesssim 0.04\mu$. Similar suggestions can be found in works of Solomon and Wickramasinghe (1969), Brecker and Arrhenius (1971) and Watson and Salpeter (1972). The essential idea is that the energy necessary for ejection of molecules need not be provided through interaction of these grains with any radiation field, but rather comes from heat released during the formation of chemical bonds. The liberated energy would be transferred to the lattice vibrations of the grains. The hot grains, during the radiative cycle may then allow the adsorbed molecules to escape. In extreme case the grains can even disintegrate when the temperature of the grain is peaked instantaneously upon the formation of the bond. Such a process can certainly operate even in the central regions of the dense dust clouds. Some tentative explanation of radioastronomical observations of OH and CO have been provided by Allen and Robinson. The calculations show that very small quartz grains may be heated sufficiently to result in atleast a partial disintegration of the grain. This may be a source of interstellar SiO in various vibrational levels (Davis et al. 1974; Kaifu et al. 1975). Such a process can be generalized to include polyatomic molecules, and a variety of grain compositions and temperatures. The laboratory experiments along this direction, simulating conditions within circumstellar envelopes and interstellar clouds, can be of great help.

Platt (1956, 1960) pointed out the importance of quantum effects for certain types of particles. Donn (1968) demonstrated that these effects are certainly important for graphite particles less than 100 Å in diameter. It was not known for what range of particle sizes the transition takes place from the classical to the quantum description. We refer to the experimentally measured graphite particle sizes and their extinction cross sections by Donn et al. (1968). The graphite particles were in the size range 0.01μ to 0.1μ. The situation in the case of the absorption spectra of large polycyclic hydrocarbons (Donn 1968) is similar. The measured spectra suggest that the transition from classical to quantum optics takes place over a plateau of sizes beginning somewhere below 100Å. Donn et al. (1968) also measured the extinction efficiency for graphite particles and found agreement with Mie theory. The experimental curves, however, exhibited a considerable amount of structure which is presumably due to quantum affects. Further experiments along this line in far UV with improved techniques to obtain narrow size distribution of particles are being planned by Dr. B. Donn and his associates.

Cohen (1973) has studied the equivalent widths and radial velocities of the interstellar lines of Ca II, Na I, CH and CH^+ for 30 stars behind or within the dense clouds. It has been found that calcium and sodium are missing from the gas to a greater extent in the clouds than in interstellar medium or supergiants. The missing atoms of Ca and Na can form condensation nuclei on which grains can grow. A certain fraction of bare nuclei or particles can co-exist with the grains because of the processes of grain formation and destruction. Similar bare particles can be possible for other depleted elements as well. Some of the structure in the observed extinction and polarization curves can be caused by peculiar optical and scattering properties of certain component of the tiny grains existing either separately or within the matrix of larger grains. For instance, very tiny spherical grains, referred to as granules hereafter, in the size range $a \lesssim 300\text{Å}$ of Na, K, Ca can produce unusual resonance features in extinction. The position and peak of resonance profile will depend greatly on the complex index of refraction, $m = m' - im''$ for these materials. It so happens that Na, K and Ca have large imaginary part m'' compared to m'. The value of m is such that the factor $(m^2 + 2)$ which occurs in the denominator of the first Mie coefficient a_1 (corresponding to electric dipole mode) is very near to zero and thus acts as a near singularity. Naturally, resonance would be exhibited whenever $(m^2 + 2)$ approaches zero and size-to-wavelength ratio is favourable. The latter condition can occur in Rayleigh scattering region. Beyond certain value of $X = 2\pi a / \lambda$, however, the contribution from the quadrupole mode (Mie coefficient a_2) can be more than that of dipole mode (Shah 1973).

The experimental results on the optical properties of thin films of alkali metals (Mayer and Hietel 1965) indicate that the conductivity of Na in the visual wavelength region, $\lambda = 0.365\ \mu$ to $0.6\ \mu$, increases by about 30 percent when the temperature is lowered from 293°K down to 80°K. This means that the imaginary part ϵ'' of the dielectric constant increases with the decrease in temperature. It is not obvious at the moment how ϵ', the real part of the dielectric constant, varies with temperature. If ϵ' remains constant or increases by as much as 20 percent or more when ϵ'' increases due to decrease in temperature, the peak in Q_{ext} could shift towards the longer wavelength side. The band width of the resonance profile will also decrease with temperature. An additional complication could arise if one considers the fact that the conductivity varies with thickness of the thin films (MacDonald 1956) because this may hold for interstellar grains too. The effect of sufficient increase in both ϵ' and ϵ'' as mentioned above is to increase the real part m' but to decrease the imaginary part m'' of the index of refraction. For example, the measured values for sodium at room temperature (Smith 1969) are $\epsilon' = -3.082$ and $\epsilon'' = 0.24$ at wavelength $\lambda = 4410\text{Å}$. Then $m' = 0.067$ and $m'' = 1.79$. Now if ϵ' and ϵ'' increase by 20 and 30 percent respectively for decrease in temperature from 293K to 80K, the value of m' and m'' become 0.09974 and 1.564, respectively. In certain cases, the decrease in m upto certain limit has the effect of shifting the peak in Q_{ext} to long wavelength side, the size of the granules being held constant. Sample calculations have been carried out for refractive index slightly different from the one suggested by Unsöld (1964), $m^2 + 2 = -(3\Upsilon/\omega_o)\,i$, where Υ = the damping constant and ω_o = the resonance frequency for the diffuse band near λ 4430. The value of $\omega_o/\Upsilon = 300$ is an average estimate for the centre of the resonance peak. The results are given in Table 1. The actual calculations are done for Q_{ext} vs. X for each value of m. The table lists only the first peak value of Q_{ext} and the corresponding location of X_o, the ratio of the circumference of the spherical particle to the wavelength. It can be seen that Q_{ext} at the first maximum and X_o are quite sensitive to small changes in m. The Q_{ext} increases monotonically with m'' whereas X_o has minimum near $X_o = 0.047$ The shift in the position of the resonance peak is brought about mainly by m'' in this particular case. This example illustrates how critical are the measurements of m' and m''.

Table 1

Variation of X_o and $(Q_{ext})_{max}$ due to resonance scattering with index of refraction.

m'	m''	X_o	$(Q_{ext})_{max}$
0.00353517	1.40290	0.082	4.4906
„	1.40855	0.056	10.543
„	1.41421	0.049	43.665
„	1.41987	0.085	90.001
0.00353552	1.40290	0.082	4.491
„	1.40572	0.068	6.4664
„	1.40855	0.056	10.544
„	1.41138	0.047	20.492
„	1.41421	0.049	43.663
„	1.41704	0.066	71.260
„	1.41987	0.085	89.993
0.00353587	1.40290	0.082	4.4914
„	1.40855	0.056	10.545
„	1.41138	0.047	20.492
„	1.41421	0.049	43.660
„	1.41704	0.066	71.254

Note : X_o is the value of $X = \frac{2\pi a}{\lambda}$ where the maximum efficiency occurs for a given m. X_o is correct to two significant digits only.

Finally we wish to mention some unusual processes relevant to grains. One of the important discoveries of low energy electron diffraction studies is that atoms adsorbed on a solid surface can form ordered periodic structures. The nature of the surface structure depends on the crystal orientation, temperature and the concentration of adsorbed gas atoms. The adsorption of O, H, and CO has been studied on a variety of metal and semiconductor surfaces (Gabor 1968). In almost every case, chemisorption was accompanied by the formation of ordered surface structures. Sometimes it may so happen that a strongly exothermic surface reaction can dislodge the surface atoms from their equilibrium positions in the surface and cause a surface structural rearrangement known as reconstruction. Radiation damage and bombardment by suprathermal cosmic ray particles ($\leqslant$ 1 MeV) can introduce defects in solid grains leading to significant change in the wavelength dependence of the absorptivity of the grain.

A possibility exists that electrically charged grains if elongated, tend to grow longer through preferential capture of ions near the ends of the grain. Piotrowski (1962) has indicated a pronounced effect only for very thin needles. Kahn (1952) has suggested that the interstellar environment might favour the growth of an electrically polarized ice crystal. This may hold for all types of grains. Accretion of new H_2O and other ice molecules would occur at the ends of the rod-shaped "electret". The resulting long and highly electrified grain would have some interesting properties. It seems possible that a dependence of temperature on shape might favour such growth or inhibit the dissipation of eccentric grains. Unfortunately these processes have not been pursued to asses their significance for grain models. Such processes might considerably modify the properties of the grains in gas-grain, grain-grain, cloud-cloud, photon-grain and cosmic ray-grain collisions. They can have important influence on the infrared spectra of the thermal reradiation from the grains. These are some of the aspects where chemists and physicists may have strong interactions. In fact, the field of interstellar grains has become broadly interdisciplinary in character, a set without END.

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