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INTERSTELLAR GRAINS

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Introduction

Since the last review of our subject in these volumes, by Lynds & Wickramasinghe (1968), there has been a remarkable accumulation of new observational evidence bearing on the nature and distribution of interstellar dust. On the theoretical side, progress has been less impressive, but not, as the bibliography will show, for want of effort. We have tried in this survey to emphasize the observations, but to discuss their interpretation has irresistibly demanded space. We hope that our survey will provide a useful guide into the now very extensive literature.

We have not been able to deal with all the topics that might reasonably be discussed under the heading *interstellar grains*. Among the topics not covered are circumstellar dust, dust clouds, dust in the nucleus of the Galaxy, and the still largely speculative question of extragalactic dust.

Useful general references on the interstellar medium are the books of Spitzer (1968a) and Kaplan & Pikel'ner (1970). The book of Wickramasinghe (1967) is devoted entirely to interstellar grains. The comprehensive review article by Greenberg (1968) remains an important reference on grains. The recent and extensive survey by Wickramasinghe & Nandy (1972) appeared as our own survey was being completed.

Recent conferences on interstellar dust or related subjects have produced important collections of papers, many of which will be referred to individually in our text. We call attention especially to the Proceedings of the International Conference on Laboratory Astrophysics, at Lunteren, published in *Physica*, Vol. 41, pp. 1–223, 1969, the papers from the IAU Colloquium on Interstellar Dust, at Jena, published in *Astronomische Nachrichten*, Vol. 293, 1971, and the forthcoming Proceedings of the IAU Symposium No. 52 on Interstellar Dust and Related Topics, held in Albany, New York, in June 1972.

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1. Interstellar Extinction

The extinction curve $A(\lambda^{-1})$ shows the amount of absorption of starlight as a function of the wavenumber λ^{-1}. For stars of the same spectral type the curve can be determined from the magnitude differences $\Delta m(\lambda)$ between a reddened star and an unreddened comparison star at a wavelength λ or, alternatively, from the ratios of color excesses $E(\lambda_1-\lambda_2)=\Delta m'_{\text{observed}}-\Delta m'_{\text{intrinsic}}$ where $\Delta m'$ is the magnitude difference (color) between the two wavelengths λ_1 and λ_2 for the same star. It is convenient to use the normalized extinction defined as

$$A(\lambda^{-1}) = [\Delta m(\lambda) - \Delta m(\lambda_V)]/[\Delta m(\lambda_B) - \Delta m(\lambda_V)] \tag{1}$$

or, alternatively,

$$A(\lambda^{-1}) = E(\lambda - V)/E(B - V) \tag{2}$$

where the subscripts V and B denote the visual and blue wavelengths, respectively 5470 Å and 4350 Å in the UBV photometric system.

In recent years the extinction curve has been extended into the far ultraviolet region as well as into the near infrared region and now covers the range of 0.3 μ^{-1}–9 μ^{-1}. Figure 1 shows extinction curves typical of the curves so far obtained. It is clear that the nature of the extinction curve is quite different from what had been expected on the basis of the simple linear "law" $A \propto \lambda^{-1}$, which approximately holds in the visual region of the spectrum.

ULTRAVIOLET REGION The ultraviolet extinction values shown in Figure 1 are from observations with the OAO-2 as reported by Bless & Savage (1970, 1972). (For a recent review of ultraviolet astronomy see Bless & Code 1972.) Similar data have been reported from rocket observations by Stecher (1965, 1969), Bless, Code & Houck (1968), and Carruthers (1969a,b, 1970b, 1971) and from balloon observations by Navach & Lehmann (1971). Celescope observations of the Vela region by Peytremann & Davis (1972) show somewhat smaller relative extinction values than the average curve in Figure 1, but this may be interpreted as "anomalous" extinction similar to the case for θ Ori and σ Sco. However, we should keep in mind that most of these observations are of hot and bright stars in relatively nearby, young associations in the galactic plane, and the extinction measurements may therefore not be truly representative of the general interstellar medium.

The ultraviolet extinction curves show the following characteristics:

(i) There are large variations in ultraviolet extinction from one star to the other and these variations are greatest in the far ultraviolet;

(ii) There is a characteristic extinction hump that usually has its maximum at 4.6 ± 0.1 μ^{-1} (2175 Å $\pm$ 25 Å). However, as shown by the curve for ζ Oph, the maximum may fall at slightly shorter wavelengths of 4.75 μ^{-1};

(iii) There is a shallow far-ultraviolet minimum in the region 5.5 μ^{-1}–7.5 μ^{-1} which falls at shorter wavelengths when the far-ultraviolet extinction is smaller;

(iv) After the shallow minimum, there is a rapid rise in the ultraviolet extinction.

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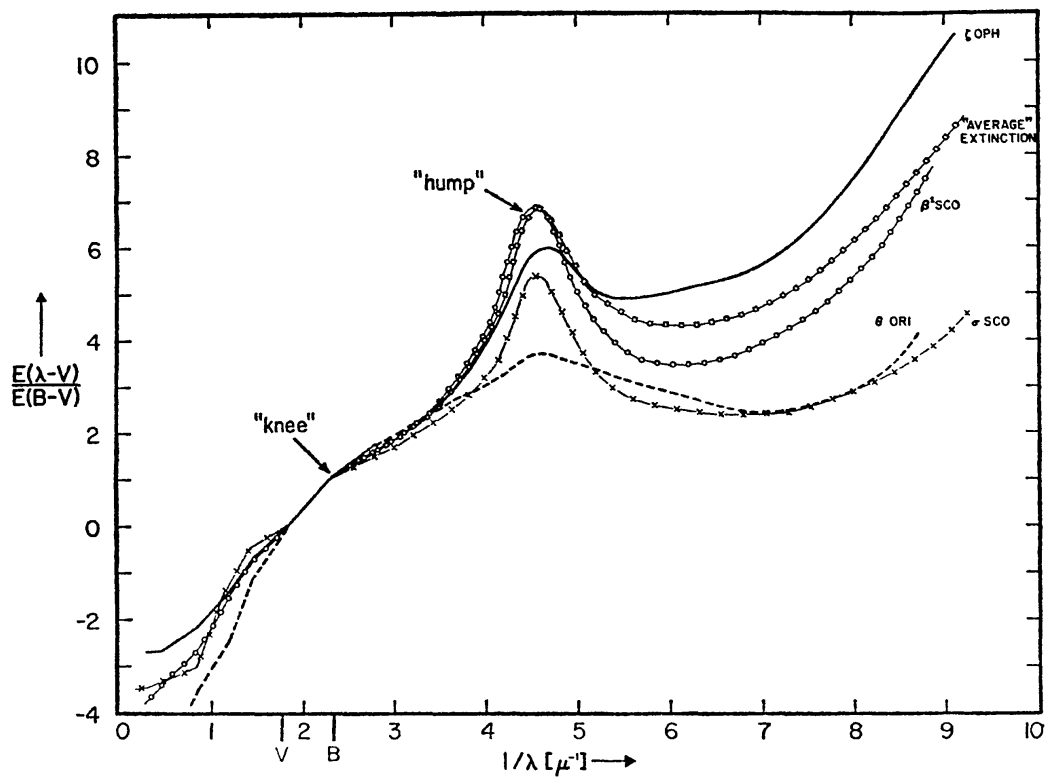

Figure 1 Interstellar extinction curves presented by Bless & Savage (1972). The ultraviolet part of the extinction curve was obtained from OAO-2 observations, and the visual and infrared parts are based on measurements by Johnson (1968).

The extinction hump is pronounced in some objects, but may be small or not detectable in other objects. Earlier results suggested that the greater the height of the hump, the greater the B−V color excess, and Savage (1972) reported that 40 out of the 75 stars showed the hump and had B−V color excesses in the range $0^m.0$–$0^m.61$, while the stars without detectable hump had $E(B-V)<0^m.05$. The stars with a detectable hump obeyed an approximate linear relationship E(2175 Å–3500 Å)$\simeq 5E(B-V)$, except for a few stars (for example, θ^{1+2} Ori, σ Sco) that showed a very small ultraviolet color excess. Also, as seen from Figure 1, less than "normal" ultraviolet extinction seems to be correlated with less than "normal" infrared extinction, or, equivalently, more than "normal" infrared emission. On the other hand, there seems to be no similarly clear correlation between the magnitude of the hump and the magnitude of the far-ultraviolet extinction, indicating that different types of grains are responsible for the hump and the far-uv extinction. However, all such conclusions still suffer from the small sample of stars.

VISUAL REGION The most notable characteristic of the extinction curve in this region apart from the roughly linear λ^{-1} law is the "corner" or "knee" that we

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can see in Figure 1 at about 2.3 μ^{-1}. This discontinuity in the slope was first noted by Whitford (1958) and thought to be caused by the broad absorption wings of the 4430-Å diffuse band (Herbig 1966, Walker 1966). However, high-resolution observations by Harris (1969) indicate that the band and the knee are two separate features. There are several possible explanations for the knee—among them, as discussed by Hayes et al (1972), a suitable distribution of grain sizes.

On the other hand, many less pronounced changes of gradient or discontinuities are found in the visual extinction curves and often coincide with or are close to the positions of diffuse lines (Honeycutt 1972, Walker, Hutchings & Younger 1969). High-resolution observations of all such features would clearly be desirable.

INFRARED REGION As shown by the extinction curves in Figure 1, there are intrinsic differences in infrared extinction from star to star. Some of these differences may imply the presence of circumstellar emission superposed on the stellar continuum.

In some cases abrupt changes or "knees" are observed, which may reflect the existence of interstellar infrared absorption bands. Such bands offer the best opportunity for identifying nonconducting grain materials. The first band searched for was the 3.1-μ band of interstellar ice in the spectrum of highly reddened supergiants (Danielson et al 1965, Knacke, Cudaback & Gaustad 1969, Knacke et al 1969). Comparing the observations with laboratory spectra of ice at temperatures down to 20°K, Knacke, Cudaback & Gaustad concluded that no more than 10% of the interstellar dust is made of ice. The main uncertainty in this result is whether all the observed extinction is caused by typical interstellar grains. The observed stars may be appreciably reddened by circumstellar dust clouds whose grains are either too hot to contain ice or have a modified composition due to the ultraviolet radiation from the nearby star. More observations of less reddened stars are needed, as well as observations at other band wavelengths in the 2.7- to 3.0-μ region (Hunter & Donn 1971).

The most important result of the infrared extinction observations has been the discovery of strong absorption bands in the 10-μ region. Such features were first reported at 9.7 μ and 10.6 μ in the spectrum of 119 Tau by Knacke et al (1969), although repeated observations by Hackwell et al (1970) showed no evidence of the same features. However, Hackwell et al reported strong absorption in the regions 9 μ–12 μ and around 20 μ in the direction of the galactic center, and also found that three reddened B stars showed absorption at 11.5 μ consistent with the galactic center observations. More recent observations by Woolf and Gillett of the galactic center show a narrower absorption feature than observed by Hackwell et al and centered at 9.7 μ (Woolf 1972). Silicates are known to have absorption bands near 10 μ (essentially due to the Si-O stretching vibration) and 20 μ (probably due to Si-O bending vibrations), but this identification is somewhat uncertain. Martin (1971c) has critically examined the procedure of infrared spectral identification and points out that the use of linear absorbance data for the absorption cross section is not adequate since the absorbance shows saturation in the regions of strongest absorption. Laboratory determinations of the re-

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fractive indices at infrared wavelengths for a wide variety of possible interstellar materials are needed for postive identification. Even then, shifts and changes in spectral features due to a mixture of shapes of interstellar grains will make exact identification difficult.

Figure 2 shows the infrared absorption spectrum recently obtained by Gillett & Forrest (1973) of the Becklin–Neugebauer star in Orion. This star is presumably attenuated by as much as 70 magnitudes of visual interstellar extinction. The absorption band seen at 3.1 μ is most likely the long-sought-after ice band, and a similar feature has been observed in the spectrum of NML Cygni and a few other stars (Woolf 1972). The broad band from 8 μ to 12 μ is very similar to the band observed in the galactic center, and this band has also been observed recently in the spectra of the infrared source IRS 2-W 51 and the compact HII region K 3–50 (Gillett 1972, personal communication). Gilra (1972) has emphasized the lack of experimental and theoretical support for the identification of this band with silicate absorption, and suggested that there should be a strong absorption band between 10 μ and 13 μ due to silicon carbide. The observations in Figure 2 seem to rule out silicon carbide as the single source for the 10-μ absorption, but absorption due to both silicates and silicon carbide (and possibly other materials) is not contradicted by these observations. Finally, it has been pointed out by Hoyle & Wickramasinghe (1969) that impure graphite becomes infrared-active in the 8- to 12-μ region. The emissivity calculated for 98.5% graphite, however, shows a very broad and flat maximum from 10 μ to 9 μ and would imply too much absorption in the 9- to 7-μ region compared with the observations in Figure 2.

Ascribing the 9.7-μ feature to silicates, Woolf (1972) calculates that there is 6–20 times as much silicate as ice present in interstellar grains. This is consistent with the upper limit on the abundance of ice as determined from the observations by Knacke, Cudaback & Gaustad (1969). In summary, this evidence suggests that ice is only a minor constituent of interstellar grains, and that silicon in the form of silicates is probably a major component of the grains.

2. *Spatial Distribution of Dust*

A clear representation of the large-scale distribution of interstellar dust in the galactic plane within 2.5 kpc from the Sun may be seen in Figure 3 (FitzGerald 1968). This figure is based on determinations of color excesses and distances [with $R = 3.0$; see equation (4)] for several thousand stars, and the shading of the obscuring areas indicates the change in color excess per kpc. Similar but less detailed maps of the dust distribution have been derived by Neckel (1966) and by Cahn & Nosek (1972). Clearly, the dust is nonuniformly distributed, and the extinction can vary rapidly with small changes in direction. It also appears that the extinction clouds in the near solar vicinity have somewhat less extinction, are larger, and are less numerous than "standard" clouds in the interstellar medium.

The distribution of dust as a function of latitude may be very "patchy," as it is in the galactic plane. In a recent investigation of the interstellar reddening from color excesses of 182 B-, A-, and F-type stars within 20° of the North Galactic

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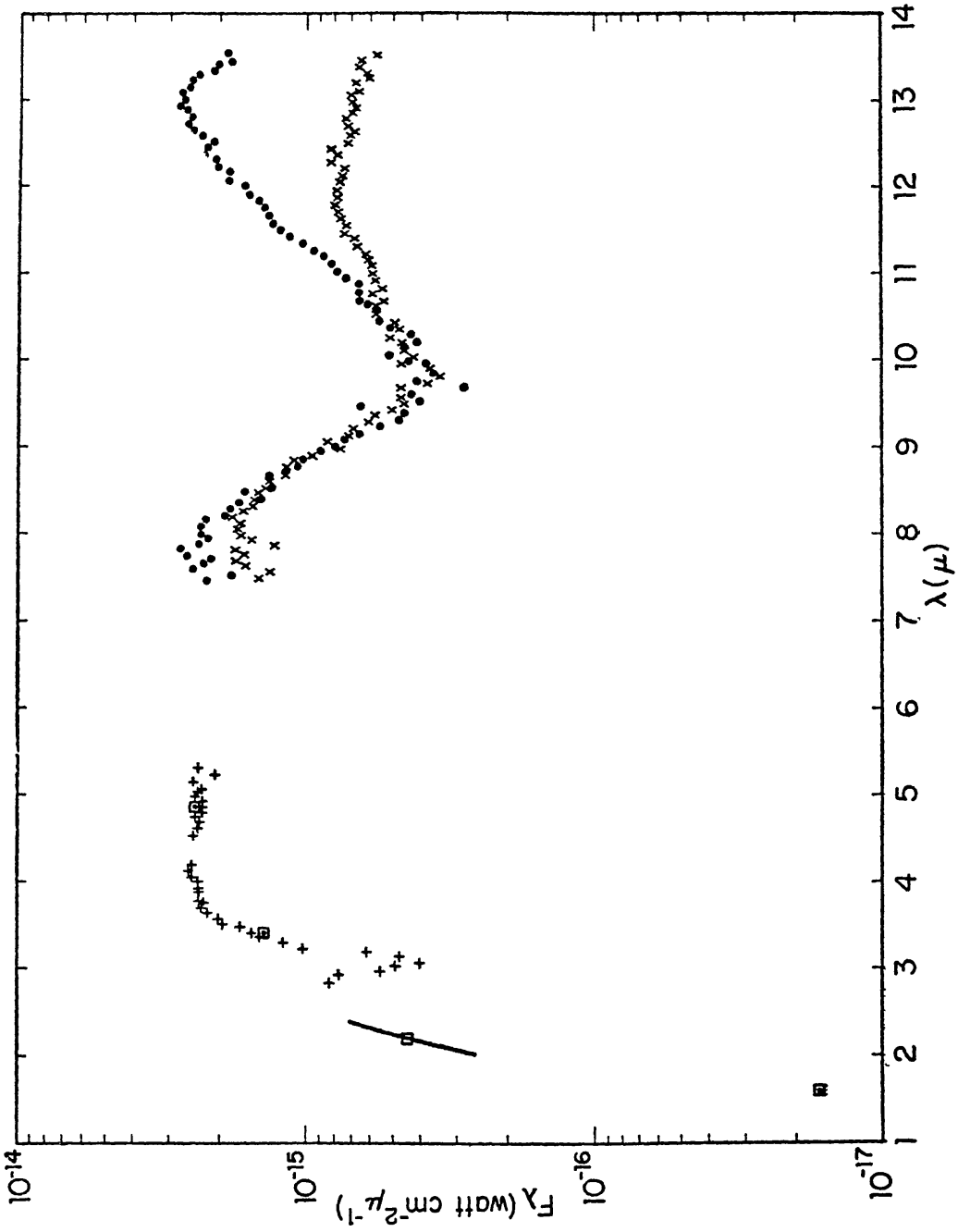

Figure 2 Spectral observations of the BNKL object in Orion presented by Gillett & Forrest (1973).

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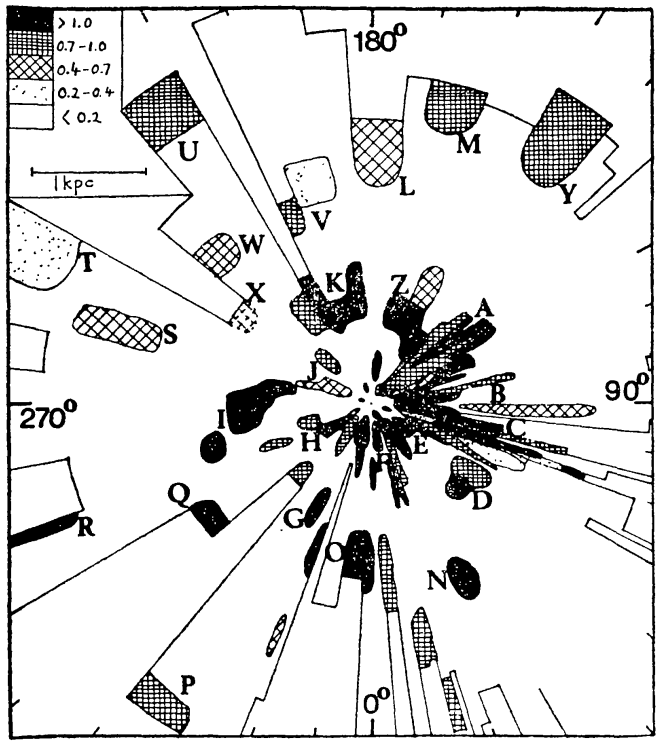

Figure 3 Map of extinction by dust within 2.5 kpc of the Sun derived by FitzGerald (1968). Shading indicates the change in B−V color excess per kpc.

Pole (NGP), Feltz (1972) found the B−V color excess to be $0.^{m}000 \pm 0.^{m}002$, a result contradicting most earlier work. A similar result was found by Philip & Tifft (1971), except for a small patch near the NGP where $E(B-V)=0.05$ mag, and Philip (1972) also found the reddening to be essentially zero ($\lesssim 0.01$ mag) within 40° of either the North or the South Galactic Pole. Feltz suggests that the discrepancies relative to earlier determinations are due to systematic errors in the previous photometric measurements. The new results are in serious conflict with the polar extinction as determined from Galaxy counts assuming the cosecant law, which gives values corresponding to (for $R=3.3$) $E(B-V) \simeq 0.07$–0.12 mag (Shane & Wirtanen 1967, de Vaucouleurs & Malik 1969, Noonan 1971). The results may be reconciled by assuming an appreciable amount of neutral absorbing material whose relative abundance is higher away from the galactic plane (Neckel 1967). However, since additional evidence for this component is lacking, it seems that the cosecant law for galactic extinction must be used with extreme caution and may be invalid in areas close to the galactic pole.

The correlation between dust and gas is an important problem and has been a matter of controversy for many years. A significant improvement in this situation is due to the recent OAO observations of Ly-α in absorption (Jenkins 1970, Savage & Code 1970, Savage & Jenkins 1972). These measurements necessarily refer to the same regions of space as the corresponding optical extinction mea-

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surements, and make possible a much more reliable study of the HI-to-dust correlation. Figure 4 shows the results of Savage and Jenkins for the hydrogen column density versus the B−V color excess of 69 stars, most of which are within 500 pc of the Sun and at galactic latitudes $|b^{\mathrm{II}}|<20°$. Although there is a fair amount of scatter in the data, there is definitely a positive correlation, and Savage and Jenkins give the average ratio as

$$N_{\mathrm{H}}/E(\mathrm{B}-\mathrm{V}) \simeq 5 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1} \tag{3}$$

This is in excellent agreement with "Lilley's Law" (Lilley 1955, Heiles 1967) of $N_{\mathrm{H}}/\Delta m_{\mathrm{pg}}=1.1\times10^{21}$ atoms cm^{-2} mag^{-1} determined from observations of 21-cm peak brightness temperatures and photographic extinction of external galaxies at high and intermediate galactic latitudes in the anticenter direction ($\Delta m_{\mathrm{pg}}\equiv4.3$ E(B−V) for $R=3.3$). It is also in fair agreement with a comparison of 21-cm

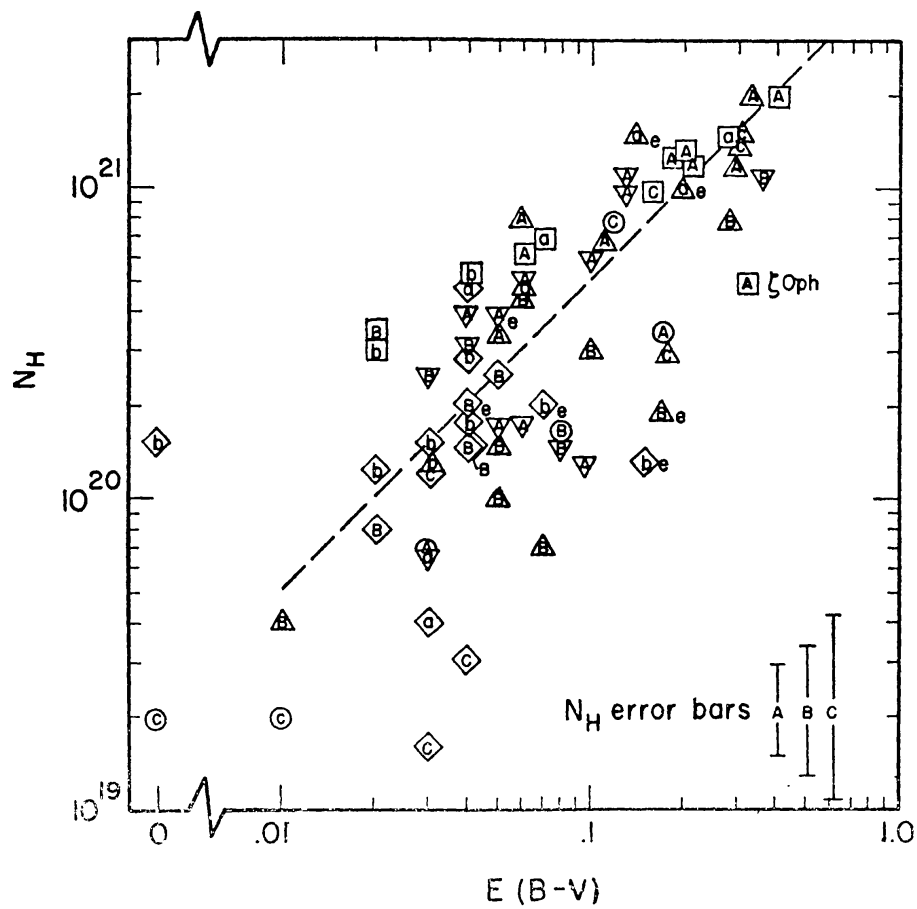

Figure 4 Comparison of measured column densities of neutral hydrogen versus the B−V color excess for stars of various spectral types (Savage & Jenkins 1972). The dashed line represents the weighted average of 5x10^{21} atoms cm^{-2} mag^{-1} for the observed N_H to E(B−V) ratios.

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absorption measurements and visual extinctions in the directions of 17 radio sources with $|b^{\mathrm{II}}| \leq 30°$ (Rohlfs 1971) and with observations of 21-cm emission and color excesses in the direction of ten globular clusters (Kerr & Knapp 1972).

We may conclude that the new observations support the correlations of hydrogen column densities and interstellar visual extinction, at least for objects confined to within $\sim 20°$ of the galactic plane and within 1 kpc of the Sun. On the other hand, some of the scatter in Figure 4 is probably real. Savage and Jenkins suggest that the lower points in the diagram may be due to varying degrees of depletion of atomic hydrogen by molecule formation or by ionization. Additional evidence for the first suggestion is discussed later. The second suggestion is supported by the evidence for substantial extinction by grains within or just outside HII regions as suggested by the regional variations in the far-uv extinction curves for O and B stars. In this case, the decrease in the gas-to-dust ratio could be offset by an increase due to ejection or destruction of the nebular grains. However, Schmidt (1970) found that stars of earlier spectral classes seemed to have smaller hydrogen-to-dust ratios than stars of later spectral classes, implying that the effect of ionization is more important. It may also be suggested that some of the variation in the observed ratio of column density to extinction is due to the growth of grain mantles within ordinary HI clouds, as discussed by Aannestad (1971).

Small-scale studies of dusty areas often show a breakdown in the positive correlation referred to above (Heiles 1969, Garzoli & Varsavsky 1970, Sancisi & Wesselius 1970, Sancisi 1971, Mahoney 1972) in the sense that the 21-cm emission is strongly deficient relative to the optical extinction values. In some cases a positive correlation is found, but with a much smaller value for the linear coefficient (Varsavsky 1968, Braumsfurth & Rohlfs 1972). In other cases an anticorrelation seems to exist (Mészáros 1968). There are at least two possible explanations for this effect. The first is that atomic hydrogen is preferentially converted to molecular hydrogen on surfaces of interstellar grains inside clouds with more than normal interstellar extinction, according to the picture developed by Hollenbach, Werner & Salpeter (1971). They predict that large-scale conversion should take place when the optical extinction through a cloud exceeds about 1 mag, and for extinction values $\Delta m_V \gtrsim 2$ mag find approximately $M_{\mathrm{H}} \propto M^{0.5}(\Delta m_{\mathrm{V}})^{-1.5}$ where M is the cloud mass. Quantitative comparisons with hydrogen line emission or absorption, however, is made difficult because of line saturation and foreground effects.

The second explanation is that the neutral hydrogen in dusty areas is much colder than the usually assumed temperature of about 100°K, so that optical depth effects cause an underestimate of the actual column density in 21-cm emission observations. Since independent observations indicate that dust clouds may have temperatures as low as 10°K (Heiles 1971), this could undoubtedly be an important effect. However, it cannot be the only answer since Quiroga & Varsavsky (1970) found from 21-cm absorption observations a relative *decrease* in the optical depth in the direction of a dust cloud in the Omega Nebula. The problem of separating the effects of variations in abundance and temperature of

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atomic hydrogen when foregound effects may be important is difficult, and independent observations of other atomic and molecular species would clearly be of value.

EXTINCTION RATIO The extinction ratio R is defined as the ratio of the visual extinction in magnitudes to the B−V color excess, that is,

$$R = \Delta m(\lambda_V)/E(B - V) \tag{4}$$

Different methods have given values of R ranging from 3 to more than 6 in certain regions of the sky, and Johnson (1968) presented evidence that indicated a strong dependence of R upon the galactic longitude ℓ^{II}, with a broad maximum of about 6 in the region $\ell^{\mathrm{II}}=100°$–$230°$. However, some of the large values of R may be the result of excess infrared emission associated with the stars (Johnson 1967, Gebel 1968), or, as shown by repeated observations of the Associations III Cephei (Garrison 1970) and I Ara (Becker 1966), may be the results of an accidental inclusion of foreground and background stars. Also, since large values of R tend to occur in regions near hot stars (Johnson 1968), destruction or ejection of small grains due to the stars' radiation field may cause large values of R as well as anomalously small far-uv extinction. Furthermore, using the change in the Oort rotation parameter A as a test for anomalously large values of R, Fernie & Hube (1968) concluded that, whatever the absolute value of R, there is no significant difference in R between the regions $\ell^{\mathrm{II}}=0°$–$80°$ and $\ell^{\mathrm{II}}=100°$–$233°$. Isobe (1968), in an investigation by the variable extinction method, concluded that $R=3.0$ for stars at distances larger than about 1 kpc and at galactic longitudes $\ell^{\mathrm{II}}=80°$–$210°$.

Clearly, a representative value of R on a galactic scale must either avoid or outnumber exceptional regions, and new and independent determinations of R are needed. Recently, Ireland & Nandy (1969), Bell & FitzGerald (1971), Martin (1971a), and Crézé (1972) have proposed methods based on models for the differential rotation of the Galaxy, and Rössiger (1971) has proposed a method based on star counts in two different colors in an area containing a dark cloud. In most of these investigations, as well as in recent investigations by the cluster-diameter method (Harris 1972) and by the color-difference method (Lee 1970), there is no evidence for systematically large values of R on a galactic scale. Some of the results are listed in Table 1; they give a weighted mean value of $R=3.3 \pm 0.5$. Crézé (1972) investigated 331 Cepheids, HII regions, and open clusters and also found average values compatible with $R=3$. However, his data suggested a correlation with the local spiral structure in the sense that measurements with the line of sight within the local spiral arm ($\ell^{\mathrm{II}}\sim 70°$ and $220°$) produced values of R larger than average ($R=4$–5), while measurements for objects outside the local arm at $\ell^{\mathrm{II}}\sim 280°$ produced fairly small values ($R=1.5$–3). This disagreement with the investigations listed in Table 1 may be due to inadequate and different statistical samples taken as a function of distance and direction from the Sun, but the suggested correlation deserves further study.

For the time being, it seems reasonable to conclude that, on the average, the

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Table 1 Determinations of the ratio R of visual extinction to B−V color excess

Method	Statistical Sample	R	Reference
Color-difference	145 high-luminosity, M-type stars, $\ell^{II}=0°–240°$	3.6 ± 0.3	Lee (1970)
Kinematic	132 cepheid variables, $\ell^{II}=0°–360°$	3.5 ± 1.0	Bell & FitzGerald (1971)
Kinematic	120 OB stars, 42 cepheids, 17 galactic clusters, $\ell^{II}=0°–360°$	$3.3^{+0.7}_{-0.5}$	Martin (1971a)
Cluster-diameter	156 open clusters, $\ell^{II}=0°–360°$	3.15 ± 0.20	Harris (1972)

extinction ratio is fairly constant in the solar neighborhood and that deviations from an average value of about 3.3 to values much greater than 4 are due to very localized conditions, such as may occur in or near young open clusters, diffuse nebulae, and infrared stars. For distances more than a few kpc from the Sun and for objects located outside the spiral arms, the extinction ratio is not well known and may differ considerably from the local neighborhood value.

REGIONAL VARIATIONS IN INTERSTELLAR EXTINCTION We have seen from the determinations of the extinction curve and the extinction ratio that individual objects or local regions may differ substantially in their extinction properties. Savage (1972) has pointed out that five out of six stars with abnormal near-ultraviolet extinction curves are associated with nebulosity, and the same general association was found by Lee (1968) for the visual and near-infrared wavelength regions. Savage also noted that abnormal extinction seems to correlate with a large ratio of yellow-to-blue polarization. On the other hand, all stars associated with nebulosity or HII regions do not necessarily show extinction anomalies (Lee 1968, Anderson 1970). In a more detailed study, Goy (1972) found that O stars that are situated outside HII regions or are isolated seem to have a fairly homogeneous reddening law with weak extinction in the near ultraviolet, while stars situated within HII regions show amounts of near-ultraviolet extinction varying from the strongest to the weakest. The latter stars showed a significant correlation between the amount of near-uv color excess and a concentration parameter related to the density of the obscuring matter near to or inside the HII region. Stars situated in a dilute HII region have weak near-uv absorption similar to that of stars not closely associated with HII regions. The curves in Figure 1 seem to show a possible correlation between a small slope in the blue and near ultraviolet and small amounts of far-uv extinction. If the correlation found by Goy is general, this implies that "anomalous" extinction curves may be more representative of typical interstellar extinction than the "average" curve in Figure

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1. It should therefore be stressed that more observations of individual reddening laws, especially of objects removed from HII regions and young associations, are needed before the shape of the "average" interstellar extinction law can be considered to be well determined.

The best examples of "nonnormal" behavior are the east Belt and the center regions of the Orion Nebula. Lee (1968) found that in both cases there is a steep infrared-extinction gradient, and the value of R is >5.5. The Trapezium stars also show much less near-ultraviolet color excess than, for example, the Cygnus region (Divan 1971) and θ^{1+2} Ori shows essentially neutral extinction in the far ultraviolet and has the smallest uv extinction hump of all the stars so far observed (Carruthers 1969a,b, 1970b, Bless & Savage 1972). The anomaly in the center of the Orion Nebula is confined to a region within 15′ of θ^2 Orionis, which corresponds to a distance of about 2.5 pc. Thus regions close to the hot stars, probably the immediate surrounding HII region, may be responsible for the anomalous extinction curves in the ultraviolet. Close-by dust would also be heated by the starlight and radiate in the infrared, providing a natural explanation for the apparent correlation of anomalous uv extinction and an excess of infrared emission.

A plausible explanation for extinction curves that show a small extinction hump and are relatively flat in the ultraviolet is that the extinction is produced by material with a modified size distribution and/or composition due to the radiation field of the star (Carruthers 1969b, Bless & Savage 1972). Destruction or ejection of small particles would tend to produce a gray extinction. Furthermore, one would expect to find objects, depending upon the age of the system, where varying amounts of ultraviolet extinction occur. The correlation found by Goy between the weakness of the near-uv extinction and the diffuseness of the HII region may indicate such an effect. On the other hand, even the cases with a fairly flat extinction curve throughout most of the far ultraviolet show the "usual" rapid increase in extinction in the extreme far ultraviolet ($1/\lambda > 8\ \mu^{-1}$), implying that ejection or destruction cannot be equally effective for all small particles.

Anomalous extinction curves may also be a consequence of an abnormally large stellar flux radiated between 2500 Å and 1100 Å (Weber, Henry & Carruthers 1971, Carruthers 1971). This possibility is strengthened by the fact that several visually unreddened or only slightly reddened stars show the same abnormal brightness in this wavelength region. The existence of apparently overluminous stars needs further investigation, both observationally and theoretically. Finally, dust associated with the stars may scatter radiation into the line of sight. Both θ^{1+2} Ori and σ Sco are associated with nebulosity. However, observations of these objects show that the ultraviolet radiation comes from sources $<1'$ in angular diameter, making nebular contamination very unlikely (Savage 1972).

3. *Theoretical Extinction Curves*

Interstellar extinction curves have now been determined over the whole wavelength range from 0.3 μ^{-1} to 9 μ^{-1} (Figure 1), and any single type grain model would be subject to fairly stringent constraints. However, as discussed above, the

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apparent lack of correlation between various parts of the extinction curve implies a multiple model for the interstellar grains, thus severely compromising the uniqueness of any proposed model. Furthermore, unless realistic wavelength-dependent refractive indices are used in the computations, a fit to the observed extinction curve often becomes a mere exercise in finding the "correct" relative abundances and size distributions whose validity is difficult to determine on other observational grounds. We also want to emphasize that interstellar particles are most likely of varying sizes and shapes, and that calculations using the Mie theory apply only to spherical particles. In experimental studies of submicron particles of iron, carbon, silicon carbide, and silica, Lefévre (1970) observed a variety of shapes, including some very complex ones. The effect of some types of surface roughness on extinction cross sections has been discussed by Greenberg, Wang & Bangs (1971) and by Shah & Vardya (1972). Unless it can be shown that a theoretical extinction curve is fairly insensitive to variations in the shapes and sizes of the particles, any conclusions as to the nature of the particles must be regarded as highly uncertain.

Although the ultraviolet part of the extinction curve has been determined only for a selected set of objects where local extinction may also be important, we assume, for the sake of this discussion, that the general interstellar extinction law is well represented by the "average" extinction curve in Figure 1. This curve is characterized by a change of slope at 2.3 μ^{-1} and by a well-defined, fairly symmetrical peak at 4.6 μ^{-1}; it has a flat extinction minimum in the far ultraviolet ($5\ \mu^{-1}<\lambda^{-1}<8\ \mu^{-1}$) and a rapidly rising extinction in the extreme ultraviolet ($\lambda^{-1}>8\ \mu^{-1}$). Below we discuss how well various grain models may account for this curve.

ICE GRAINS An extinction curve for "dirty" ice grains (assumed refractive index $m=1.5\text{–}0.05i$) that fits the observations in the visible region (grain radii $\sim$0.12 μ) levels off at about 4 μ^{-1} and cannot reproduce the uv extinction hump nor the amount of far-uv extinction (Krishna Swamy & O'Dell 1967b). If the strong uv absorption of H_2O and CH_4 is taken into account (Field, Partridge & Sobel 1967, Greenberg & Lind 1967, Greenberg & Shah 1969), the uv extinction for spherical particles increases considerably, but becomes essentially flat for $\lambda^{-1}\gtrsim 6\ \mu^{-1}$. Calculations for a two-component size distribution of infinite dielectric cylinders (Greenberg & Shah 1969) as well as for dirty ice with a small percentage of molecules and metallic compounds (Krishna Swamy, Jackson & Donn 1971) give only small improvements and it seems that dirty ice grains of various shapes, sizes, or refractive indices can be ruled out as the main contributor to the interstellar extinction in the ultraviolet. This is qualitatively consistent with the relative amount of H_2O in the grains as determined from the infrared absorption observations (Gillett & Forrest 1973).

GRAPHITE GRAINS The strongest support for graphite as a major contributor to interstellar extinction is the existence of a strong absorption peak in the 2200-Å region, thus coinciding with the observed extinction hump. Although sometimes

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referred to as the "signature" of graphite, this identification may, however, not be unique (discussed subsequently). Emphasizing that the feature in graphite is due to plasma oscillations, Gilra (1972) shows that the exact position and width of the resonance feature depends upon the size and shape of the particles, with increasing size and oblateness shifting the feature to longer wavelengths. If graphite particles are to explain the observed extinction hump, the particles must be fairly small with a mean radius $\simeq 0.02\ \mu$, be nearly spherical, and have almost no coating whatsoever. Such grains produce an extinction minimum that coincides well in wavelengths with the observed broad minimum in the far uv and furthermore give a rising extinction in the extreme ultraviolet, with a peak at about $10\ \mu^{-1}$, roughly equal in height to the $4.6\text{-}\mu^{-1}$ peak (Gilra 1971). However, the observations indicate a much less pronounced minimum and a $9\text{-}\mu^{-1}$ to $10\text{-}\mu^{-1}$ extinction larger than the extinction at $4.6\ \mu^{-1}$. Furthermore, the small grains also give too little extinction at wavelengths longward of the $4.6\text{-}\mu^{-1}$ peak. Larger graphite grains with an appropriate size distribution (radii $\sim 0.05\ \mu$) improve the fit for the longer wavelengths, but are wholly unsatisfactory for $\lambda^{-1} > 5\ \mu^{-1}$, and shift the peak to $4.4\ \mu^{-1}$ (Wickramasinghe 1970a). One may conclude that small graphite particles can explain the extinction hump, but that other components are then needed to satisfy the observations for other wavelength regions.

Turning to another form of carbon, we note the suggestion of Saslaw & Gaustad (1969) that carbon may condense in cool stellar atmospheres in the form of diamond grains that are subsequently injected into interstellar space. Donn & Krishna Swamy (1969b) pointed out problems with the formation of diamonds, and from extinction calculations Wickramasinghe (1969) obtained not even a rough agreement with the interstellar extinction curves. However, using a somewhat more specialized size distribution, Landau (1970) obtained a fit to within $1\frac{1}{2}$ error bar of all the observations from the infrared to the extreme uv. As emphasized by the latter author, this does not "prove" the existence of interstellar diamonds, but rather illustrates that a rough fit to the extinction observations can often be contrived for a material, if the size distribution is suitably adjusted.

POLYCYCLIC HYDROCARBONS Polycyclic aromatic molecules have been suggested as a possible source for the interstellar extinction (Donn 1968, Vdovykin 1970). Donn & Krishna Swamy (1969a) calculated the extinction curves for a combination of selected polycyclic aromatic molecules, but unfortunately their curves end at 3000 Å since insufficient measurements are available for shorter wavelengths. It appears that the curves level off at about $3\ \mu^{-1}$, but the extinction may increase again for shorter wavelengths, as shown by the absorption peak at about 2500 Å in anthracene and its derivatives. For a mixture of such derivatives, the fine structure would be more or less smoothed out, approaching the rather featureless character of the observed extinction curve. One would expect, however, that much of the uv absorption must be due to photodissociation and photoionization, thus requiring an efficient process for renewal. Also, if the extinction

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is due to true absorption in the far and extreme uv, the albedo should be low at these wavelengths, which is contradicted by the observations of the diffuse galactic light (Witt 1972).

SILICATE GRAINS We remarked earlier that infrared spectra of a few highly reddened objects show strong absorption features in the 10-μ region, indicating the possible existence of silicates in interstellar grains. A similar feature in emission has been observed in many late-type stars (for a review see Neugebauer, Becklin & Hyland 1971), and seems to fit the emission from basic silicate particles such as enstatite and olivines (Dorschner 1971b, Gammon, Gaustad & Treffers 1972). However, no one substance can match the circumstellar features exactly, but particles of different sizes, shapes, and compositions will tend to smooth out any fine structure. From the observed width of the 10-μ absorption feature in Figure 2, it seems that most or all of the different types of silicates may be included as absorbers.

Manning (1971) suggested that the 2200-Å absorption feature is similar in origin to the 2250-Å band observed in the spectra of the terrestrial Fe of Al-bearing quartz, and Huffman & Stapp (1971) determined experimentally the optical constants for enstatite. The latter authors obtained an extinction curve with a strong peak at 4.5 μ^{-1}, which fitted the observations reasonably well for wavelengths longward of the peak. Shortward of the peak, the curve is flat, and enstatite can thus not explain the increasing extinction in the extreme uv. Although silicates appear better suited than graphite to explain both the extinction hump and the flat minimum beyond the hump, calculations seem to show that the 4.5-μ^{-1} feature is extremely sensitive to the particle size (Wickramasinghe & Nandy 1971b, Gilra 1972). The sensitivity to particle size (and hence to particle shape) is a major objection to ascribing the extinction hump to silicates. The same objection holds to a lesser degree to graphite grains. Furthermore, as was the case for the small graphite grains, the observed visible extinction cannot be accounted for unless other components different in either composition or size are included. However, these conclusions are based entirely on the calculations for one silicate material (enstatite) only, and experimental determination of the optical constants for other materials are obviously needed.

CORE-MANTLE GRAINS Calculations of extinction curves for graphite particles surrounded by a dirty ice mantle, taking into account the far-uv absorption of dirty ice, have been performed by Greenberg & Lind (1967), Greenberg & Shah (1969), and Donn & Krishna Swamy (1969a). However, the curves show two extinction peaks and are essentially flat in the far and extreme uv, in disagreement with existing observations. It appears (Gilra 1972) that only very small or negligible amounts of "ice" can actually be present as a mantle if the 4.6-μ^{-1} observed feature is due to graphite.

Calculations of the extinction curves for graphite particles covered with solid hydrogen (Wickramasinghe & Nandy 1968, Wickramasinghe & Krishna Swamy 1969) and for quartz particles covered with dirty ice (Krishna Swamy & Wick-

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ramasinghe 1968a) are equally unsatisfactory in their match to the observed extinction curve. Also, for a solid H_2 mantle, Graham & Duley (1971) found that using measured refractive indices gave characteristic spectral variations for $\lambda^{-1} > 8.5\ \mu^{-1}$ that were in disagreement with the ultraviolet observations.

MIXTURES OF GRAINS The shortcomings of one-component grain models have prompted a search for mixtures of grains that will explain the extinction observations. Unless independent arguments can be given for a particular choice of the relative abundances and sizes, it becomes even more important than in the case of a one-component model to include realistic wavelength-dependent refractive indices. Since these are not always available, however, some multiple-component models may be no more than arbitrarily selected solutions.

We have seen that there are spectral features in the infrared and in the ultraviolet indicating the existence of silicates and graphite, which individually may be related to either one or both of the features. Calculations of extinction curves for a graphite-silicate mixture (Hoyle & Wickramasinghe 1969) and for a similar mixture with the silicates covered by ice or solid H_2 (Wickramasinghe 1970a) show a wide extinction hump as well as one or two extra, equally conspicuous maxima in the far uv. Although very small graphite particles ($\lesssim 0.02\ \mu$) may improve the agreement, the predicted extinction by such mixtures must still be considered in disagreement with the observed extinction curves in Figure 1.

In general, most of the models provide too little extinction in the far ultraviolet. Huffman & Stapp (1971) added 12% by volume of small ($\sim$100 Å) iron oxide grains to the enstatite grains and achieved a fair fit to the extinction curve for ζ Oph (Figure 1) up to $\lambda^{-1} \lesssim 8\ \mu^{-1}$, at which point the calculations again gave too little extinction. Wickramasinghe & Nandy (1970, 1971a,c) added iron grains to the graphite-silicate mixture and also achieved a rough fit to the data for $\lambda^{-1} < 8\ \mu^{-1}$. However, the extinction feature due to graphite appears much broader than allowed by the recent observations, and the calculated curves seem more representative of the anomalous extinction curves, except that the extinction longward of the "hump" rises more steeply than the observations indicate.

Another component that may provide fairly uniform extinction throughout the ultraviolet is silicon carbide, which may be ejected from stellar atmospheres (Gilman 1969, Friedemann 1969a,b). Extinction calculations were performed by Gilra (1971) for a mixture of graphite, meteoritic silicate, and silicon carbide particles, and this model has so far provided the "best" fit to the observed extinction curves. The model predicts that the mass ratios of silicon carbide and silicate grains relative to graphite grains are about 4 and 5, respectively. This requires about three times more silicon in the grains than is actually available from cosmic abundances, but Gilra argues that a different size distribution with fewer small grains may relieve this problem without changing the extinction curves. One shortcoming of this model is the sensitivity of the extinction hump to variations in the sizes or shapes of the graphite component. Also, it does not embody a realistic wavelength-dependent refractive index for the silicate component in the far uv.

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From the preceding discussion, it is clear that the gross features of the extinction curve in Figure 1 may easily, but not uniquely, be reproduced by a mixture of grains of which small graphite particles are one component, but where otherwise only a bimodal size distribution of dielectric grains is needed. The larger grains may account for the extinction in the visible and infrared wavelength regions, while the smaller grains cause the increasing extinction in the ultraviolet. Such a distribution is consistent with the albedo and phase-function requirements discussed below. Of course, a wholly convincing model must account for the observed polarization as well as the observed extinction and scattering. Nor can the burden of producing the polarization be allotted to a minor constituent of any mixture (Section 8).

THE TOTAL AMOUNT OF DUST The models that have been described generally lead to estimates of the average spatial density of condensed matter ρ_d, roughly representable by

$$\rho_d \sim 10^{-26}\rho_g(\Delta m_V/L) \tag{5}$$

where ρ_g is the density of a grain and $\Delta m_V/L$ is expressed in mag/kpc. In fact, a condition on the amount of matter required to produce the observed extinction can be derived from quite general principles (Purcell 1969b). The idea is that a certain integral over the observed extinction function Δm_λ can be related by the Kramers–Kronig relations to the *static* dielectric constant of the "medium" vacuum-plus-dust, which in turn depends only upon the fraction of space v_d occupied by grain material, upon the shape of the grains, and upon ϵ_0, the static dielectric constant of the grain material. The lowest possible v_d is attained for $\epsilon_0 = \infty$ (metallic grains, or what is practically equivalent, grains with $\epsilon_0 \gg 1$ at low frequencies). If we assume that the grains are spherical, the "average" extinction curve in Figure 1 leads directly, without further assumptions, to

$$v_d \geq 4.3 \times 10^{-27}\Delta m_V/L \tag{6}$$

Thus, for example, in any region characterized by a visual extinction of 2 mag/kpc we must expect to find at least $8.6\times10^{-27}\rho_g$ gm/cm³ of dust. Together with the empirical relation between n_H and Δm_V [equations (3) and (4)] this would imply a dust/hydrogen ratio

$$\rho_d/\rho_H = 0.5 \times 10^{-2}\rho_g \tag{7}$$

with ρ_g in gm/cm³. The equality applies above only if $\epsilon_0 \gg 1$ and only negligible contributions would have been made to the integral by spectral regions omitted. For spheroidal grains one obtains a somewhat lower limit on v_d.

This result applies equally well to grain mixtures. It can be applied with only slight modifications to "grains" that are nothing but large molecules, and in that form disposes of the recurring conjecture that absorbing molecules might produce a given extinction with much less total mass of material, as compared with macroscopic grains. Indeed, the general conclusion may be drawn that in any

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model or mixture of models that reproduces the whole extinction curve, the total volume occupied by grain substance will be largely independent of grain size and not strongly dependent on grain composition.

4. *Scattering of Light by Grains*

Something can be learned about the grains by observing scattered starlight, either the diffuse galactic light (DGL) caused by the scattering of general starlight in the galactic disc, or light from reflection nebulae where the dust is illuminated by a bright star. The goal is to deduce the grains' albedo a, that is, the ratio of scattering cross section to total extinction cross section, and also the "phase factor" g, which is simply $\overline{\cos\theta}$ where θ is the scattering angle. To extract finer details of the angular dependence of scattering is presently hopeless. Even a and g are rather indirectly related to the variable actually observed, which in the case of DGL is the intensity of the diffuse background as a function of galactic latitude.

The observations of DGL in the visible spectrum by Witt (1968) have been analyzed by van de Hulst & de Jong (1969). It turned out that a and g could not be separately extracted. For any g value between 0.0 (isotropic scattering) and 1.0 (totally forward scattering) there is a value of a that produces a fit. According to van de Hulst and de Jong, a ranges from about 0.7 for $g=0.0$ down to 0.2 for $g=1.0$, with very little difference between the results derived from observations with a B filter ($\lambda_{\text{eff}}=4350$ Å) and those derived from U-filter observations ($\lambda_{\text{eff}}=3600$ Å). Mattila (1971), analyzing the data of Witt in a somewhat different way, including allowance for concentration of the dust in clouds, got rather similar results except that his albedo values are generally 0.1 to 0.2 higher. If one now considers the a and g values that are predicted by various grain models it appears that graphite-with-ice-mantle grains fall closest to the a–g locus of van de Hulst and de Jong, in the neighborhood of $a=0.5$, $g=0.5$, while "dirty ice" falls closest to Mattila's curve, around $a=0.7$, $g=0.75$. More generally, both papers indicate that the albedo cannot be greater than 0.7 or less than 0.2 and that the forward scattering is strong.

Studies of the diffuse galactic light have been extended into the ultraviolet by rocket and satellite observations. Hayakawa, Yamashita & Yoshioka (1969) reported rocket measurements of diffuse radiation in the far uv, 1350 Å–1480 Å, looking toward the galactic anticenter. Their data did not yield very definite grain parameters, mainly because of uncertainty in the optical depth of the galactic dust distribution at these wavelengths, but are consistent with a fairly high albedo (Rozkovskij & Matjagin 1971, Yoshioka 1972). Sudbury & Ingham (1970) analyzed photometric scans of the Milky Way between $\ell^{\text{II}}=72°$ and $\ell^{\text{II}}=126°$, around 2500 Å. As concerns the dust albedo, they found some evidence for a significantly low albedo within their window of 2020 Å to 2790 Å.

Far more data has now come from photometers aboard OAO-2, with striking implications about grain properties. Witt & Lillie (1972, 1973) have obtained from these measurements the albedo of interstellar particles, as a function of wavelength, from 1500 Å to 4250 Å (Figure 5). At the long-wave end they find $a\simeq0.5$, in reasonable agreement with the analyses of ground-based observations.

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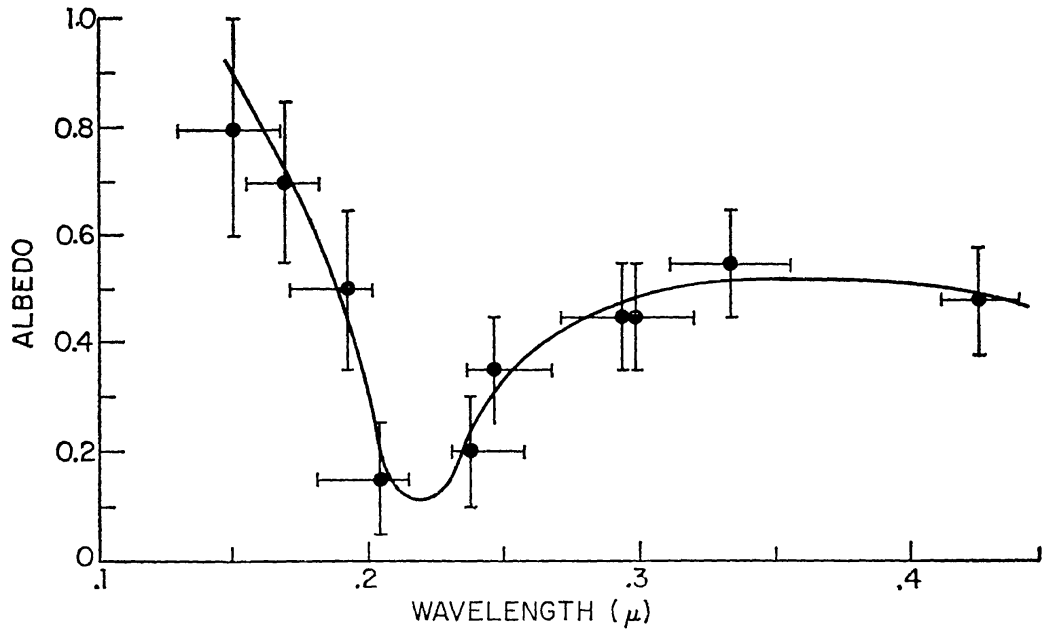

Figure 5 The albedo of interstellar dust as a function of wavelength based on OAO-2 measurements of the diffuse galactic light (Witt & Lillie 1973).

The albedo shows a deep minimum, approximately 0.2, around 2200 Å, the location of the extinction "hump." From 2000 Å down to 1500 Å, *a* rises rapidly to a value near 0.8. The scattering is strongly forward, they find, down to 1800 Å, but at shorter wavelengths it is much more nearly isotropic.

The implication of the albedo dip is not unexpected: the 2200-Å extinction hump must be due to practically pure absorption. More surprising is the high albedo at 1500 Å, which with the accompanying low *g* value seems to require extremely small, highly transparent particles. Witt (1972) regards these results as supporting a strongly bimodal grain size distribution, and suggests that the behavior of the extinction, albedo, and phase factor over the whole range might be explained by a mixture of big icy grains dominating the visual spectrum, dielectric grains much smaller and more numerous dominating the uv, plus graphite particles contributing the absorption peak at 2200 Å. The nature of such dielectric particles remains an enigma, and the question of polarization has not been addressed.

Lillie & Witt (1972) have reported uv observations of the surface brightness of the Merope Nebula and of Barnard's Loop Nebulae. From the Merope observations they derive an albedo curve that resembles their result for the interstellar medium in exhibiting the rise in *a* below 2000 Å, but lacks the pronounced dip associated with the 2200-Å absorption feature—suggesting a deficiency of the graphite-like grains in the local radiation field. From the Barnard's Loop observations, however, they obtain albedo values that agree rather well with their DGL results, including the absorption dip.

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An extensive review on reflection nebulae and the nature of interstellar grains has been given by Ványsek (1967). Calculations (Hanner 1971) of models of reflection nebulae have shown that the observed range in colors across a nebula is larger than predicted for particles composed of either graphite, silicates, or ice.

The albedo and phase-factor determinations have a decisive bearing on the possibility of explaining the extinction curve, or a portion of it, by free molecular complexes—for example, the polycyclic aromatic compounds discussed by Donn & Krishna Swamy (1969a). These would surely scatter isotropically and therefore appear to be ruled out wherever $g>0$, if not also by the albedo. The high albedo in the far uv appears to rule out, as Witt noted, absorption by H_2^+ (suggested by Stecher & Williams 1969) as the cause of the extinction in that region.

5. *Diffuse Interstellar Absorption Lines*

Diffuse absorption lines of interstellar origin are usually attributed to material residing in the interstellar grains. Supporting that interpretation is the fact that the lines, or bands, are wide and featureless. Also, their intensity correlates to some extent with the general interstellar extinction (Wampler 1966, Kellman 1970). Alternative explanations involving absorption by free molecules have been suggested (Herzberg 1967) for one or more of the features, but no specific proposals have yet met the requirements. We shall not discuss that possibility; for the purposes of this review we simply adopt the hypothesis that the diffuse interstellar absorption lines are associated with the grains. Naturally the case for origin in the grains will be strengthened if plausible grain models can account in detail for the absorption features.

Earlier observations of the diffuse interstellar lines have been reviewed by Herbig (1967). York (1971) has recently carried out a photographic study of the extinction curves for twelve stars. Interstellar features were extracted by subtracting spectra of nonreddened comparison stars. Figure 6, summarizing York's results schematically, is reproduced from his paper, which should be consulted for a discussion of the individual spectral features. Conspicuous common features, in addition to the famous absorption line, or band, at 4430 Å, are seen close to 4765 Å, 4880 Å, 5780 Å, 5800 Å, 6180 Å, and 6280 Å. York also discerns some broader absorption bands, extending over more than 100 Å, in some of the spectra. As for line strength, although there is some disagreement among observers, a useful round number for the 4430-Å band can be obtained from York's tabulation of equivalent widths W, and the corresponding color excess values E_{B-V}. Within a factor of 2 or so, his values for W_{4430} fit the relation

$$W_{4430}\ (\text{Ångstroms}) = 3 \times E_{B-V}\ (\text{mag}) \tag{8}$$

as did the data assembled by Lynds (1969). Thus for HD 183143 with $E_{B-V} = 1.36$ mag, York finds an equivalent width $W_{4430} = 4.4$ Å. (The actual width of the absorption dip appears to be 30 to 40 Å.) If we use 3.3 for $\Delta m_V/E_{B-V}$, the ratio of total to selective extinction (Section 2), we can derive from the empirical relation above a prescription for the number N of individual absorbers with oscillar

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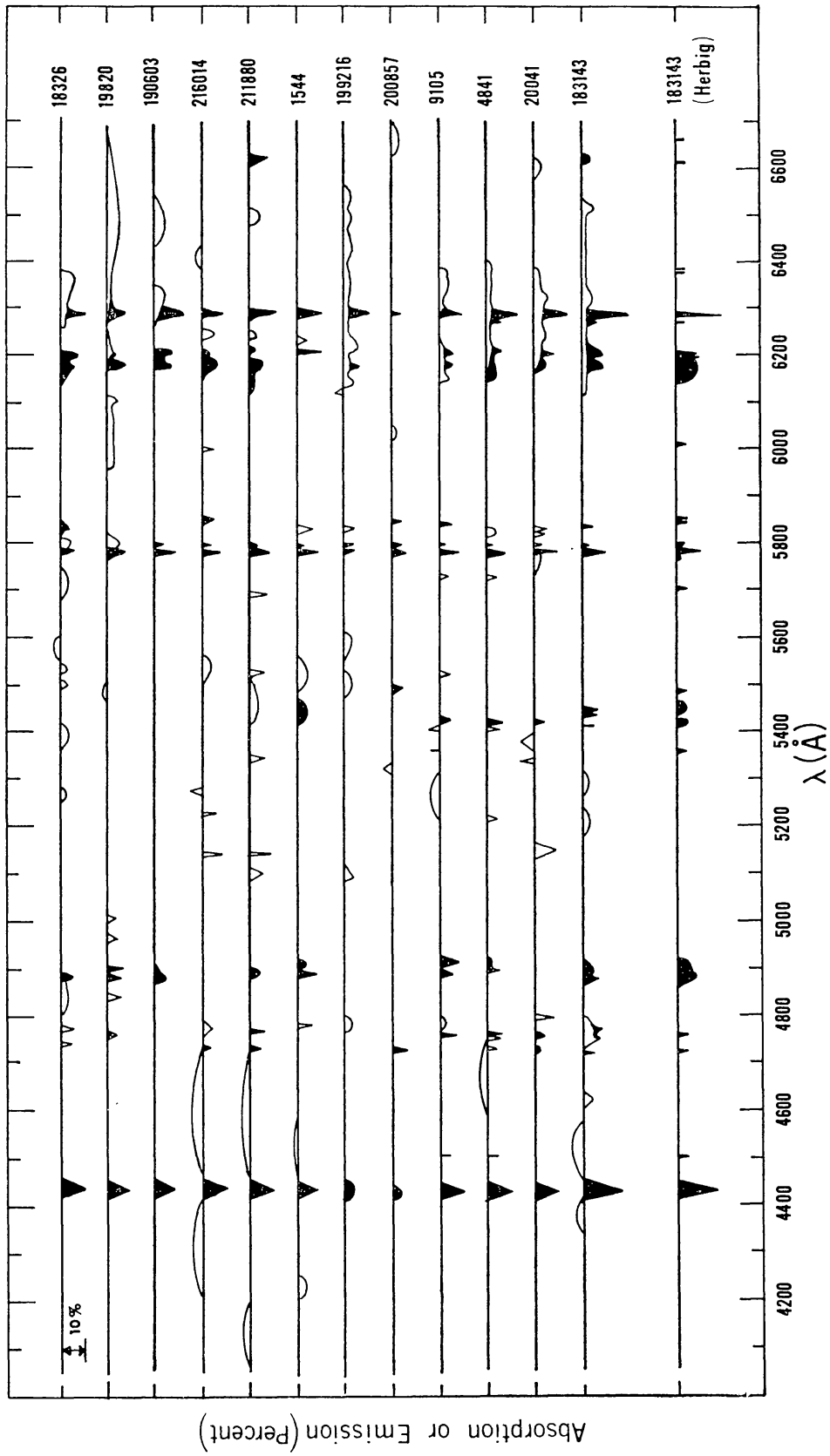

Figure 6 Schematic diagram of the interstellar features, from York (1971). Filled-in features correspond in wavelength to features discovered by Herbig in HD 183143 (bottom spectrum). Features are represented as absorption (pointing downward) or emission with respect to a continuum curve drawn independently for each star (horizontal lines).

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strength f, per cm² per magnitude of visual extinction, which would be required to produce the 4430-Å band:

$$Nf = 5 \times 10^{12} \text{ cm}^{-2} \text{ mag}^{-1} \tag{9}$$

Thus 2 mag/kpc of visual extinction calls for a volume density of 4430-Å absorbers amounting to $3 \times 10^{-9} f \text{ cm}^{-3}$. This provides one firm constraint on speculation about the nature of the absorbers.

Correlation between different features has been clearly established by Murdin (1972) for the 4430-Å and 6284-Å lines. Studying 48 stars, he found essentially complete correlation in the variation of these lines from region to region. Wu (1972) observed the lines at 5780 Å and 5797 Å in 66 stars and found a close correlation in their equivalent widths.

"Emission wings," that is, regions where the extinction is less than would correspond to a smoothly interpolated background, adjoin some of the absorption dips, as determined by York. Walker, Hutchings & Younger (1969) derived extinction curves for nine stars from photoelectric observations and reported emission wings flanking 4430 on both sides in some cases. York agrees with Walker et al on the presence of emission wings in the 4430 profile for HD 183143, the one star common to their surveys. Brück & Nandy (1968) had earlier reported observation of an emission wing on the blue side only of the 4430-Å absorption. The lines observed by Wu (1972) were asymmetric, steeper on the blue side. Bromage (1972) has made a careful investigation of diffuse line profiles around 4430 Å, 4765 Å, and 4885 Å. His "average" profile for the 4430-Å band shows a blue-side emission wing only. One of Bromage's sources, HD20041, also observed by Brück and Nandy, is shown in York's chart as exhibiting no "4430" wings at all. (Some disagreement in this difficult observational problem is hardly to be wondered at; a glance at the spectra themselves will show why.)

Asymmetry in the extinction profile may be a clue to the size and refractive index of the grain in which the resonant absorber is embedded. The idea goes back to van de Hulst (1957). A thorough treatment has been given by Bromage in the paper just cited. Assuming that a line arises from impurities within spherical grains, Bromage has derived the extinction profile to be expected for optical indices appropriate to each of several hypothetical grain materials, and for different grain radii. Central frequency, line width, and intensity are assigned to fit these features of the observed line; the theoretical profile is then compared with that observed in respect to the amplitude of the "emission wing" relative to the absorption dip. This ratio, it turns out, is strongly dependent on the grain radius, increasing rapidly within a rather narrow range of grain radius for a given grain composition. Thus for silicate spheres, Bromage finds that whereas a radius of .06 μ gives no asymmetry to speak of, for twice that radius the profile is already more asymmetric than his observed 4430-Å profile, the emission peak being practically as large as the absorption dip. For graphite, because of its greater optical index, this behavior sets in at a smaller radius, so that if one wants to attribute the

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4430-Å absorption profile to impurities in graphite he is obliged to adopt a grain radius not greater than .05 μ. Bromage derived profiles also for grains with a distribution in size, and for grains with coatings of solid H_2 and of ice. All these calculations apply strictly only to spheres. However, a similar investigation of infinite cylinders by Greenberg & Stoeckly (1971) and Bromage's approximate treatment of a spheroidal case indicated that the size dependence of the asymmetry is much the same as for spheres. Thus we may have in the profiles of diffuse interstellar lines an instrument for eliminating hypothetical grain compositions and sizes, even without identifying the impurity responsible for the resonance. Further observational work could make an important contribution to the grain problem. Already Bromage's results provide arguments against ice grains of a size to account for the extinction curve, against iron grains small enough to be plausible on other grounds, and against graphite grains quite as large as those assumed in the mixture of Wickramasinghe & Nandy (1971c)—unless the graphite grains are coated with ice.

Whether the diffuse lines exhibit anomalous polarization—as compared with the polarization of the continuum to either side—is a crucial question. If they do, the case for the association of the diffuse lines with grains is secure, for no mechanism is known by which free molecules in interstellar space could be aligned on a large scale to serve as a selective polarizer. Although Wampler (1966) observed no polarization anomaly in the 4430-Å band, Nandy & Seddon (1970) reported that in the star 55 Cyg the polarization rises to 5% within the 4430-Å band, as compared with 2.7% in the adjacent continuum. However, more accurate measurements by A'Hearn (1972) on five stars, including 55 Cyg, have now shown that there is no significant change in polarization through the 4430-Å band.

As for the identity of the resonant absorber, or absorbers, responsible for the diffuse lines, transitions involving Fe^{3+} or Fe^{2+} ions in a silicate matrix have been proposed or discussed by Huffman (1970a), Manning (1970a,b), Dorschner (1970b), and Runciman (1970). So numerous are the absorption bands of 3d ions that have been detected in terrestrial silicates (Dorschner 1971a) that the assignment of bands to interstellar absorption frequencies is easy and not very convincing. Dorschner has emphasized, however, a serious difficulty: the oscillator strengths for the postulated crystal-field transitions in 3d states of Fe^{3+} ions are extremely weak. For the iron-bearing garnet of the andradite type proposed by Manning, $f=3.5\times10^{-6}$. Assuming 2 mag/kpc extinction, we find from equation (9) that we need 4×10^{-4} Fe^{3+} per cm^3. And these must be accompanied by no fewer than 6×10^{-4} silicon atoms per cm^3 even if all grains are the pure garnet. Both numbers are incompatible with presently accepted cosmic abundances by an order of magnitude. Huffman (1970b) has also proposed that Fe^{3+} transitions in γ-Fe may account for the 4430-Å band and two other bands, with oscillator strengths that would not strain the cosmic Fe abundance. This suggestion is especially interesting in relation to the problem of grain alignment, as γ-Fe_2O_3 grains are ferromagnetic. In none of these instances have the pertinent absorption frequencies and oscillator strengths yet been measured under conditions

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resembling those in interstellar grains, that is, in submicron particles at temperatures as low as 10°K. However, Huffman reports absorbance measurements on related materials at 77°K.

Wickramasinghe et al (1968) have discussed in rather general terms the possibility that the diffuse bands, and in particular the 4430-Å band, arise from electronic transitions at impurity centers, broadened by vibrational interaction with the host lattice. Wickramasinghe et al had no specific impurity to propose. Indeed, most known bands of this sort are considerably broader than we want. Moreover, if the impurity is strongly coupled to its environment in the grain, we would hardly expect its central frequency to be such a sharply defined and ubiquitous property of the interstellar material as Figure 6 plainly shows that it is.

F. M. Johnson (1972) has proposed a single molecule, magnesium tetrabenzporphin, Mg $C_{46}H_{30}N_6$, as the source of the interstellar absorption lines. He reports that the laboratory absorption spectrum of this molecule embedded in a matrix of paraffin shows lines coinciding with most of the recognized interstellar absorption dips. He argues that this molecule is peculiarly stable, which explains why, implausible as it would otherwise seem, other equally or less complex organic molecules play no comparable role.

6. *Interstellar Polarization*

Since the discovery of interstellar polarization by Hall (1949) and by Hiltner (1949) there has been a massive accumulation of polarimetric observations. The most comprehensive recent survey is that of Mathewson & Ford (1970), who have catalogued polarization data for 1800 southern stars observed from the Siding Springs Observatory. Mathewson and Ford have combined with this material the results of several earlier northern surveys (Hiltner 1956, Hall 1958, Behr 1959, Lodén 1961, Appenzeller 1968) and two southern surveys (Smith 1956, Visvanathan 1967) to produce the complete plot in galactic coordinates reproduced in Figure 7. On this plot the percent polarization and position angle of the electric vector are indicated for nearly 7000 stars. The length of each line is proportional to the percentage polarization (notice the two scales for P in the upper left corner). Small circles are drawn about stars with $P<0.08\%$. Not entering in this compilation were the results of Klare, Neckel & Schnur (1971, 1972), who have reported polarization observations, made at the Boyden Observatory, for 1660 southern OB stars.

To give an overview of a complicated situation we remark first that interstellar linear polarization amounts typically to no more than a few percent. The polarization P is defined as $(I_{max}-I_{min})/(I_{max}+I_{min})$ where I_{max} and I_{min} are the maximum and minimum intensities recorded as a perfect linear filter rotates in the optical path. Sometimes the degree of polarization is expressed by giving Δm_p, the ratio I_{max}/I_{min}, in magnitudes. The relation between P and Δm_p is then (accurately enough for the small values of P here encountered): $\Delta m_p = 2.17P$. In the catalogue of Mathewson and Ford the largest polarization recorded is $P=.071$. Of their 1800 stars, 120 had $P>.010$, only 33 had $P>.020$. In the catalogue of Klare, Neckel & Schnur (1972), which includes many more stars in the highly polarized

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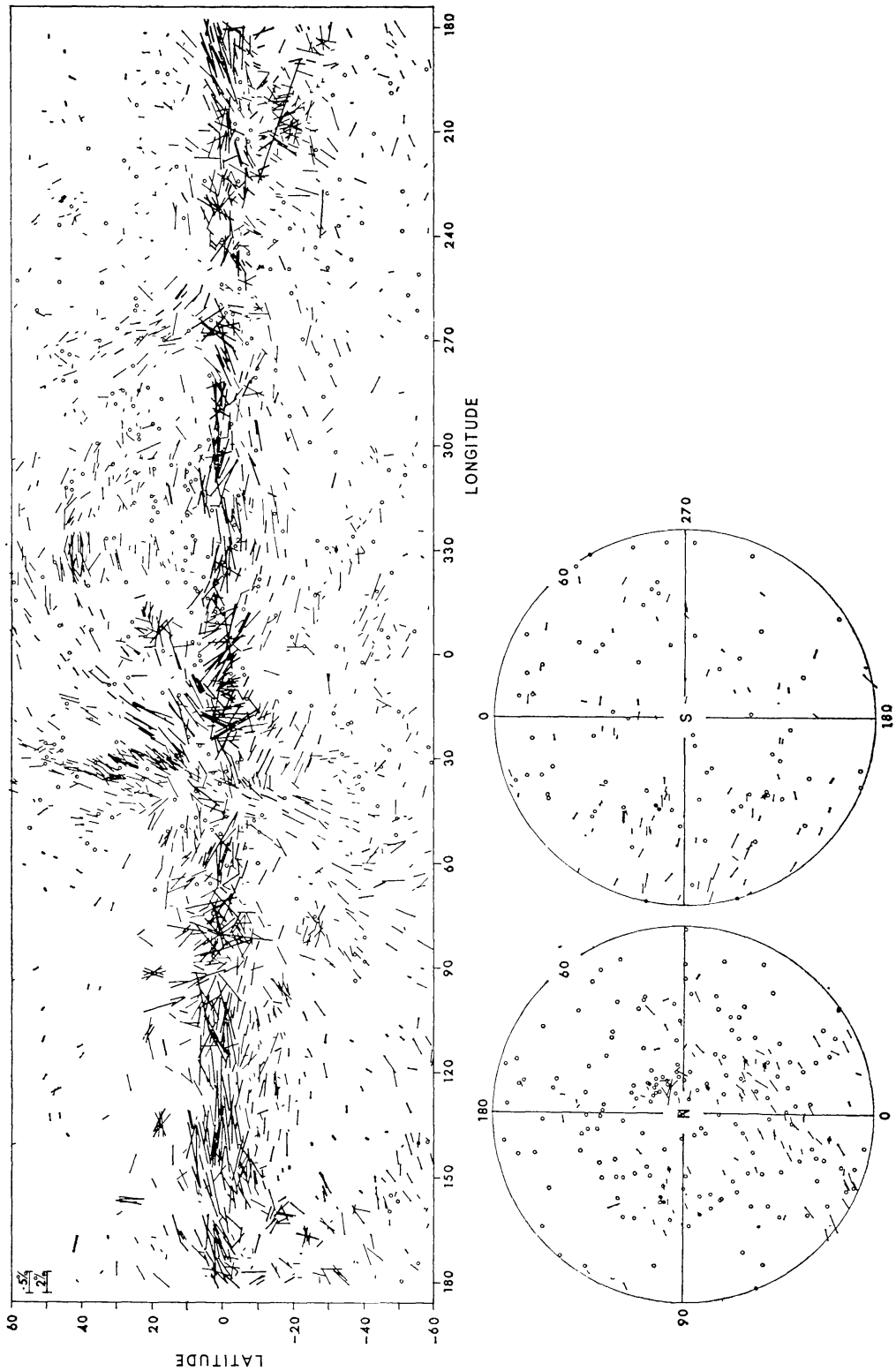

Figure 7 Interstellar polarization. From Mathewson & Ford (1970); see text.

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region between $\ell^{II} = 300°$ and $\ell^{II} = 340°$, the fraction with polarization exceeding 1% is much larger (more than half), while the greatest polarization reported is again 7%. More significant is the ratio of polarization, in magnitudes, to visual extinction $\Delta m_p/\Delta m_V$, which tells us how selective the interstellar polarizing filter must be, whatever its nature. Klare, Neckel and Schnur do not report visual extinctions in their catalogue, but Mathewson and Ford agree with earlier surveys in finding that the ratio $\Delta m_p/\Delta m_V$ averages around 0.03, and ranges up to, but seldom exceeds, 0.06. This would imply a difference of 3 to 6% in the extinction coefficients of a grain for the two orthogonal polarizations if the grains were all perfectly lined up in one direction perpendicular to the optical path. Actually the alignment must be far from perfect, the difference in the extinction coefficients therefore considerably greater. And it must be greater still if only a fraction of the grains are responsible for the polarization.

It has nearly always been assumed that the celestial pattern of interstellar polarization is a manifestation of the galactic magnetic field. Alignment of elongated paramagnetic particles by the process described by Davis & Greenstein (1951) favors transverse orientation, with respect to the magnetic field **B**, of the longer dimension of the grain. As the extinction cross section will generally be greater for electric vibration parallel to the long dimension, light filtered through such dust would be expected to show the greatest residual intensity in that component with electric vibration in the plane of **B** and the direction of propagation. Clearly, in Figure 7 the most orderly regions are those with polarization mainly horizontal. It is consistent, then, to assume that the magnetic field runs mainly parallel to the galactic plane, and that the alignment of grains is effected by the Davis–Greenstein mechanism. In the past there was a suspicious tendency to regard each assumption as confirmation of the other. Now that radioastronomy has provided independent evidence on the magnetic field configuration from Faraday rotation and polarization of the background continuum, the argument is strong that the grains are indeed aligned preferentially perpendicular to **B**.

The directions in which one is looking perpendicular to magnetic field lines, as inferred from Figure 7, are about $\ell^{II} = 140°$ and $\ell^{II} = 320°$. Halfway between, where the pattern is jumbled, one might suppose that we are looking more or less along the field, near the direction of the local spiral arm. But it is probably not that simple. Mathewson (1968, see also Mathewson & Nicholls 1968), by a detailed study of the optical polarization pattern and the radio data, found evidence for a flattened helical configuration of the field lines within about 500 pc of the Sun. A discussion of this question is beyond the scope of our review; for references to recent papers on the structure of the galactic field see Schmidt (1971).

A statistical study by Jokipii, Lerche & Schommer (1969) of regional variations in polarization was based on the catalogue of Behr (1959). They deduced a correlation length, for the polarizing properties of the interstellar medium, of about 150 pc.

The wavelength dependence of interstellar polarization has been investigated by several observers, notably Behr, Coyne, Gehrels, and Serkowski, for a total of

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Table 2 Wavelength dependence of polarization and of the ratio of polarization to extinction[a]

λ^{-1}	1.06	1.21	1.56	1.93	2.33	2.78	3.03	μ^{-1}
$\overline{P}_{24}$	0.695	0.797	0.973	1.000	0.974	0.865	0.820	
$\overline{P}_{22}$	0.712	0.818	0.973	1.000	0.947	0.839	0.783	
$\overline{P}_{46}$	0.704	0.808	0.973	1.000	0.960	0.851	0.801	
$A(\lambda^{-1})/A(1.81)$	0.45	0.55	0.80	1.07	1.35	1.54	1.74	
$P_\lambda/\Delta m_\lambda$	1.67	1.57	1.29	1.00	0.76	0.59	0.49	

[a] Based on observed percentages of polarization reported in Table III of Coyne & Gehrels (1967) and Table II of Coyne & Wickramasinghe (1969). $\overline{P}_{24}$ is the mean polarization for 24 stars in the former table; $\overline{P}_{22}$ is the mean polarization for 22 stars in the latter table; $\overline{P}_{46}$ includes both groups. For each row we have normalized with respect to the value at $\lambda^{-1}=1.93\ \mu^{-1}$ after taking the mean of the observed percentages at each effective wavenumber, a procedure somewhat different from that used by Coyne and Gehrels to arrive at the mean polarizations given in their Table VII. The ratio of polarization to extinction, also normalized arbitrarily at 1.93 μ^{-1}, has been computed from $\overline{P}_{46}$ and the assumed A_λ/A_V values listed on the preceding line.

well over one hundred stars. The more recent and comprehensive reports, Coyne & Gehrels (1967), Coyne & Wickramasinghe (1969), Serkowski & Robertson (1969), and Serkowski (1972), contain references to the earlier work. The first two papers report polarizations for approximately 50 early-type stars near the galactic plane. We give in Table 2 the average of the polarizations observed. A comparison of the averages for the two tabulations computed separately may give some idea of the universality of such an average. There are significant variations from star to star, for which the papers themselves must be consulted. But the overall uniformity of behavior is striking. Quite generally the percentage polarization shows a flattish maximum somewhere between 0.5 μ and 0.6 μ; in fewer than 10% of the stars does it fall, at either end of the observed spectrum, below half its maximum value. It is more instructive to consider the ratio of average polarization to extinction, computed with an assumed reddening law and listed in the last line of Table 2. Notice that $P_\lambda/\Delta m_\lambda$ decreases monotonically with increasing frequency. This holds true with very few exceptions for the individual stars and bears directly on the question of grain size and shape, to which we shall return presently.

A significant regularity emerges, as emphasized by Serkowski (1972) and exhibited by the observations of highly polarized stars by Serkowski et al (1969), if one plots $P_\lambda/P_{\max}$ against $\lambda/\lambda_{\max}$, where $\lambda_{\max}$ is the wavelength of maximum polarization for that star. Thus plotted the similarity in behavior from star to star is striking—see especially Figure 5 in Serkowski (1971)—and poses a clear challenge to grain models.

The general character of the variation of polarization with wavelength recalls a point made many years ago by van de Hulst (1957). The ratio of the extinction cross sections for orthogonal polarizations for an absorbing grain of dimension

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a must approach a constant at long wavelengths, $\lambda \gg a$, and this limiting value of the ratio is generally *larger* than the ratio at shorter wavelengths. The monotonic decrease of $(\Delta m_p/\Delta m)_\lambda$ from the infrared through the visible is thus easily understood. Indeed, a rough idea of the size of grains, assuming an optical index, can be got from it. For example, using the cross sections for infinite cylinders for index $n=\sqrt{2}(1-i)$ plotted in van de Hulst's Figure 69, one can fit the variation of $(\Delta m_p/\Delta m)_\lambda$ in Table 2 by choosing a cylinder diameter around .06 μ. Much more elaborate calculations of variation of polarization for different models have been made (Greenberg 1968), but the general point just made is about all one can conclude at this time. The extension of polarization measurements into the ultraviolet would be extremely important. Theory leads one to expect one or more "cross-overs" where the polarization actually reverses for a uniform population of grains. Perhaps these will be smeared out into a featureless monotonic decline; the observation of the contrary would be highly significant.

Aligned grains cause the linear dichroism of the interstellar medium, resulting in the polarization of starlight that we have been discussing. But they must in general cause linear birefringence also, that is, a difference in the real part of the refractive index of the medium for waves polarized respectively parallel and perpendicular to the direction of grain alignment. Thus arises the possibility of observing a small component of circular polarization in the light from a linearly polarized source that has traversed a region where grains are aligned in some direction neither parallel nor perpendicular to the polarization vector of the source. Martin (1972c) has developed the theory of this effect, including the wavelength dependence of the degree of elliptical polarization various model grains would be expected to produce. An important finding is that various grain models, for all of which the dependence of polarization on wavelength is practically indistinguishable from the observed behavior, differ markedly in the wavelength dependence of birefringence. In particular, a striking difference is predicted between dielectric and metallic grains. This opens up, wherever the prerequisites for observation can be met, a much-needed new and independent source of information. The first such observation has now been reported by Martin, Illing & Angel (1972), who used the Crab Nebula as a source with known linear polarization. Ellipticity of interstellar origin was indeed detected, and although the statistical uncertainty was still rather large, the observed wavelength dependence distinctly favored dielectric rather than metallic grains.

Elliptical polarization can also arise when originally unpolarized light passes through clouds of aligned grains in which the direction of alignment gradually rotates around the direction of propagation, like the steps of a spiral staircase. Such an effect has now been observed for six early-type stars by Kemp & Wolstencroft (1972). Two-color observations for five of the stars, and more detailed spectra for two of them, σ Sco and σ Sco A, show that in every instance the circular component reverses sign between the blue and the red. Kemp and Wolstencroft explain that this behavior is to be expected on quite general grounds, independent of the nature of the grains, given only that the linear polarization has a maximum in the visible. From a simple model they deduce the sense and the ap-

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proximate amount of angular twist along the line of sight. For further theoretical discussion, see Kemp (1972).

Sparrow & Ney (1972) report that observations of polarization from the satellite OSO-5 reveal a residue of polarization attributable to diffuse galactic light after the generally larger effect of zodiacal light is subtracted. The data are meager, but further work along this line may prove fruitful.

7. *Grain Temperature and Grain Potential*

GRAIN TEMPERATURE The temperature of the grains is important in processes of molecule formation and in the orientation of grains through magnetic relaxation. It determines, too, whether the grains can retain mantles of frozen hydrogen. The temperature of a grain is determined solely by the balance between radiation absorbed and radiation emitted, exchange of thermal energy with the surrounding gas being much too slow (by a factor of the order of 10^7) to matter. Whereas a large, perfectly black object in the interstellar radiation field would attain a temperature around 3°K, the grain runs warmer because its small size makes it a very poor emitter in the far infrared. The equilibrium temperatures of spherical grains with various assumed refractive indices and wavelength dependence thereof have been calculated by Greenberg (1971), Krishna Swamy & Wickramasinghe (1968b), and Werner & Salpeter (1969). For the radiation field in interstellar space not cloaked in a dark cloud, temperatures of 10 to 20°K are predicted for grains of "dirty ice" of radius $\sim 10^{-5}$ cm, with somewhat higher temperatures for graphite grains.

Inside a dark cloud from which most of the starlight has been excluded by absorption in grains near the outside of the cloud, the grains should be considerably cooler. This radiation transfer problem has been thoroughly treated by Werner & Salpeter (1969). They find that the grain temperature in the deep interior is not drastically reduced below the equilibrium grain temperature outside even when the optical depth of the cloud is quite large. The reason is that energy is transported into the cloud by infrared photons radiated by the grains near the outside. Thus the temperature of a 0.15-μ-radius ice grain with a graphite core has fallen only from about 16°K to 8°K between the outside and inside of a cloud of optical depth 10.

A grain's temperature depends strongly on its emissivity in the far infrared. The presence in the grain of impurities with long-wave resonances, as suggested by Hoyle & Wickramasinghe (1967), could lower the equilibrium temperature significantly. However, a fundamental limitation on the emissivity thus achievable, which was not recognized by Hoyle and Wickramasinghe, makes it practically impossible for a grain to cool below 5° or 7°K in the typical interstellar radiation field, given a normal albedo in the visible. Field (1969) made this point by deriving the maximum integrated absorption efficiency obtainable by oscillators in a spherical grain when proper allowance is made for the dielectric effect upon the oscillators themselves. Purcell (1969b) reached similar conclusions, applicable also to spheroidal grains, by a somewhat more general treatment based on the Kramers–Kronig relations. Expressed for spherical grains in terms

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of the extinction efficiency Q, defined as $\sigma_t/\pi a^2$ where σ_t is the total extinction cross section of a spherical grain of radius a, the extinction must obey

$$\int_0^\infty Q(\lambda)d\lambda = 4\pi^2 a(\epsilon_0 - 1)/(\epsilon_0 + 2) \tag{10}$$

where ϵ_0 is the low-frequency dielectric constant of the grain.

Field concluded that grains cannot retain solid H_2 mantles in normal interstellar clouds. From the results of Werner and Salpeter it appears doubtful that solid H_2 can be retained even within dense dark clouds. These conclusions together with the spectroscopic evidence for a paucity of interstellar ice (Knacke, Cudaback & Gaustad 1969, Gillett & Forrest 1973) make core-mantle grain models involving solid hydrogen or ice less attractive as major contributors to extinction.

ELECTRIC POTENTIAL AND CHARGE Photoelectric emission and electron capture compete to determine the electric potential of an interstellar grain. Watson (1972) has examined this problem in the light of the most recent information on uv photon densities, electron densities, and photoemissive efficiencies of solid surfaces. With the possible exception of ice grains and metal particles, both of which he expects to show low photoelectric yield, Watson finds that grains in unshielded HI regions will acquire a net positive charge, even for rather high electron densities. Thus for a gas temperature of 120°K he predicts a grain potential around $+0.9$ V for $n_e = 5\times10^{-3}$ cm^{-3}, dropping to $+0.1$ V for $n_e = 5\times10^{-2}$ cm^{-3}. However, in HI clouds with moderate optical extinction the attenuation of uv will be severe enough to permit the grains to become negatively charged. Watson's paper is chiefly concerned with photoemission from grains as a heating mechanism for HI clouds. He points out, incidentally, that the positive grain potential will drastically inhibit the collection of carbon atoms by the grains, interstellar carbon being nearly completely ionized in unshielded HI regions. The question of grain potential may need to be reexamined in the light of the surprisingly high albedo associated with the far-uv extinction. Unusually low absorption may well be coupled with low photoelectric efficiency. Of course the equilibrium charge of grains in the same environment could have opposite signs for two components of a grain mixture.

By its electric charge q a grain of mass M is coupled dynamically to the magnetic field. The importance of the coupling can be judged from the product of the cyclotron frequency ω_c, given simply by qB/Mc, and the damping time τ for motions of the grain through the gas. For a grain of unit density in typical HI conditions this number turns out to be approximately

$$\omega_c\tau \simeq 3 \times 10^4 VB/a \tag{11}$$

if V is the grain potential in volts, B the field strength in gauss, and a the grain radius in cm. It is thus a large number under any reasonable assumptions, which means that interstellar grains, like ions, are locked to the magnetic field. The implications of this for magnetic alignment will be mentioned later. The

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effect ought to be taken into account in any transport problem involving large-scale motion of the grains.

Although the grain may be nominally nonconducting, we would expect that on the appropriate time-scale—a grain acquires its equilibrium charge in days—the charge will distribute itself so that the surface of the grain is an equipotential, at least macroscopically. Even so, the center of charge of an irregularly shaped grain need not coincide precisely with its center of mass. Thus arises a possibility of a rotating electric dipole moment, causing radiation at the grain's rotation frequency. Hoyle & Wickramasinghe (1967) suggested that an interesting amount of meter wave energy might be emitted by very small ($a \sim 10^{-7}$ cm) grains in very hot regions. The effect proves on closer analysis to be quantitatively insignificant. Conversely, Martin (1972a) has considered the effect of the ambient low-frequency radiation field on the angular momentum distribution of grains that have permanent dipole moments, either electric or magnetic. Significant effects are predicted only for dipole moments as large as we get if the grain is a single ferroelectric or ferromagnetic domain. That is 2 or 3 orders of magnitude larger than the moment a charged grain could exhibit simply by virtue of its asymmetrical shape.

8. *Grain Alignment*

The theory of grain alignment has progressed in several directions without, however, arriving at a thoroughly convincing explanation of the observed polarization. Indeed, the problem is more puzzling than it appeared several years ago, when it was generally thought that the Davis–Greenstein mechanism operating on grains with some paramagnetic impurities would suffice to produce the required grain alignment. More thorough analysis of this process, on the one hand, and accumulating evidence on the magnitude of the interstellar magnetic field on the other, have revealed quantitative difficulty, which will be described below, with alignment through paramagnetic relaxation. Meanwhile a number of other ingenious alignment mechanisms have been suggested but on closer scrutiny have proved, so far without exception, to be quite inadequate. This has not impeded the proliferation of hypothetical grain models, many of which have been put forward with little attention to the physical requirements for adequate alignment.

To state in simplest form the problem posed by the observations of interstellar polarization we consider a grain with a unique axis of symmetry A. Let us confine our attention, at the moment, to grains enough smaller than a wavelength that the extinction is mainly by absorption rather than by scattering. That is probably a good approximation for wavelengths larger than 0.5 μ. For such small grains the extinction cross section depends on the angle between the grain's axis **A** and the oscillating electric field, but not otherwise on the direction of propagation. Let $\sigma_{\parallel}$ be the extinction cross section of the grain for light with its electric vector parallel to **A**, $\sigma_{\perp}$ the extinction cross section if the electric vector is perpendicular to the axis **A**. Let **B** denote the fixed direction in space with respect to which the grains are aligned—it is of course the magnetic field direction in the case of magnetic

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alignment. Denoting by θ the instantaneous angle between **B** and a grain's axis **A**, we express the average alignment in an ensemble of such grains by Q_A:

$$Q_A = \tfrac{1}{2}(3\langle\cos^2\theta\rangle - 1) \tag{12}$$

The bracket $\langle\ \rangle$ means ensemble average.

Suppose originally unpolarized light propagates through a cloud of grains in a direction making angle ψ with **B**. The observed ratio of polarization to extinction, if Q_A is not large, will be in good approximation to

$$\Delta m_p/\Delta m_V = Q_A \sin^2(\sigma_\parallel - \sigma_\perp)/\bar{\sigma} \tag{13}$$

where we have defined the mean extinction cross-section $\bar{\sigma}$ by $\bar{\sigma}=(\sigma_\parallel+2\sigma_\perp)/3$. Equation (13) connects the optical anisotropy of the grain and the degree of alignment directly with an observed quantity $\Delta m_p/\Delta m_V$, which, as noted earlier, ranges in the visible up to 0.60 with an average value around 0.03. For grains only a fraction of a wavelength in size, the anisotropy of absorption depends on the shape and the optical index n. It involves the "depolarizing factor," readily calculable for spheroidal shapes. For infinitely long cylinders of radius $a \ll \lambda/2\pi$, with $n=1.4$, $(\sigma_\parallel-\sigma_\perp)/\bar{\sigma}=0.85$, while a thin disk of the same material would have $(\sigma_\parallel-\sigma_\perp)/\bar{\sigma}=-0.98$.

All the schemes that have been proposed for aligning interstellar grains depend on the alignment of the grain's angular momentum. Let ψ_{JB} be the angle between the unique spatial direction **B** and a grain's angular momentum **J**. Anisotropy in the distribution of directions of **J** in an ensemble of grains can be described by an alignment measure $Q_J=\frac{1}{2}(3\langle\cos^2\psi_{JB}\rangle-1)$.

For nonspherical grains a statistical-mechanical consequence of the partial alignment of **J** is partial alignment of the grain's own figure axis, in the sense that there is a tendency for the grain's major axis of inertia to be found in the direction favored by **J**. Thus the symmetry axis **A** of an oblate spheroidal grain will be statistically distributed with its alignment measure $Q_A>0$, if $Q_J>0$, while the figure axis **A** of a prolate grain will exhibit alignment with $Q_A<0$, if $Q_J>0$. However, $|Q_A|$ is generally considerably less than $|Q_J|$, a fact not adequately allowed for in some earlier treatments of grain alignment. The alignment of the figure axis, although it is the only result with any observable consequences, is really a corollary effect.

A grain is driven in rotation mainly by impinging gas atoms. Its mean kinetic energy of rotation $(3/2)kT_{\rm rot}$ should then correspond to the gas temperature $T_{\rm gas}$ (or to a somewhat lower temperature, depending on the accommodation coefficient). The corresponding angular velocity for a spherical grain of density 1 gm/cm^3, radius 10^{-5} cm, for $T_{\rm gas}=100$°K is 3×10^5 rad/sec. Gas friction determines for the rotational motion a relaxation time τ_r which, like that of the grain's linear motion through the gas, is approximately the time required for the grain to be struck by its own mass in gas atoms. Thus τ_r is proportional to a linear dimension of the grain; under typical HI conditions it is around 10^{13} sec for a spherical grain of radius 10^{-5} cm. The intervention of any process that either increases or

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decreases, with respect to some fixed direction, this "Brownian rotation" of the grain will align **J**, and thus, indirectly, **A**.

MAGNETIC ALIGNMENT Grains are not aligned like compass needles. The energy involved in turning over a totally magnetized iron sphere 10^{-5} cm in radius, in 10^{-5} gauss, is less than $10^{-2}\ kT_{\rm gas}$. All grains, whatever their nature, must be continually rotating.

The magnetic alignment process envisaged by Davis & Greenstein (1951) depends on the dissipative torque which opposes the rotation of a paramagnetic crystal about an axis perpendicular to a constant magnetic field **B**. The torque is proportional to B^2 and to χ'', the imaginary part of the magnetic susceptibility, which in turn is proportional to frequency ω for sufficiently low frequencies, i.e., sufficiently low angular velocities:

$$\chi''=K\omega \tag{14}$$

The effect of the retarding torque is to slow down rotation of a grain about any axis transverse to **B**, so that the grain, if not otherwise disturbed, would eventually be left spinning with **J** parallel to **B**. This magnetic damping would take effect in a characteristic time τ_m. The ratio $\delta\equiv\tau_r/\tau_m$, which is proportional to KB^2, is the appropriate measure of the magnetic friction. Disturbance by gas atom impacts (necessary to excite the rotation of the grain in the first place) prevents complete alignment of **J**, but in the steady state a distribution with $Q_J>0$ will have developed, causing prolate grains to be partially aligned with $Q_A<0$ and oblate grains to be aligned with $Q_A>0$. In either case the grains will absorb light preferentially, with the electric vector perpendicular to **B**, providing the grains are small enough so that we can be sure that $\sigma_\parallel>\sigma_\perp$ for prolate grains and the reverse for oblate grains.

The theory of D-G alignment was considerably advanced by Jones & Spitzer (1967), who gave a rigorous treatment of the angular momentum alignment for spherical particles and developed an approximate method for predicting the degree of axis alignment Q_A for spheroidal grains. They elucidated the role of grain temperature, pointing out that a difference between $T_{\rm gr}$ and $T_{\rm gas}$ is essential for alignment.

Jones and Spitzer discussed the aspects of magnetic relaxation, paramagnetic and ferromagnetic, that determine how large a value of the constant K in equation (14) might be realized in interstellar grains. For paramagnetic substances in the low-frequency limit, χ''/ω depends remarkably little on the composition of the grain or the concentration of paramagnetic ions. The value of K in seconds will be approximately $2\times10^{-12}/T_{\rm gr}$ if dipole-dipole interactions dominate. This holds even for nuclear paramagnetism in pure ice. Hyperfine interactions if present can reduce the value of K. The range of frequency over which χ'' increases linearly with ω does depend on the concentration of magnetic moments and their strength. For electronic paramagnetism the upper limit on ω, in rad/sec, is roughly 10^{-12} times the number of unpaired electron spins per cm^3. Thus for a 1% atomic concentration of Fe ions, equation (14) should hold up to $\omega\sim10^8$ sec^{-1},

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well beyond the expected rotation rates. However, for nuclear paramagnetism in ice, the upper limit is around 2×10^5 sec^{-1}, just in the range of interest. The important point is that no paramagnetic substance can be expected to have K significantly larger than $2\times10^{-12}/T_{gr}$.

Ferromagnetism, involving cooperative behavior of atomic moments, presents a richer prospect. Jones and Spitzer concluded that much larger values of K could result from relaxation processes involving ferromagnetic domains. An especially attractive possibility is "super-paramagnetism," in which isolated clusters of iron atoms behave like single giant magnetic moments. These might be metallic iron or magnetite precipitates, some tens of Å in size, distributed through the grain. With favorable parameters, K values several orders of magnitude larger than $10^{-12}/T_{gr}$ might be realized for overall Fe concentrations no more than 1%. If only a few of several hundred such precipitates in a grain have the optimum size, the K value would still be amply large.

D–G alignment of nonspherical particles was investigated by Purcell (1969a) by means of a Monte Carlo model of the whole physical process. The results appeared to be in reasonable agreement with the findings of Jones and Spitzer and in particular confirmed their conclusion that adequate alignment of paramagnetic particles would require a field strength somewhat higher than had been commonly assumed. Subsequently Purcell & Spitzer (1971) carried out a more extensive Monte Carlo study, and by comparing the results with the approximate theory of Jones and Spitzer extended the latter so that Q_A values can be reliably predicted for a wide range of grain shapes, given the value of KB^2 and the relevant temperatures.

Cugnon (1971) has developed a theory of D–G alignment that is based, like that of Jones and Spitzer, on the Fokker–Planck equation. He obtains formulas for the alignment in the limiting cases of either weak magnetic coupling ($\delta\ll1$) or nearly spherical grains. The agreement with Jones and Spitzer and with the Monte Carlo results of Purcell and Spitzer is fairly good for shapes with axial ratios less than 2, but for more eccentric prolate shapes Cugnon predicts somewhat larger values of Q_A/δ. Actually, a linear dependence of Q_A on δ breaks down in the region of interest, $\delta\sim1$. Consequently Cugnon's estimate of 2×10^{-5} gauss as the minimum magnetic field required for adequate alignment of ice grains is certainly too low. (For the conditions he assumed, $\delta\simeq2.1$.) It is doubtful whether the alignment he postulates, $Q_A\simeq0.18$, would be attained at any field strength.

To show what field strengths are needed to explain the observed polarization by D–G alignment, we present three cases based on the results of Purcell and Spitzer. As examples we take two prolate grains and one oblate grain of approximately the same volume, 10^{-15} cm^3. These we show in Figure 8 as square prisms with length-to-width ratios 5, 2, and 0.2. The results would be practically the same for spheroids of the same axial ratio. Figure 8 gives the degree of axial alignment Q_A as a function of magnetic field strength, attained under the following conditions: gas temperature and density, 100°K; paramagnetic constant K, $2.5\times10^{-12}/T_{gr}$. Notice that $|Q_A|$ remains far below the values that correspond

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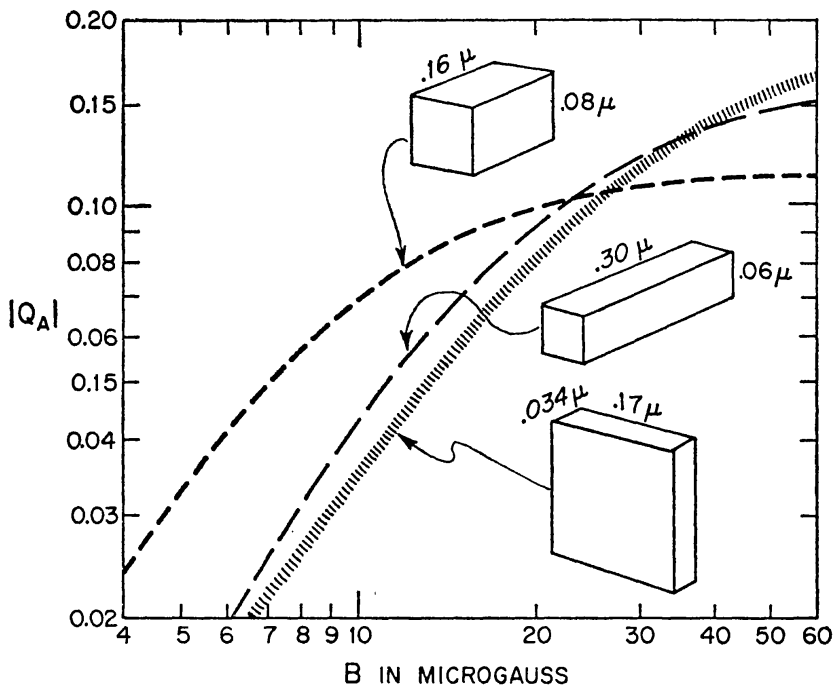

Figure 8 Axial alignment measure Q_A for three prism-shaped grains of approximately equal volume $V_{gr} = 10^{-15}$ cm³, as a function of magnetic field. Assumed are: $T_{gas} = 100°K$; $T_{gr} = 11°K$; $K = 2.5 \times 10^{-12}/T_{gr}$. For similar grains of different size, $B \propto V_{gr}^{1/6}$ for the same Q_A if other parameters including T_{gr} are held constant. But if the dependence of T_{gr} on grain size is allowed for, $B \propto V_{gr}^{0.12}$ approximately. If we could change T_{gr} while keeping V_{gr} constant, we would find, approximately, $B \propto T_{gr}^{0.9}$ for the same Q_A. Based on results of Purcell & Spitzer (1971).

to "perfect" D–G alignment, which are 0.5 for prolate shapes, 1.0 for oblate shapes. Clearly Q_A is not proportional to δ in this range; if it were, the curves would rise linearly with slope 2, since $\delta \propto B^2$. Larger grains require a stronger field; with other parameters constant, $B \propto V_{gr}^{1/6}$ for the same value of δ and Q_A.

The polarization resulting from the alignment given in Figure 8 is predicted in Figure 9, in terms of the ratio of polarization to extinction $(\Delta m_p/\Delta m)_{lw}$ in the *long wave limit*. We first computed $\sigma_{\parallel}/\sigma_{\perp}$ for a spheroid of the given axial ratio. This depends on the refractive index n, the real part of which is chosen as 1.3, 1.5, and 1.7 for these examples. (Of course, n is complex, since we are considering absorption; the imaginary part of $n-1$ is here assumed to be small, but the result would not be much different if it were comparable with the real part.) Then with equation (13) we compute $(\Delta m_p/\Delta m_{lw})$. Also indicated are the limiting curves for $n \to \infty$.

The observed $(\Delta m_p/\Delta m)_\lambda$ seems, according to Table 2, to be rising toward a long-wave value at least twice $(\Delta m_p/\Delta m)_V$, as earlier discussed. Hence we must account for a mean value in Figure 9 of 0.06 and a maximum value possibly twice as great. Notice that, regardless of the field strength, highly eccentric

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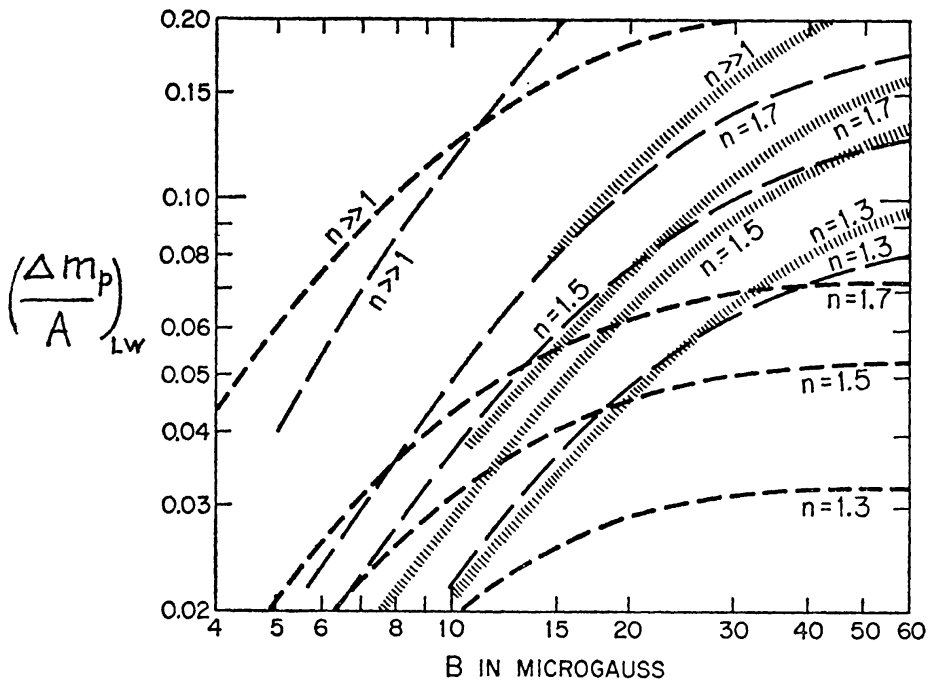

Figure 9 For grains of Figure 8, the ratio of polarization to extinction is $\Delta m_p/\Delta m$ in the long wavelength limit, for various values of refractive index n, including the limiting behavior for $n \gg 1$. We expect $(\Delta m_p/\Delta m)_V \simeq 1/2(\Delta m_p/\Delta m)_{lW}$, so the *average* observed $(\Delta m_p/\Delta m)_V$ of .03 corresponds to an ordinate $\simeq$.06 in the graph. The absorption cross-section ratios were actually computed for spheroids of the same proportions. (In the ordinate label, read Δm for A.)

particles with a moderately high refractive index are needed. Given such particles, adequate alignment could be expected for field strengths of the order of 20 to 30 μG. But note that we have assumed that all the particles responsible for extinction are contributing fully to the polarization, that **B** is transverse to the line of sight, and that the direction of **B** remains the same along the entire path where extinction occurs. Relaxation of any of these conditions would imply a larger ratio $\Delta m_p/\Delta m$ either locally or for the effectively polarizing fraction of the grain population. Figure 9 shows that any substantial increase would be hard to explain, even by invoking a strong field or a much larger paramagnetic constant K, unless one postulates slender prolate grains with a high dielectric constant. Notice that for thin oblate grains such as graphite flakes (it doesn't matter how thin) even an infinite dielectric constant brings no very great gain in polarization.[2]

[2] Some authors seem to think the electrical anisotropy of graphite would make graphite flakes peculiarly efficacious as polarizers—assuming, of course, that means for orienting graphite flakes could be assured. But in fact the anisotropy of conductivity will augment only slightly the electrical anisotropy due to shape. It can at most make $\sigma_{\parallel}/\sigma_{\perp}=0$, resulting in $(\sigma_{\parallel}-\sigma_{\perp})/\bar{\sigma}=-1.5$, a limit that is already approached by any thin flake with

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Thus alignment by paramagnetic relaxation, as presently understood, appears to require a magnetic field several times stronger than other lines of evidence (Verschuur 1969, Jokipii & Lerche 1969, Manchester 1972) have been pointing to. That Shah (1972) reached a contrary conclusion may be explained by his use for long cylinders of a formula for δ appropriate for spheres and by his neglect of the difference between Q_A and Q_J. The field strength problem would be eased for grains of much smaller size—especially if they are long thin semimetallic filaments, which would help to keep their temperature down (Purcell 1969b) as well as polarizing efficiently. Or the problem may be resolved by postulating suitable ferromagnetic inclusions. But even then, the limited degree of alignment attainable may rule out grains of low optical index, and perhaps even oblate grains of high index.

Graphite presents an interesting special problem. Cayrel & Schatzman (1954) suggested that with the anomalous diamagnetism of graphite must be associated a "diamagnetic relaxation" through which D–G alignment of graphite flakes might be effected. Unfortunately, further theoretical study (Greenberg 1969, Purcell 1969a) showed that the effect is considerably weaker than paramagnetic relaxation. Moreover, Cugnon (1971) has been able to apply his theory to *magnetically* anisotropic disks and has found that even if the magnetic field were strong enough to orient graphite flakes by diamagnetic relaxation, the alignment and the resulting polarization would be the *reverse* of that expected! At this time no mechanism other than ordinary electronic paramagnetism is known that could magnetically align graphite flakes.

OTHER ALIGNMENT MECHANISMS As explained by Gold (1952), if dust grains are caused to move with hypersonic velocity through the interstellar gas, prolate grains will acquire an axial alignment $Q_A > 0$ and oblate grains an alignment $Q_A < 0$, with respect to the direction of motion. Relative motion of dust and gas certainly exists temporarily where clouds collide, but only a minor fraction of the interstellar dust could be involved in a collision front at one time. The damping time for relative motion and the time both for establishment and for dissipation of alignment are necessarily the same, $\sim 10^{13}$ sec. Radiation pressure, however, could sustain a steady motion of grains through gas. If its extinction cross section is geometrical, a grain of any size and shape will be driven at atomic velocity through an HI cloud by a unidirectional photon flux of 0.002 erg cm^{-2} sec^{-1}. A quantitative study of the Gold alignment process (Purcell 1969a) concluded that directed radiation pressure in the Galaxy, on the large scale, is insufficient by an order of magnitude or so to explain the large-scale pattern of polarization. But

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a moderately large isotropic dielectric constant. Only under the implausible assumption that the graphite grains grew not as flakes, but as nearly spherical lumps, would one need to invoke the electrical anisotropy of the atomic lattice. Even less important would be the birefringence of a grain substance like quartz. So mild an internal anisotropy would be utterly inconsequential, compared with the anisotropy of form needed to align the grain in the first place.

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there can be no doubt that grains are aligned by this process in local regions where the radiation pressure is sufficient. Indeed the resulting polarization may be observable in Figure 7, if we could only recognize it.

Because of the electric charge acquired by an interstellar grain, the magnetic field plays an important role in the Gold process and in other "nonmagnetic" processes. As we have already noted, the cyclotron period for a grain is expected to be short compared with the characteristic time for frictional damping. In that case the grain will be locked to the field lines and can only acquire a high velocity parallel to **B**. Only the component of the driving force in that direction can lead to alignment, and so alignment by the Gold mechanism will appear, after all, as alignment with respect to the field direction **B**. Note, however, that it will be just the *reverse* of Davis–Greenstein alignment; prolate grains will tend to lie along rather than across the field direction.

Martin (1971b) pointed out that a rotating charged grain must also *precess* in the magnetic field, with the quite general consequence that grains aligned by any process will exhibit, in the time average, an axis distribution symmetrical around **B**. The angular rate of spin-axis precession is practically the same as the cyclotron frequency in equation (11) (it is $5/6\ \omega_c$ for a solid sphere), almost certainly faster than any alignment process. The important conclusion is that the observed interstellar polarization *must* be correlated with the interstellar magnetic field, *regardless* of the mechanism responsible for grain alignment. The only question is what the light is telling us: is **B** parallel to the observed *E*-vector, as in Davis–Greenstein alignment, or is it perpendicular thereto, as in Gold alignment? Looking at Figure 7, one will hardly hesitate to adopt the first alternative—but we cannot exclude the possibility that the second prevails in some directions.

Salpeter & Wickramasinghe (1969) called attention to the effect of cosmic-ray bombardment on the angular momentum of grains and suggested that in combination with differential motion of grains through gas, an alignment different from the Gold alignment would ensue. Further analysis of this effect (Purcell & Spitzer 1971), confirmed by Monte Carlo modeling, showed that the alignment is insignificant.

Wickramasinghe (1970b) suggested that the ejection of photoelectrons from grains by soft X rays would bring about an anisotropic angular momentum distribution, thus grain alignment, providing the X-ray flux was directional, and in particular, if there is sufficient excess X-ray flux in the galactic plane. However, the intensity of excess radiation required under the most favorable assumptions appears to be 1 or 2 orders of magnitude more than could be expected (Mack 1971a,b, Wickramasinghe 1971).

What is perhaps the most elegant of grain alignment mechanisms was proposed by Harwit (1970). He pointed out that a very small grain absorbing unpolarized starlight from a particular direction acquires angular momentum anisotropically, owing to the intrinsic angular momentum of the photon with its component $\pm\hbar$ in the direction of propagation. Or more correctly, following Martin (1972b) we should say that the mean square angular momentum deposited is $\hbar^2$ in the direction of the light, and also $\hbar^2$, not $2\hbar^2$, transverse thereto, leading

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to $\langle J_z^2\rangle/\langle J^2\rangle=1/2$, or $Q_J=+1/4$, if no other torques were acting. In the resulting axial alignment, prolate grains would be mainly transverse to the direction of the starlight. Unfortunately, the effect is severely diluted, not only by atomic impacts but also by the isotropic emission by the grain of low-energy photons, each of which carries away $2\hbar^2$ in squared-angular-momentum, so that no significant alignment can be expected.

9. *Processes on Grain Surfaces*

Most of the reactions by which molecules are formed in interstellar space occur on grain surfaces. In a moderately dense cloud ($n_H \sim 10^2$ cm^{-3}) a grain will be struck by a hydrogen atom every few minutes. If all incident atoms were retained on the grain surface, a monolayer would accumulate in something like 10^9 sec. A given H atom in the cloud collides with a grain once in a few million years; a heavy atom takes somewhat longer. Thus the grains provide a means for processing a substantial fraction of the interstellar gas in a time short compared with the age of the Galaxy. Processes that have to be considered are adsorption of atoms at the grain surface, migration over the surface, chemical reactions on the surface, evaporation or ejection of atoms and molecules from the surface.

Williams (1968) discussed the adsorption of atoms and molecules on graphite and the conditions required for the growth of mantles on graphite grains. Hollenbach & Salpeter (1970) treated the adsorption of light gas atoms on perfect crystal surfaces, estimating the adsorption energy, the accommodation coefficient and sticking probability for an incident H atom and the mobility of H atoms on the surface. Day (1972) has measured experimentally the accommodation coefficient for H_2 on cold graphite with results that confirm Hollenbach and Salpeter's estimates of this quantity. Day derives, in agreement with Hollenbach and Salpeter, a sticking probability about 0.3 for H from a 100°K gas striking a cold grain. Heavy atoms should stick with probability near one. On the perfect crystal surface an H atom is retained by van der Waals forces; the adsorption energy U_H is estimated at 0.8 to 0.9 kcal/mole. Augason (1970) considered other binding mechanisms as well and arrived at U_H values in this range or higher.

Lee (1972) has measured the adsorption energy of H_2 on ice and solid CO in the temperature range 4°K to 40°K. He finds $U(H_2)=1.7$ kcal/mole and 0.7 kcal/mole, respectively, for the bare substrates of H_2O and CO, falling to 0.2 kcal/mole, the sublimation energy of solid H_2, after many monolayers have formed. The first value is higher than the figure adopted by Hollenbach and Salpeter; Lee suggests that U(H) is probably also greater than their assumed 0.9 kcal/mole.

The surface mobility of an H atom results from quantum mechanical tunneling which, as Hollenbach and Salpeter emphasize, differs in an important respect from thermal diffusion over the crystal surface. Roughly speaking, in tunneling over a regular surface, the random walk step is not a lattice space, but the distance to an imperfection.

Will an adsorbed H atom meet another such atom before one of them evaporates? The answer depends on the H mobility and also, according to Hollenbach

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& Salpeter (1971), on the presence of lattice defects in the grain's surface, inevitable in a cold grain exposed to cosmic rays, where a migrating atom can be trapped with a binding energy $> U_H$. These sites of enhanced binding widen the range of grain temperature permitting efficient H recombination. Hollenbach and Salpeter conclude that if the grain temperature is less than 25°K, as it almost certainly is, a majority of the H atoms that stick on grains will leave as H_2 molecules. Lee's results appear to strengthen this conclusion, perhaps even allowing H_2 formation on top of an H_2 monolayer. The exothermic recombination will usually result in the prompt and energetic ejection of the molecule from the grain surface. Using rates of formation thus calculated, Hollenbach, Werner & Salpeter (1971) have estimated the equilibrium fraction of molecular hydrogen in clouds of various densities and opacities. Their prediction that the fractional H_2 abundance should arise to about 50% in a cloud of opacity 0.5 is compatible with the subsequent observation of interstellar H_2 by Carruthers (1970a). A competing process for the formation of H_2 in dark clouds, the associative detachment of H^- ($H^- + H \rightarrow H_2 + e$) has been thoroughly analyzed by de Jong (1972).

The formation of other molecules on grains has been treated by Watson & Salpeter (1972a). The course of events following the arrival of a heavy atom (for example, C, O, or N) at the grain is more problematic than the behavior of an H atom. Migration by tunneling will be much slower, possibly less effective than thermal diffusion over the surface potential barriers. It is hard to decide whether two heavy atoms will be mobile enough to find each other. If they are, reactions like $C + O \rightarrow CO$ may occur. But a heavy atom, even if it can't move, will eventually be visited by a migrating H atom. In fact, Watson and Salpeter conclude that "every heavy reactive particle hitting a grain produces some molecule." What now happens to such a molecule is of great interest. According to Watson and Salpeter it is less likely to be ejected by the reaction than was the H_2 molecule, and may often remain to take part in a further reaction, leading to a more nearly saturated product. Indeed the problem with the heavy molecules is not how to keep them on the grain, but how to get them back into the gas. Watson and Salpeter find that an effective nonthermal ejection mechanism in lightly shielded regions is the absorption of uv photons in the range 6–11 eV. It is not clear what ejection mechanism can prevent molecules other than H_2 from condensing out on grains in very dark clouds. Grain growth by the accumulation of mantles containing heavy atoms has been discussed by Aannestad (1973a). There remains considerable uncertainty in the relevant adsorption energies. Aannestad estimates that heavy mantle growth requires a grain temperature lower than 15°K.

In a second paper, Watson & Salpeter (1972b) estimate the equilibrium abundances of various molecular species which these processes, competing with photodissociation and certain exchange reactions in the gas phase, might lead to. Their predictions cannot be briefly summarized. The situation in lightly shielded clouds is quite different from that in moderately or heavily shielded regions. One striking feature predicted for moderately or heavily shielded clouds is that the abundance of CO should be much larger than that of any other heavy molecule. On

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the other hand, complex molecules generally may be most abundant in the gas in regions of moderate shielding, and not in the densest clouds where it seems that they should have condensed out more or less permanently as grain mantles. Future observations, with good spatial resolution, of molecular abundances in cloud complexes, are clearly needed.

10. X-Rays and Interstellar Grains

Overbeck (1965) suggested that the small angle scattering of X-rays by interstellar grains might cause an observable halo around a point source of X rays. A single scattering would deflect an X-ray photon by an angle $0.1\ \lambda/a$, in order of magnitude a minute of arc, or so, for a reasonable grain radius a. The grain's cross section for scattering would be typically a few hundredths of its geometrical cross section. A core of unscattered photons would mark the center of the halo. Slysh (1969) made a similar suggestion with reference to the pulsed X-ray source in the Crab Nebula. He pointed out that the scattered photons would not only be spread into a halo, they would incur delays much longer than a pulse period, obliterating their pulsed character. Slysh suggested that the extended X-ray source in the Crab might actually be the halo of the pulsed source NP 0532. But it has been shown by Bowyer, Mack & Lampton (1970) and by Ryter (1970) and by Naranan & Shah (1970) that the observations rule this out. The amount of dust required to reduce the pulsed component to the observed level is much greater than indicated by the visual extinction, and the wavelength dependence of the pulsed intensity ought to be much stronger than observed. Ryter notes, however, that the existing amount of dust may have an observable pulse-smearing effect at X-ray energies below 1 keV, an observation of which could yield rather direct information about grain size.

Martin & Sciama (1970) proposed that the detection of a halo around an X-ray source might permit the identification of light elements in grains through the anomalous scattering behavior near a K absorption edge. A similar proposal was made by Hayakawa (1970), who calculated the X-ray scattering for model grains of graphite, of ice, and of silicate. Hayakawa concluded that scattering of hard X rays ($\lambda \lesssim 10$ Å) by silicate grains might be observed with very distant strong sources, while in the soft X-ray region, in particular at wavelengths slightly longer than the K-edge of oxygen, distinctive scattering by silicate grains, with or without ice mantles, might be observed. A more detailed theory of X-ray extinction and scattering by spherical grains, including K-edge effects and multiple scattering, has been given by Martin (1970). No observations have been reported. Even if element identification could not be achieved, the observation of the intensity profile of an X-ray halo at two or more wavelengths would reveal the actual grain size distribution.

A quite different role for grains in X-ray astronomy was suggested by Johansson (1971), who considered the possibility that the diffuse X-ray background is "transition radiation" generated by cosmic-ray electrons passing through grains. When it abruptly enters or leaves condensed matter, an electron of energy γmc^2 causes, with probability of order $e^2/\hbar c = 1/137$, the emission of a photon in the

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energy range from zero to roughly $\gamma h\omega_p$, where ω_p is the plasma frequency in the material. For a 1-GeV electron entering aluminum this transition radiation spectrum extends up to 60 keV with a maximum around 20 keV. (See the laboratory observations by Yuan et al (1970a,b.) Johansson made a rough estimate of the X-ray flux that might thus arise from grains in the galactic disc and discussed other possible astronomical sources of transition radiation. Unfortunately there is a size effect that severely reduces the yield of transition X rays above 1 keV from grains as small as 10^{-5} cm. Ramaty & Bleach (1972) have shown that when this is taken into account, no significant contribution to the X-ray background in the kV region can be expected. They also conclude that even in the soft X-ray region transition radiation from grains cannot be an important source of photons.

11. Origin, Growth and Destruction of Grains

The probability of a condensation nucleus forming out of gas atoms and molecules under interstellar conditions is extremely small. Rather, as discussed in Section 9, it seems that interstellar grains are required for the formation of the molecules. The grains are therefore thought to originate under much denser conditions, mainly in the atmospheres of cool stars and in circumstellar space, and to be subsequently ejected into interstellar space by the radiation pressure from the star. For a review of the origin of circumstellar dust we refer to Woolf (1972). Below we discuss briefly the possible relationship between such dust and interstellar dust.

Graphite particles of sizes $\sim 0.1\ \mu$ may be formed in the atmospheres of carbon stars (Hoyle & Wickramasinghe 1962, Donn et al 1968, Kamijo 1969, Fix 1969a,b, Friedemann & Schmidt 1967). The particles are accelerated up to 10^3 kms^{-1} by the radiation pressure, and Friedemann & Schmidt investigated in detail the subsequent motion and destruction of these particles as they are ejected into the interstellar gas. The main destruction mechanism is sputtering due to hydrogen atoms impinging on the grains with energies of a few keV. For a gas density of $n_H \sim 1$ cm^{-3}, particles of final radii $\sim 0.05\ \mu$ reach distances ~ 10 pc after the radius has been decreased by factors of 2–3 due to the sputtering process. If the particles are exposed to the intercloud medium immediately after escaping from the stellar atmosphere, the gas density is as low as ~ 0.1 cm^{-3}, and the stopping distance becomes ~ 100 pc, comparable with the mean distance between interstellar clouds. It follows that grains with radii $\geq 0.05\ \mu$ may be stopped within the nearest interstellar cloud of density $n_H \geq 10$ cm^{-3}, while much smaller grains may be "strung out" before reaching the nearest cloud. This assumes that the dust moves parallel to the magnetic field lines, and that there is no resistance due to circumstellar gas. In a recent investigation of the same processes, Wickramasinghe (1972) has suggested that the preferential stopping of grains within clouds may explain the observed density correlation between dust and gas (Section 2). If we assume that most clouds have about the same age, accreted dust mass $\propto$ (radius)^2, and this would explain the rather remarkable fact that the total extinction for widely different-sized clouds (Spitzer 1968b, p. 6) is independent of the radius. However, it remains to be seen if a valid correlation is obtained when the statistical

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distributions of stars and clouds are considered. Also, the drag force due to circumstellar gas may couple gas and dust, decreasing the grain escape velocities to less than or about 100 km/sec (Gilman 1973).

Formation of solid particles—in particular, silicates—may occur in oxygen-rich stars (O $\geq$C) (Gilman 1969, Fix 1970), and iron particles may originate in planetary nebulae, novae, and supernovae (Hoyle & Wickramasinghe 1970). Hoyle & Wickramasinghe (1968) showed that condensation of dust particles may take place also in explosions of massive objects ($\sim 10^5\ M_\odot$) in the nuclei of galaxies, and Codina (1971) investigated the formation of polycyclic hydrocarbons in galactic nuclei and supernovae, as well as in the atmospheres of very cool stars. It is estimated by Woolf (1972) that most of the solids originating from stars consist of silicates, and that iron may be more abundant than carbon, but no firm values for the relative abundances can be given at this stage. However, if interstellar grains originate solely within stellar atmospheres, the total amount of dust ejected into space from stars must be comparable with the observed amount of interstellar dust. An estimate of the latter may be obtained from the relationship between the hydrogen-to-dust-mass ratio ρ_H/ρ_d and the ratio of hydrogen column density to color excess $N_H/E(B-V)$. With a value for the extinction ratio of $R=3.3$ and with $N_H/E(B-V)=5\times10^{21}$ atoms cm^{-2} mag^{-1} (Section 2),

$$\frac{\rho_H}{\rho_d} \simeq 20\,\frac{Q_V}{a(\mu)\rho_g} \tag{15}$$

Here Q_V is the visual extinction efficiency of the dust particles with a radius $a(\mu)$ in microns and a density ρ_g in gcm^{-3}. For dielectric particles like silicates or silicon carbide with sizes that give a fit to the extinction curve, $\rho_H/\rho_d=100$–150, while for graphite particles of sizes 0.02 μ–0.1 μ, $\rho_H/\rho_d=100$–300. If we assume an average interstellar hydrogen density $n_H\sim1$ cm^{-3}, the required amount of dust is about $10^{-4}\ M_\odot$ pc^{-3}. The lifetime of a typical dust particle is probably no longer than 10^9 years; thus the average rate at which dust is formed must be at least $10^{-13}\ M_\odot$ pc^{-3} year^{-1}. According to current estimates of mass loss (Pottasch 1970, Boyarchuk 1970), the total mass loss for all stars averaged over the Galaxy (10^{12} pc^3) cannot be much larger than $10^{-12}\ M_\odot$ pc^{-3} year^{-1}. Since the total mass fraction of condensible matter (atoms heavier than He) is about 10^{-2}, it appears that at most 10% of the observed dust can have originated directly in stellar atmospheres. The theoretical calculations by Donn et al (1968) for graphite grains formed in the atmospheres of N stars gave a rate of dust formation of $2.5\times10^{-14}\ M_\odot$ pc^{-3} year^{-1}, thus raising the possible contribution to about 25%. Unless the mass loss rates were larger earlier in the history of the Galaxy, it appears that grains ejected from stellar atmospheres cannot account for all the observed dust, but may constitute about 10% of the grains, possibly in the form of initial condensation nuclei.

Grains may form and grow also in the circumstellar regions around either young or evolved stars and subsequently be expelled by the radiation pressure. The matter around the evolved stars may originally have been ejected from the

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stellar atmospheres or may be similar in origin to the solar nebula. Herbig (1969) and Dorschner (1970a, 1971c) have suggested that interstellar dust is essentially a byproduct of star formation, and that the dust is similar to particles formed in the primitive solar nebula. The mass of the solar nebula is estimated to be $\sim 0.2\ M_\odot$, and if all the condensible material went into solids, the amount of dust produced by stars like the Sun [F, G, and K dwarfs with a space density of 2×10^{-2} pc^{-3} (Pottasch 1970)] would be about $2\times10^{-5}\ M_\odot$ pc^{-3}, or a factor of 5 smaller than the required amount of interstellar dust estimated above. It is unlikely that these stars are the sole sources of interstellar dust, but they may account for a fraction of the dust mass.

Solar nebula-type condensates may offer an explanation for anomalies in the observed abundances of some interstellar elements. In particular, the anomalously low Ca-to-Na ratio may be due to a preferential condensation of Ca relative to Na which occurs at temperatures >1000°K (Herbig 1969, K.-H. Schmidt 1971).

One further interesting consequence of this hypothesis is that cometary and meteoritic material, in particular the carbonaceous chondrites, may provide clues to the composition and properties of interstellar dust (Cameron 1972). It has been found that the cometary particles have a visual albedo ~ 0.3 and typical radii $\sim 0.1\ \mu$ (O'Dell 1971), values similar to the deduced values for the interstellar grains.

Circumstellar formation of dust just prior to the formation of early-type young stars may require initial condensation nuclei to be present, but the high densities ($n_H \sim 10^7$ cm^{-3}) may cause a rapid growth if gas atoms can stick to the grain surfaces. For circumstellar shells around OB stars with masses $\sim 30\ M_\odot$ and for a sticking probability $\gtrsim 10^{-2}$, K.-H. Schmidt (1971) showed that grains may grow to $\sim 0.05\ \mu$ in a time less than or equal to the contraction time for the star. However, the production rate of dust from such stars is at most $4\times10^{-15}\ M_\odot$ pc^{-3} year^{-1} (for a birth rate of 5×10^{-2} pc^{-2} year^{-1}, according to Schmidt) and fails by at least a factor of 25 to account for the observed interstellar dust mass, unless the dust has an unlikely long lifetime of 10^{10} years, comparable with the age of the Galaxy.

It appears difficult to account for all the interstellar dust mass purely in terms of stellar and circumstellar sources; the discrepancy is about 1 order of magnitude. Since such sources may provide core nuclei injected into the interstellar gas, the grains could continue to grow within the clouds. That some form of heavy element depletion is taking place in interstellar clouds is indicated by the observed strengths of interstellar absorption lines. In particular, calcium and sodium are depleted to various degrees (Savage & Jenkins 1972, White 1973). Also, a depletion of the cooling element C^+ is required by a current theoretical model for the heating and cooling of interstellar clouds (Field, Goldsmith & Habing 1969). (For a review of the thermodynamic structure of the interstellar medium see Field 1971, Dalgarno & McCray 1972.) Further, it has been found (Hoffleit 1956) that the strengths of interstellar absorption lines are greater near regions of ionized hydrogen (Hoffleit's correlation), recently confirmed to hold on a small scale by Walborn (1971). This may indicate that adsorbed atoms tend to come off

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grains in such regions. If elements heavier than Ne could accrete onto the grain, it would take about 5×10^8 years until a core radius of 0.05 μ had increased by a factor of 2; this would increase the total mass of dust in the cloud by a factor of about 10 and could explain the observed amount of interstellar dust. If all the heavy elements can stick to the grains, the corresponding time scale is about 10^7 years. The evolution of interstellar clouds due to depletion of cooling elements onto the grains has been treated by Mészáros (1972), and Aannestad (1973a) investigated the corresponding buildup of a "dirty ice" mantle and the production of simple molecules by surface reactions. However, the grain charge may be positive in interstellar clouds (Section 7), strongly prohibiting any accretion of ions. In that case, the observed depletion of the heavy ions may be due to their existence as part of (unknown) molecules, but it follows that these molecules cannot have been formed on the grains. Interpretation of the absorption observations of calcium and sodium (White 1973) shows that there is an intrinsic abundance anomaly, but that additional variations seem to take place within the clouds.

A positive grain charge would not, however, affect the neutral atoms O and N, and these atoms may recombine rapidly with H atoms on the surface to form H_2O and NH_3, respectively (Section 9). On the other hand, molecules may not stay on the surface for any length of time. Watson & Salpeter (1972a) found it likely that ejection by uv photons would take place with unit efficiency for such particles, limiting the coverage to about 10^{-4} of the grain surface. The main uncertainties in this estimate are the strength and nature of the adsorption to the core and the probability of efficient transfer of the absorbed photon energy to other surface particles. If initial layers could build up, further growth would be greatly facilitated since transfer of energy would then become efficient. Adsorbed molecules might also migrate to "growth edges" and become incorporated in the crystal structure. Experimental information on the photodesorption by near-uv photons has been obtained by Greenberg (1972) for various molecules physically adsorbed on cold quartz. If Y is the photodesorption yield (molecules/photon) and δ denotes the fraction of molecules that remain on the surface during formation, the criterion for mantle growth is

$$\delta > 7(mT)^{1/2}Y/x \tag{16}$$

where T(°K) is the temperature of the gas (assumed to be in pressure equilibrium with the intercloud gas at $n_{\mathrm{H}}T\sim2000$ cm^{-3}°K), m is the atomic mass of the heavy atom forming a molecule, and x is the number fraction relative to H of such atoms. A uv photon flux of 10^8 photons cm^{-2} sec^{-1} has been assumed (Habing 1968). According to Greenberg, $Y=10^{-6}$–10^{-7} for H_2O, so that for $O\rightarrow H_2O$, it is required (with $T=70$°K) that $\delta>0.4$–0.04. This is not an unreasonable requirement according to the estimates by Watson and Salpeter (Section 9), but far-uv photons may give higher yields as well as have a larger flux than assumed here (Witt & Johnson 1973). No desorption was observed from a second monolayer, indicating that the yield may decrease strongly with efficient energy transfer to similar neighboring particles; this would tend to make the grain grow nonran-

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domly. Also, if growth by H_2O formation occurs, the grain could become negatively charged, facilitating further growth by the accretion of ions.

If, as seems possible, but uncertain, mantles build up on interstellar grains in spite of ongoing photodesorption, they may in some instances be effectively destroyed due to sputtering by gas atoms and ions. Unfortunately, experimental information on sputtering is usually limited to high-energy bombardment ($\gtrsim$100 eV) of metal surfaces with normally incident heavy ions, making most astrophysical applications quite uncertain. Aannestad (1973b) treated low-energy sputtering of "dirty ice" mantles in interstellar shock waves, which are set up by cloud-cloud collisions every $\sim 10^7$ years. Due to their larger mass, He atoms were more important sputtering agents than H atoms, and the sputtering yields were determined mainly by the large relative velocities between grains and atoms set up at the shock front. The typical lifetime of a mantle was found to be about 5×10^7 years, leading to an average mantle size of 0.07 μ–0.1 μ for a core radius of 0.05 μ. The amount of ice in interstellar grains as determined from the infrared observations (Section 1) would limit the mantle to about 0.06 μ, somewhat less than, but not inconsistent with, the lower limit above. Since grains are effectively stopped by the gas within a narrow region ($\lesssim 10^{-3}$ pc) of the shock front, the probability of grain-grain collisions is small, and the corresponding destruction probability is at least a factor of 10^3 smaller than the destruction probability due to the sputtering process. Faster destruction of the mantles may occur if rapid depletion of cooling elements onto the grains takes place in the dense ($n_H \gtrsim 10^5$ cm^{-3}) region behind the shock front, causing a cloud to make a sudden phase transition to the intercloud state (Mészáros 1973). The grains would then be exposed to the hot ($T\sim$8000°K), but still mostly neutral, intercloud medium, and the radius of a dirty ice grain would decrease from 0.15 μ to 0.05 μ in about 3×10^7 years (Aannestad 1972). Finally, we note that very small grains, which seem to be required to explain the extinction observations in the extreme uv, may be destroyed by cosmic rays (Spitzer 1968a, p. 156).

Many of the processes that are thought to determine the growth and destruction of interstellar grains are poorly understood. Experimental information about these processes obtained under laboratory conditions that resemble those of the interstellar medium are badly needed. The embarrassing situation is that it appears difficult to account for most of the observed dust mass, since insufficient amounts seem to be flowing from stars and circumstellar regions, and because growth of grains in typical interstellar clouds is largely prohibited due to either electrostatic repulsion between grains and ions, photodesorption of molecules, or sputtering of mantles. One recourse is to hypothesize a much more efficient dust production early in the evolution of the Galaxy, maybe connected with violent activity in the nucleus. However, such ideas are just conjectures at the present time.

12. Dust in HII Regions

Observations of interstellar extinction show that increasing amounts of dust are found around the younger and more luminous O and B stars (Reddish 1967),

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and observations of scattered stellar and nebular light imply that dust particles exist inside as well as outside the HII regions (O'Dell, Hubbard & Peimbert 1966, Robbins 1970, Münch & Persson 1971). The discovery of the coincidence of many far-infrared sources with galactic HII regions (Harper & Low 1971, Hoffmann, Frederick & Emery 1971, Wynn-Williams, Becklin & Neugebauer 1972) provides additional, indirect evidence for the existence of dust within the HII regions. The dust appears to be heated to temperatures of 30°K–60°K and the infrared intensities are often larger than expected on the basis of absorption by dust of the Ly-α photons only, implying that dust is absorbing Ly-continuum photons (Petrosian 1972). The influence of internal dust on the structure of HII regions is beyond the scope of this review; we refer to recent work by Mathis (1972) and Petrosian, Silk & Field (1972). In principle, physical characteristics of the emitting dust can be inferred from the infrared observations, but this is currently limited by large uncertainties in the ultraviolet and far-infrared absorptive properties of possible grain materials.

Dust existing within HII regions is subject to an intense radiation field which may cause destruction of the particles through evaporation, as well as ejection of particles from the nebula. As discussed in Section 2, such mechanisms have been invoked to explain the "anomalous" extinction curves in certain regions. Mathews (1967) discussed the dynamic effects of radiation pressure in HII regions and showed that photoelectric charging of the grains effectively "freezes" the grains to the ionized gas. Ireland (1970) has numerically integrated the equations of motion of grains in HII regions and finds transit times greater than 10^6 years. Only the minor fraction of grains originating within about 0.1 pc for a nebula that is a few pc in radius will be able to move substantially during the lifetime of an HII region. It therefore appears that ejection of small particles cannot explain large-scale variations in the dust-to-gas ratio, as for example in the Orion Nebula, which has an age $<10^5$ years and where the dust-to-gas ratio is found to be smaller by a factor of $\sim$30 in the inner region (at $\sim$0.1 pc) relative to the outer region (at $\sim$1 pc) (O'Dell, Hubbard & Peimbert 1966). Very small dielectric grains ($a<0.01\ \mu$), would move slower than somewhat larger dielectric grains, and maximum initial velocities are imparted to the grains that have sizes a of the order of the wavelength of maximum starlight intensity λ_m. (Calculations of radiation pressure on dust grains for stars of various spectral classes have been performed by Divari & Reznova 1970 and by Pecker 1972.) A preferential ejection of grain sizes $a\sim\lambda_m$ and retention of much smaller (and larger) grains could explain the flat extinction in the far uv as well as the increasing extinction in the extreme uv for the "anomalous" curves in Figure 1, but it appears that the magnitude of the effect is severely limited by the electrostatic drag, except in the near vicinity of the central star.

Most grains are not able to move out of an HII region except over very long time scales and by moving with the gas. However, grains that are close enough to the central star may heat up and evaporate. Since the equilibrium temperature of a grain increases with decreasing grain radius, we note that for a given distance from the central star, all similar particles smaller than a certain radius will evap-

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orate. This suggests that if evaporation is the cause of the relatively flat extinction curves in the far uv, the small particles responsible for the increasing extinction for $\lambda^{-1} > 8\ \mu^{-1}$ must have widely different thermal properties compared with the larger particles.

Krishna Swamy & O'Dell (1967a) suggested evaporation of ice-like grains through Ly-α heating as the reason for the extensive variation in the gas/dust ratio in the Orion Nebula. The evaporation time for grains at temperatures $T_g \gtrsim 100°K$ is less than 10^5 years, consistent with estimates for the age of the nebula, and oxygen atoms may be abundant in the central region but deficient in the outer regions (Isobe 1970, 1971). However, Krishna Swamy & O'Dell found no depletion of oxygen in the Trifid Nebula, which has an anomalously high dust-to-gas ratio. Even if all the metals were in the grains, the dust-to-gas ratio would be only one half the observed ratio.

Destruction of volatile grains in HII regions by physical sputtering due to the impacts of protons on the grain surface has been considered by Mathews (1969), who found that the photoelectric charging of the grains was important in shielding the grains. The time scale for destruction was found to be $\lesssim 10^4$ years for dense HII regions ($n \lesssim 10^3\ cm^{-3}$), but this value should be revised upward by a factor of 10^3 (Barlow 1971), making sputtering unimportant for the destruction of grains. Chemical sputtering, where an incoming ion reacts with a molecule on the grain surface through an exchange reaction, has been suggested by Wickramasinghe & Williams (1968) as a destruction mechanism for grains in HII regions. For a charged H_2O grain of radius 0.1 μ, they estimate a destruction time of $\lesssim 10^4$ years. Such a high destruction rate would argue against the presence of ice-like grains in any of the observed HII regions.

The existence of dust in HII regions may be taken as evidence that the grains are refractory particles with evaporation temperatures $\lesssim 10^3°K$. However, with the possible exception of the importance of the chemical sputtering process, even ice-like particles with an evaporation temperature $\sim 100°K$ may exist in a substantial part of an HII region for time scales $\gtrsim 10^6$ years. High-temperature grains seem unlikely to explain the anomalous gas-to-dust ratio in the Orion Nebula, but particles with evaporation temperatures $\lesssim 500°K$ may be evaporated over large parts of the nebula. On the other hand, it is not clear why the outer regions in Orion have an anomalously high dust-to-gas ratio relative to the average interstellar value, unless recent grain growth has taken place.

Concluding Remarks

The nature of the interstellar grains is a question far from settled in spite of the great advance in our knowledge represented by the extension of the extinction and albedo curves far into the ultraviolet, the observations of infrared absorption, and massive additions to the chart of interstellar polarizations. But the range of tenable explanations seems at last to be narrowing. Taking present observations at face value, one is nearly persuaded that some mixture of grain types must be involved, that the matter responsible for extinction in the visible—or elsewhere

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—cannot be mainly ice, and must be in the form of macroscopic grains, not isolated molecules. Silicates and/or iron compounds emerge as the strong candidates for the visually absorbing particles, compatible with present ideas of cosmic abundance, although the origin of the observed amount of dust remains unexplained. Solid hydrogen has generally lost out. Graphite remains a strong contender for the 2200-Å hump—partly by default. The remarkable rise in extinction beyond the hump, with the accompanying increase in albedo, is a mystery.

Demonstrations of theoretical extinction curves for model mixtures provided with numerous adjustable parameters are not yet convincing, but now that we have the whole curve of Figure 1 to fit, that approach will surely be more instructive than it was when the nearly featureless reddening curve in the visible was the only datum. Claimed fits notwithstanding, present theories are generally deficient in at least two respects. First, except for a few calculations for infinite cylinders, all the models use Mie formulas for spheres. We know that the particles causing visual extinction, at least, cannot be spherical, or even nearly spherical. Until one can use good values for the extinction by realistically shaped grains, the fine adjustment of spherical model parameters will remain a rather pointless exercise. Second, the manifest requirement that the grains responsible for visual extinction be capable of alignment in the galactic field has often been ignored or dismissed lightly. Finally, the albedo and phase factor determinations are clearly imposing important new constraints. A skeptical critic may conclude that none of the models or mixtures so far proposed is capable of explaining all the presently known facts.

One further caution needs emphasis. Our information comes in part from observations in the ultraviolet of highly reddened hot stars, and in part from observations in the infrared of highly reddened cool stars, observations which may be referring to very different galactic regions. Presently unavoidable observational selection effects may be oversimplifying or distorting the problem. Still, irregular as the distribution of dust in the Galaxy is, wherever it is observed some properties are strikingly uniform. For example, the relative constancy of the ratio of total to selective extinction suggests that the formation and destruction mechanisms of the dust must be fairly similar in widely separated regions.

The diffuse absorption features seem to offer a tantalizing wealth of information. Surely modern solid-state spectroscopy will be able to decipher this message. Here much more laboratory work, of the kind Huffman has begun, is urgently needed. Extension of polarization measurements into the ultraviolet could be an extremely important source of new information. Progress in infrared astronomy will undoubtedly contribute significantly, perhaps decisively, in identifying a major component of the grain material.

With all these unsolved puzzles, it is encouraging that good progress is being made on such important aspects of interstellar astrophysics as the role of the grains in molecule formation, where, when one has put together all we do know, significant and fairly solid conclusions can be reached. The dust grains provide a link between observations of ionizing radiation, infrared radiation, and molecules. The understanding of these diverse but related phenomena may be crucial to our eventual understanding of the nature of the interstellar dust itself.

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