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N86 - 23502

INTERSTELLAR GRAINS

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There are few aspects of interstellar grains that can be unambiguously defined. Very little can be said that is independent of models or presuppositions; hence this report will primarily raise issues and categorize questions, rather than providing definitive answers.

The questions and issues that have arisen during the conference fall into three general areas: (1) the general physical and chemical nature of the grains; (2) the processes by which they are formed and destroyed; and (3) future observational approaches to (1) and (2). A fourth category, discussion of alternative models for the grains, could be added, but the models have been well described in this volume by Mathis, and the reader may judge how well the data summarized here compare with the models.

As an introduction, though, certain general characteristics of the interstellar medium (ISM) need to be mentioned. There are several types of environments, distinguished on the basis of density and temperatures: (1) dark clouds, constituting the majority of the mass in the ISM, having densities over 10^3 particles per cm^3 and temperatures below 50K; diffuse clouds, containing perhaps 25-50 percent of the mass, characterized by densities of $1-100/\text{cm}^3$ and T in the range 50-100K; "intercloud" gas (which may actually represent the surfaces of diffuse clouds), containing between 1 and 30 percent of the mass, with densities of roughly $1/\text{cm}^3$ and T near 10^3K ; and the so-called coronal gas, containing insignificant quantities of mass (but filling most of the volume of the ISM) with n of $10^{-2}/\text{cm}^3$ and T on the order of 10^{5-6}K . Grains are detectable in the first three of these environments; The greatest quantity of information comes from those in the dark clouds and the diffuse clouds. Hence, this report will concentrate on these two environments, but it is worth noting here that attempts to detect and analyze grains in the other regimes of the ISM would be of interest.

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I. THE PHYSICAL AND CHEMICAL NATURE OF INTERSTELLAR GRAINS

Based on observations and relatively model-free interpretations, we can specify several important aspects of interstellar grains, and raise questions associated with each.

Scattering theory indicates that grains represent roughly 1 percent of the mass in the interstellar medium. This value is consistent with the fraction of the mass that is depleted from the diffuse interstellar gas, so it is thought that rather little diffuse-cloud mass is tied up in grains (such as very large particles) that do not affect interstellar extinction, or in molecules.

From the observed scattering and extinction properties of interstellar grains, it is clear that there must be a range of sizes. The precise size distribution is not well known. The review by Mathis in this volume discusses several alternatives which have been suggested. Infrared data from reflection nebulae (Sellgren, 1984; Witt *et al.*, 1984) indicate that the size distribution extends to very small ($<100\text{\AA}$) grains, but it is not known what the lower limit on grain sizes is, nor whether in fact the distribution represents distinct populations rather than a continuum. (There is, in fact, a substantial question about the distinction between large molecules and small grains for typical sizes below 100\AA).

The narrowing of the linear polarization curve in dense clouds (Wilking, Lebofsky, and Rieke, 1982) indicates a reduction in the range of particle sizes, as would be expected if grains coagulate in the clouds or if the grains grow mantles which are thick in comparison to the cores (Aannestad and Greenberg, 1983). Scattering data in the infrared (for clumps around IRC2 in OMC-1) indicate that grain sizes in dark clouds are substantially larger than in diffuse clouds and could typically be a fraction of a micron (Ronan and Leger, 1984).

Little is known definitively about the composition of interstellar grains, but cosmic abundances impose severe constraints. The 9.7 micron emis-

sion feature probably shows that silicates are present and it has been argued that organic material is also present (Allen and Wickramasinge, 1981; Allamandola, 1984). Other spectroscopic indicators are ambiguous or unidentified. Grains containing graphite are suspected to be present, since carbon stars are rich sources of grains. Graphite may account for the 2175A extinction feature, but there are difficulties in this interpretation. One problem is that a plausible variation in the size distribution for graphite grains (Mathis, Rimpl, and Nordsieck, 1977) should produce a range of bump wavelengths that is not observed; another problem is that the bump is absent (and replaced by a feature near 2400A) in the best-observed carbon star (R Cr B; Hecht et al., 1984).

Observations of circular and linear polarization due to grains (Martin and Angel, 1977) indicate that the polarizing grains are dielectric in nature, implying that they are nearly pure scatterers. On the other hand, data on extinction in emission nebulae (Israel and Kennicutt, 1980) and on scattering in reflection nebulae indicate that some absorption occurs. Models of reflection nebulae (Witt and Cottrell, 1980) show that typical grain albedos are roughly 0.6. This is consistent with infrared emission data from IRAS as well, but is inconsistent with the requirement that dielectric (i.e., purely scattering, non-absorbing) grains produce the observed polarization. Hence, the evidence is strong that at least two distinct types of grains contribute visible-wavelength polarization and extinction. Other data may show a significant shift in the scattering phase function between visible and ultraviolet wavelengths, so a third distinct population, responsible for extinction in the ultraviolet, seems also to be present.

Studies of grain formation (discussed in Section II below) indicate that there are at least two distinct environments in which formation may occur: (1) oxygen-rich environments, yielding grain compositions dominated by silicates or oxides; and (2) carbon-rich environments, producing grains made of pure carbon or carbon compounds such as SiC. This picture may be consistent with the independent evidence (cited above) for distinct grain populations, but few observational tests can be made. Evidently, the different grain popu-

lations are rather well mixed in the interstellar medium, so it is difficult to associate specific grain origins with specific observable grain properties.

Beyond the general assumption that there are silicate grains and carbon grains in the diffuse medium, very little specific information is available on grain compositions. One possibility is "quenched carbonaceous condensate", produced in the laboratory, which shows a 2175A feature (Sakata *et al.*, 1984). Another very recent suggestion, consistent with near-infrared photometric data indicating the presence of a population of very tiny grains, is that polycyclic aromatic hydrocarbons (PAH's) exist in abundance (Leger and Puget, 1984). These molecules may be viewed as constituents of graphite particles. They may account for several previously unidentified infrared emission features in emission and reflection nebulae (although molecular vibrational transitions induced by charged grains have also been suggested (Puetter, this volume)) and in solid form (as on grain mantles) they may also play a role in creating the broad near-IR emission observed in several reflection nebulae (Wdowiak, this volume). Furthermore, they may also explain the emission in the 12 micron band by the "interstellar cirrus" clouds discovered by IRAS (Leger, this volume; although thermal emission by tiny silicates is another possibility), and appear potentially interesting as candidates for the carriers of the confounding unidentified diffuse interstellar bands (DIB's) in the visible (Leger and d'Hendecourt, 1985; van der Zwet and Allamandola, 1985; Crawford, Tielens and Allamandola, 1985).

The potential for PAH's is tempered, however, by a lack of information. It remains to be seen how well they will withstand more careful scrutiny. For example, little is known about the detailed spectra of specific species, and quantitative measurements of their ultraviolet extinction properties are available for only a few relevant species.

Summary of key questions:

1. **Grain Size Distribution:** It is important to know how small and how abundant grains are at the small end of the distribution. This has important implications for the observed near-IR broadband emissions from some regions,

and for the surface area available for depletion and for other surface processes such as H₂ formation.

2. Grain Composition: Is there graphite in the interstellar medium, or not? Meteoritic data suggests that there may not be (Nuth, this volume). In either case, how do we account for the invariability of the 2175A extinction feature, since shifts in wavelength are expected if it is due to a continuum of grains? How much graphite is needed to produce the 2175A feature and how well-ordered must its structure be? Can we find regions dominated by either carbon-rich or oxygen-rich grains, so that we can directly associate grain properties with grain origins? Do polycyclic aromatic hydrocarbons or quenched carbonaceous condensates exist in the interstellar medium? Can we explain the simultaneous indications that visible polarization is produced by pure scatterers, while visible extinction is in part due to absorption?

II. GRAIN FORMATION AND DESTRUCTION

Analysis of grain formation rates (in the atmospheres of red giants and in supernovae) shows that the entire mass of galactic dust and gas population can be produced in about 3×10^9 years. On the other hand, grain destruction in shocks apparently can destroy grains in 10^8 years (Draine and Salpeter, 1979; Dwek and Scalo, 1980; Seab and Shull, 1983). This indicates that there must be an additional source of grains, in order to maintain the observed population. The only suggested additional source is the growth of grains by accretion onto small seeds in dense interstellar clouds (Draine, 1984; Greenberg, 1984). There is substantial observational evidence, in the form of measured depletions and IR absorption due to icy grain mantles, that grains can grow due to accretion of material from the gas. There are substantial questions, however, about the source of nucleation seeds for such growth, about the time-scale on which the growth occurs, and about whether such growth can produce grains with all the observed properties.

Nucleation seeds may be available from shock processing of grains, if the grains are broken into fragments rather than being fully vaporized. Constraints can be placed on this by observations of shocked gas, which show that

most of the grain material is vaporized in high-velocity shocks (as indicated by the lack of depletion in shocked gas (e.g. Shull and York, 1977; Snow and Meyers, 1979). Lower-velocity shocks may, however, break grains into pieces without fully vaporizing them.

The timescale for grain growth in interstellar clouds depends on the available surface area; recent indications that a large number of very small grains are present (Sellgren, 1984; Draine and Anderson, 1985) have substantially increased the estimated surface area, and hence, have reduced the grain-growth timescales to reasonable values.

Potentially difficult aspects of grain growth in the interstellar medium have to do with the observational constraints placed on the resulting grains. Several specific grain features must be reproduced by grains grown in the interstellar medium. For example, the 9.7 micron feature indicates the presence of silicates, which might be formed by condensation at high temperature in a stellar atmosphere, but which may be more difficult to form from the deposition of silicon atoms onto cold grains in the presence of hydrogen. Amorphous films of SiO and Mg + SiO have been grown in argon matrices at 50K. These films have infrared absorption properties which resemble interstellar silicates (Stranz et al., 1981; Donn et al., 1981). It is noteworthy in this context that virtually all silicon in the diffuse ISM is in the grains, so the process of grain growth in the ISM must be very efficient. Also, the analysis of interplanetary material reveals isotopic ratios that probably were created by r-process (supernova) or s-process (stellar atmospheres) during circumstellar grain formation, and which would be very difficult or impossible to recreate in grains grown by accretion in the interstellar medium. This implies that some fraction of the interstellar grains present when the solar system formed were pristine products of the formation processes in supernovae or stellar atmospheres, and had not been destroyed and regrown in interstellar environments. Also, as noted in Section II, there apparently are distinct grain populations, as evidenced by scattering and polarization analyses. It is possible to attribute these to distinct formation environments if grains are produced in stars or supernovae, but this is not so easy to do if grains are grown in the ISM. Perhaps the distinct populations arise from nucleation

cores with distinct compositions and differing abilities to grow or retain mantles.

Apart from the general question of grain formation rates versus grain destruction rates, more specific information is available on grain growth. There is a general pattern of elemental depletions indicating that certain elements (generally refractories) are more highly concentrated in grains than others. It is not clear whether this pattern is due to selective accretion of refractories onto grains, to selective sputtering or photodesorption of volatiles off of grains, or to a grain formation process in which the refractory elements are bound into grain cores. Possibly all four processes are at work. It is clear that accretion onto grains does occur; that the overall level of depletion correlates at least roughly with cloud density (although the evidence for this is not as strong as commonly supposed; curve-of-growth ambiguities due to line saturation on one hand, and regional variations on the other apparently conspire to enhance the appearance of a correlation).

A grain growth process that competes with mantle accretion is the coagulation of grains, as implied by the low ratio of scattering optical depth to grain mass that characterizes certain diffuse clouds (Jura, 1980; Mathis and Wallenhorst, 1981), and by the particle size distribution in dark clouds inferred from infrared scattering studies (Ronan and Leger, 1984). This process has no effect on depletions, however, and so it cannot explain the enhanced overall depletions in dense clouds. Hence, grain growth must occur in dark clouds both by the accretion of mantles as well as by coagulation. Evidence for mantle growth is found in the 3.1 micron water ice feature and in many other bands (e.g. Hagen et al., 1980; Tielens et al., 1984, 1985; Allamandola, 1984; Kitta and Kratschmer, 1983). A quantitative analysis of the mantle features in one line of sight (W33) implies that 30% of the carbon and oxygen are in grain mantles.

Summary of key questions:

- 1. Formation And Destruction Rates:** Is the timescale for grain destruction really shorter than that for grain formation in supernovae and stel-

lar atmospheres? If so, then great difficulty arises in finding a way to grow grains in the interstellar medium with all the observed properties. More specifically, what is the source of nucleation cores, and how does grain growth produce grains capable of creating the observed polarization, silicate emission, silicon (and other) depletions, isotopic ratios, and distinct grain populations?

2. **Depletions:** What are the relative roles of grain formation, selective accretion, and selective sputtering and photodesorption in creating the observed pattern of depletions? Which grains are responsible for the depletions: is it a simple matter of surface area, which favors the abundant small grains, or is there a strong dependence on grain composition, temperature, charge, or other factors?

3. **Grain Chemistry:** What is the chemistry that produces the variety of mantles seen in dense clouds? What fraction of the simple molecules in accretion mantles can be converted to large molecular residues? What is the dominant conversion mechanism?

III. FUTURE RESEARCH

It is fitting that some discussion of future research directions be included here. This discussion will be partially redundant with the foregoing, but it seems worthwhile to try to systematically collect future strategies in one place.

1. **The 2175A Extinction Feature:** The invariance of the wavelength of this feature (to within a few tens of Å) is established, but it is important to refine this measurement further. There remains the possibility of finding a dependence of the bump strength on some physical or chemical parameter that might help to identify its origin. For example, it has been attributed to graphite, but so far there is no clear-cut definition of what this really means. Specifically, does carbon have to be highly ordered, as is normally assumed, or is partial ordering sufficient? If the feature is due to carbon in some form, perhaps it should be enhanced in carbon-rich environments, but

not in grains formed in oxygen-rich environments. If so, it would be very helpful to try to isolate both types of environments and to see whether the feature is associated with one and not the other (this is being pursued for planetary nebulae). Another approach is to see whether carbon depletion from the gas correlates with bump strength. Studies of mantle growth and bump strengths may also be helpful. A couple of clouds have been formed in which the 2175A feature is strongly suppressed, and it has been suggested that mantle growth is responsible. Further study of these or similar cases may help reveal what has happened to modify the dust so that the feature is absent. A more sensitive search for the predicted 11.5 micron graphite feature (Draine, 1984b) in dark clouds should be made. Finally, polarization structure (or the lack thereof) in the 2175A feature may help specify the carrier; data will be available within a year.

2. Spectroscopic Exploration Of Candidate Materials: Here there are several important considerations. First, it is essential to isolate specific compounds or molecules (as in the case of the PAH's) and measure their detailed spectra. Many close coincidences are already found, but that is not sufficient to establish the identity of observed interstellar features. This applies to the unidentified infrared emission bands, the broad red-near-IR emissions in reflection nebulae, and to the visible-wavelength diffuse interstellar bands. Second, predictions should be made, based on laboratory spectra, of interstellar features in wavelength regions not yet explored. Of great potential importance here is the tentative indications that proposed candidate materials, particularly the PAH's, have strong ultraviolet signatures. Extensive visible ultraviolet measurements of such materials are available for comparison (see references in Donn, 1968). The laboratory data should be translated into predicted ultraviolet extinction structure, so that quantitative comparisons can be made. Conversely, continued attempts at measuring structure in UV extinction curves should be made.

3. Polarization And Scattering Measurements: Models of interstellar grains should be extended to predict polarization properties in presently observed wavelengths. Again, the ultraviolet is important, and will be ob-

served within a year or so by the WUPPE experiment on the Space Shuttle. Also, grain shapes and grain alignment mechanisms should be studied further.

On the basis of polarization measurements, it should be possible to place lower limits on the ratio of the axes of grains in various environments. It should also be possible to distinguish between oblate and prolate grain shapes. In the case of silicate grains, for example, this can be done by comparing the wavelengths of maximum absorption and maximum polarization in the 10 and 20 micron absorption features (Lee and Draine, 1985).

Measurements on the high (or low) frequency side of the thermal emission peak of a cloud will favor detection of radiation from low (or high) emissivity grains. Polarimetry of the thermal emission at different wavelengths may therefore show correlations between grain properties related to temperature (dielectric constant and size) and those related to grain alignment and emission of polarized radiation (magnetic susceptibility and shape). (Hildebrand, 1983).

4. Scattering Properties: The analysis of scattering properties of grains, such as albedos and phase functions, can reveal a great deal about the size distribution and the presence or absence of distinct populations (as opposed to a continuum of sizes). Ambiguities about star-nebulae geometries, which plague present analyses, can be reduced by statistical studies of larger numbers of nebulae.

5. Mantle Growth: Laboratory measurements are capable of simulating mantle growth on grains and need to be pursued (Hagen et al., 1979). There are important questions having to do with mantle composition in particular, which require information on the surface physics. For example, hydrogen atoms collide with grains far more frequently than other species do, but the role of hydrogen on grain surfaces is not well known: does it desorb immediately, or does it dominate the chemistry of other elements? What is the role of ultraviolet photodesorption and photolysis?

In addition to continued laboratory work, astronomical observations relevant to grain mantles need to be extended. Better-quality infrared spectra from 2 to 14 microns are needed, as are better data on possible ultraviolet extinction features. There is very little data on the 3.4 micron absorption feature seen in diffuse ISM grains (Mathis, this volume).

The observation of polarized absorption (Jones et al., 1984) and polarized thermal emission from a cool dense cloud (Hildebrand, Dragovan, and Novak, 1984) shows either that the growth of grain mantles in such a cloud does not destroy the persistent surface features required for suprathermal rotation (Purcell, 1979), or that grains can be aligned by mechanisms not requiring suprathermal rotation. Duley (1978) has discussed alignment by ferromagnetic materials. Mathis (this volume) has quantitatively estimated the wavelength dependence of polarization of this mechanism. Alternatively, Greenberg et al. (1972) have suggested that radicals embedded in grain mantles could give grains "permanent" magnetic moments.

6. Depletions: Further explanation of the dependence of depletions on cloud physical conditions is needed. Improved accuracy in abundance determinations, requiring high S/N data at very high spectral resolution, should further clarify the process of grain destruction in shocks, which is very important in assessing the relative roles of grain formation and mantle accretion in creating the depletions in the first place. Another important approach is to make abundance and depletion measurements in dark clouds, something that is technology-limited but becoming more feasible.

7. Laboratory Experimentation: In addition to the chemical and spectroscopic experiments described in the foregoing sections, it would be useful to try to simulate physical processes that may affect grains in the interstellar environment. For example, it may be feasible to simulate grain-grain collisions to get real data on how grains are affected: what is required to fully atomize them; can they be broken up into small fragments but not atomized; does selective sputtering of elements occur; under what conditions does coagulation take place? What are the effects of very small grain sizes on

physical processes such as vaporization and mantle growth? How do UV photons affect surface processes?

Laboratory measurements of low-energy sputtering yields for candidate grain materials (both refractory and ice) are needed to check existing theoretical estimates for these yields. Measurements of photodesorption cross sections are required to clarify the role that ultraviolet radiation may play in selectively removing atoms and molecules which accrete onto grain surfaces in diffuse clouds. Photoelectric emission from dust grains plays an important role both in grain charging and in heating of interstellar gas; studies of photoelectric emission yields from small particles or thin films of candidate materials are therefore needed to model these processes.

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