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Observations and Theories of Interstellar Dust

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Introduction and Disclaimer: I will try to summarize the observational properties of dust, as based on (1) the extinction over a factor of 100 in wavelength (0.1 μm - 10 μm), (2) on polarization, both linear and circular, (3) on rather narrow emission and absorption features in the spectrum, and (4) on reflection nebulae. I will then discuss theories. Clearly, I cannot mention much of the vast literature which is relevant. There are reviews in Savage and Mathis (1979), Stein and Soifer (1983), and Draine (1984). To the many workers in the field whose papers I will fail to cite, I say: please don't feel slighted; you have plenty of company.

It is essential to realize that the words "interstellar dust" refer to different materials when they refer to the diffuse ISM, to the outer edges of dense clouds, or to the dark central regions of those clouds. There are obvious observational selections which make it difficult to study dust in dense regions. Most of what I will say refers to dust in diffuse regions, which I will call "diffuse dust".

I. Observations

A. Extinction. There is very good agreement on a "standard" extinction law for diffuse dust for $\lambda > 0.3$ μm. In dense regions, extinction for $\lambda > 0.55$ μm seems to be the same as for diffuse dust,but the value of $R(V)$ ($= A(V)/E(B-V)$) increases from the diffuse ISM value of 3.1 to 4 or 5. The change seems to be in the B magnitude, in the sense that the extinction becomes more grey. In the IUE ultraviolet, the situation is quite different: there are certainly real variations of the extinction even in the diffuse ISM, especially for $\lambda < 0.16$ μm (Massa et al. 1983; Witt et al. 1984a). These variations are often shared by all stars in a common region of the sky. The changes in extinction from one star to another have a universal wavelength dependence, suggesting that a single grain population is responsible for the far-UV rise (Greenberg and Chlewicki 1983; Massa and Savage 1984). The famous λ2175 "bump" is the only extinction feature in the whole visual-UV region (I am not considering the diffuse interstellar bands, which are likely produced by some material associated with dust). Unpublished work by E. L. Fitzpatrick and D. Massa (private communication) show that the wavelength of the maximum of the bump is exceedingly constant from direction to direction, while the width and strength of the bump vary significantly. This behavior is not at all like that expected from graphite; more about this later...

The only other spectral absorption features are in the near-infrared (NIR): the 9.7 μm "silicate" feature, which is matched well by amorphous silicates but somewhat better by the absorption in the oxygen-rich star μ Cep (Roche and Aitken 1984). There is a 20 μm absorption feature which is also present in silicates. A 3.4 μm absorption is weak but consistent with absorption by C-H stretching. The absorption coefficients of individual hydrocarbons vary greatly, and only tiny amounts of some substances could produce the entire 3.4 μm band, while other materials would require most of the cosmically available carbon in order to have sufficient strength (Duley and Williams 1979). The 3.4 μm absorption is seen only when there is a huge amount of visual extinction, such as A(V) = 25 - 40 mag towards IRS 7 near the galactic center (Jones et al., 1983; Allen and Wickramasinghe 1981). We happen to be viewing the galactic center through only diffuse ISM, so the 3.4 μm band is presumably found in standard diffuse dust.

There is an absorption feature at 3.07 μm which does not occur in diffuse dust. It is sometimes not visible until A(V) = 25 mag (Harris et al. 1978), but it can appear at A(V) = 4 - 6 mag (Whittet et al. 1983). It can be fitted very well by solid water and ammonia ices (Hagen et al. 1983). There is also a 4.67 μm feature in very dark clouds which is presumably caused by solid CO (Lacy et al. 1984). Hence, there is no doubt that deep within dark clouds the grains have coatings of ices.

Emission features are observed at 3.3, 3.4, 6.2, 7.6, 8.8, and 11.9 μm in such diverse sources as some Seyfert I galaxies, planetary nebulae, and stellar sources deep within molecular clouds. There is a good review by Aitken (1981).

Linear polarization caused by alignment of grains shows a maximum at a wavelength, λ(max), which varies from star to star. It is in the range 0.4 to 1.0 μm, with an average of 0.55 μm. An empirical law (Wilking et al. 1982) fits the form of p(λ) very well. There is a good linear correlation between λ(max) and R(V) (Whittet and van Breda 1978), understood in a reasonable but qualitative way by the idea that both large λ(max) and R(V) are associated with particles which are larger than average (but see Chini and Kruegel 1983 for a note of caution on this point). There is no correlation between p(max) and E(B-V), except that their ratio never exceeds 9% per mag. This fact is easily explained: a tangled magnetic field or imperfect grain alignment can easily lower p(max)/E(B-V). The largest values of p(max)/E(B-V) must be associated with those directions with the most uniform magnetic field and perfect alignment. The observed maximum value implies almost perfect spinning alignment (Greenberg 1968).

The 9.7 μm "silicate" absorption band shows very strong linear polarization in some cases, such as the Orion BN object. The significance of this fact is that the grains responsible for the 9.7 μm band must be elongated and aligned.

Circular polarization provides a powerful diagnostic regarding those grains which are aligned (but, of course, only those) because it goes through zero at a wavelength λ(cir) which is quite sensitive to the dielectric constant of the material. Observations (Martin and Angel 1977) show that λ(cir) = λ(max), the wavelength at which linear polarization is a maximum. Martin (1974) showed that this condition implies that the polarizing material is a dielectric, with a real index of refraction and no true absorption, if the index of refraction is independent of wavelength. The material magnetite has an index of refraction which varies with λ in such a way that at 0.55 μm, it would have λ(cir) = λ(max). However, the condition is met for stars which have different values of λ(max), and magnetite would not provide the observed condition for other wavelengths. Thus, the grains which provide the polarization have an albedo of almost unity. As we shall see, this fact puts powerful pressure on theories of grains.

Reflection nebulae and the diffuse galactic light can in principle provide information about grains, but unfortunately the interpretation of observations is highly dependent on the unknown geometry of the nebula. The most interesting observation is that there is an excess of emission in the NIR, probably extending into the red spectral region (Sellgren 1984, Witt et al. 1984b). I would guess that it extends into the IRAS 12 and 25 μm channels as well. It is presumably caused by either a fluorescence (excited by a UV stellar photon) or by the heating of very tiny grains by single UV photons, followed by radiative cooling. The spectrum of the excess emission, and its variation with spectral type of the exciting star, will be an interesting diagnostic of grains.

There are other diagnostics I will not discuss. One is the spectrum of the far infrared (60 - 200 μm) emission from the grains heated by the galactic starlight. The spectrum depends on the dielectric properties of the materials through the absorption of the visual/UV and the emissivity in the FIR. The formation and destruction of grains, and the depletions of elements from the gas phase of the ISM, also are important clues as to the kinds of particles which ought to be present in space.

II. Theories of Grains

There are at least four "complete" theories of grains which claim to explain the entire range of observable wavelengths (0.1 - 20 μm). They have one feature in common, in my opinion: each is in conflict with at least one observation. Possibly the real answer is a combination of some of these ideas, plus, I suspect, several concepts which no one has thought of yet.

I discuss the theories in turn, followed by a contrast of the two most commonly discussed ones.

A. F. Hoyle and N. C. Wickramasinghe (1982) advocate a mixture of anhydrous biological material, plus graphite for the λ2175 bump. Jabir, Hoyle, and Wickramasinghe (1982) give a specific list of materials in the model, but the ingredients seem to vary from time to time. The only concrete objection I am aware of (Whittet 1984) is that the model uses an order of magnitude more phosphorus than is cosmically available.

B. W. W. Duley, T. J. Millar, and associates (e. g., Duley and Najdowsky 1983) explain the extinction with various metallic oxides and amorphous carbon. The λ2175 bump is caused by transitions of surface oxygen ions on tiny (10 Angstrom) MgO crystals. The tiny size is required because only surface atoms carry the transition (in fact, bulk MgO has a very strong absorption at 0.164 μm which is not seen). There are also SiO and FeO grains which are large (0.1 μm), elongated, and aligned in the galactic magnetic field. These grains provide the polarization. The strongest laboratory support of this model is the study (MacLean et al. 1982) of blue flourescence radiation produced by UV of various wavelengths incident upon MgO crystals. The blue emission is a maximum when the UV is at λ2200. A direct measurement of the λ2175 absorption would be much more convincing.

It seems strange to me that one has tiny MgO and large SiO and FeO particles. Another serious objection to this theory is the strong polarization of the BN object at 20 μm (Knacke and Capps 1979). The polarization is caused by FeO and SiO; MgO cannot produce polarization because its crystals are cubic and are therefore too symmetrical. SiO has no bands at 20 μm, and FeO provides much less absorption than MgO at 20 - 25 μm (Brehat et al. 1966).

C. J. M. Greenberg and his associates have developed a three-component model (e. g., Greenberg 1984a,b). The constituents are: (1) A population of tiny grains, probably silicates, to provide the steep rise of extinction with 1/λ at λ < 0.16 μm. (2) Small graphite grains (or something similar) to provide the λ2175 bump. (3) Mantle-coated silicate grains to provide almost all of the extinction from 0.3 μm through the visual/NIR. The mantles, which occupy 90% of the volume, are assumed to be the "yellow stuff" refractory residue left behind after warming UV-photolyzed ices of CO, water, ammonia etc., to a few degrees Kelvin. The free radicals in the ices react and produce the yellow material which is stable at room temperatures. These reactions provide the gas-phase molecules which are observed in dark clouds. The observations of the 3.07 μm absorption band strongly indicate that icy mantles do form within dark clouds; the question is how much of the refractory residue of the mantle can remain after the grain has been injected into the diffuse ISM and has been subjected to shocks and other harsh environments.

D. Mathis, Rumpl, and Nordsieck (1977; hereafter MRN) have two populations of bare refractory grains for the diffuse ISM. One component is graphite; the other is silicates. Both have a power-law size distribution in sizes. There is a rather arbitrary cutoff in sizes at both ends. Originally, the smallest size was assumed to be about 0.005 μm because the data were insufficient to determine the distribution of smaller sizes. The observed excess NIR emission of reflection nebulae suggests that the smallest particles might be about 0.001 μm, which makes them molecules rather than grains. The largest particle size is also rather arbitrary, but about 0.25 μm or so fits the extinction and polarization quite well. Increasing the largest size for silicates fits observed extinction in the edges of dark clouds. Recently, the optical constants of graphite and silicates have been rediscussed by Draine and Lee (1984), and any predictions of the MRN model should be made with their constants.

The MRN model almost surely needs modification regarding the origin of the λ2175 bump. MRN requires the bump to be produced by a size distribution of graphite particles rather than entirely by small ones. The maximum is shifted about 0.01 μm to longer wavelengths by the contributions of small but not tiny (e.g., 0.02 μm) particles, which also contribute scattering in the $\lambda < 0.15$ μm region. This picture makes the constancy of the wavelength of the maximum of the bump, and the lack of correlation of the bump strength with the $\lambda < 0.15$ μm extinction, hard to understand (Greenberg and Chlewicki 1983).

I think that two recent ideas probably go a long way towards clearing up the problems with the λ2175 bump. They are theoretical calculations by Leger and Puget (1984, and preprints) and laboratory work by Sakata and coworkers (1983, 1984). In the Sakata et al. work, methane is subjected to a discharge, and the products are quenched onto a substrate. The residue is called QCC ("quenched carbonaceous composite"). The QCC shows both the λ2175 bump and absorption features at most of the wavelengths of the NIR emission bands in the ISM. The Leger and Puget theory suggests that mixtures of polycyclic aromatic molecules of molecular weights of about 50 or so, which I think of as pieces of graphite, should produce the emission features and the NIR excess in reflection nebulae. However, it is somewhat obscure to me how the width of the bump can vary much with the QCC or polycyclic aromatics ideas.

It has always been difficult to understand how carbon can be annealed into graphite in the brief time it spends as a hot solid in a carbon-star atmosphere. Annealing in interstellar space seems even more difficult. Therefore, I find the suggestions outlined above very appealing, and feel that MRN should be modified to include the polycylic aromatics, or whatever QCC is.

Observational confrontation of MRN and Greenberg theories is possible because of the predictions of the nature of visual extinction. The reasoning is that the circular and linear polarization, taken together, show that the polarizing material is a dielectric. If there is only one kind of grain providing the extinction, as in the Greenberg theory, then the visual albedo must be almost unity (see Greenberg 1984b). Using the optical constants of Draine and Lee (1984), I estimate that less than 7% of the extinction at Hα is provided by the graphite required to produce all of the bump, and I suspect that QCC or polycyclic aromatic molecules probably have about the same absorption as graphite because of a similar chemical structure. Thus, the albedo of the Greenberg theory should be 0.93 because only the "graphite" is providing true absorption. Yet, we know that H II regions have fairly large absorption of their Balmer lines, as judged from the Hα/radio continuum ratios (e.g., Israel and Kennicutt 1980). If there were just scattering, the line photons would escape, and we would see no reduction in line strength. Thus, the albedo at Hα must be appreciably different from unity, and 0.93 is nowhere near different enough.

Similar reasoning applies to reflection nebulae; most analyses suggest a visual albedo of 0.6 - 0.7. The MRN predicts an albedo of about 0.55 at Hα and 0.61 at V.

Another point of disagreement between MRN and Greenberg is whether the grains in the outer parts of dark clouds are larger because of coagulation (MRN; see Mathis and Wallenhorst 1981) or accretion of mantles (Aannestad and Greenberg 1983). Accretion is a reasonable idea, and must certainly take place beyond some point in the cloud. However, observations of two stars embedded in clouds, ρ Oph and NU Ori (Shull and van Steenberg 1985) show that the ratio of the column density of H I to extinction, N(H I)/A(V) is greater for these stars than for the average ISM. In other words, the extinction cross section per neutral H drops as we go into the cloud. This is predicted by coagulation (Jura 1980), becuase larger grains are less efficient absorbers. The fact that only two stars show the increase does not imply that others do not show coagulation. In dark clouds, most H is molecular, which IUE cannot detect. If accretion were the true situation, the conversion of atomic H to molecular alone should decrease N(H I)/A(V), since the cloud material contributes dust without atomic H. Adding new material to each grain, thereby increasing A(V) for the fixed number of grains per H nucleus, makes matters so much worse. Thus, accretion in the outer parts of clouds predicts the wrong sign of the observed extinction per H nucleus.

Supposedly the wavelength dependence of linear polarization is a strong point in favor of the Greenberg model (Aannestad and Greenberg 1983). I have a poster in this workshop giving what seems to me to be a natural and quantitative explanation of both the shape and changes from region to region of the linear polarization. Since it hasn't been properly refereed, I will not comment on it further. I invite criticisms of the poster.

Overview: I close with the thought that there have been great strides in the understanding of the nature of dust in the past ten years. I feel that the new ideas regarding QCC and polycyclic aromatic hydrocarbons are very exciting. I suspect that no one theory will emerge as the "winner", and that the true one has yet to be formulated.

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