Summary

CRITICAL QUESTIONS FOR THE FUTURE

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All participants at this meeting agree that it has been very exciting, this for three reasons. First, it has put together astrophysicists, laboratory and theoretical physicists and also chemists, thanks to the interdisciplinary nature of the field of interstellar dust. Second, we have had a very exciting confrontation between meteolitiscists, and specialists of interstellar, and cometary dust, and we saw growing evidence that interstellar dust is a pervasive solar-system material, although the history of this dust may have been peculiar. Third, last but not least, there has been in the recent years a wealth of new data on interstellar dust emerging from observations in various wavelength ranges, especially the infrared , and a lot of new laboratory data and sophisticated theories that allow us to interpret the observations. Clearly the study of interstellar dust, which had remained in its infancy for such a long time, is becoming a mature and much less speculative field.

There is a danger in all this: that concentrating on the most exciting things we tend to forget about the routine-type of observations or laboratory work. However, those routine tasks (e.g. photometry) remain absolutely essential for a full understanding of the problems. This is a warning to the funding agencies and to the observing program committees. Also, long-standing unsolved problems such as the origin of the diffuse interstellar bands should never be forgotten as their solution can come in most unexpected ways and mean fundamental advances in our understanding of dust.

One of the major discoveries of the recent years of astronomy is that of the far-infrared thermal emission of dust. This was not unexpected, of course, but one had not fully realized in advance that dust is emitting half of the radiation of our Galaxy, and that so much information would come out of far-IR studies. The launch of IRAS has been a real breakthrough in this field, but much more is certainly to come from future space observatories like ISO and, if launched, SIRTF, as well as from airborne and ground-based observatories. In spite of recent efforts our knowledge of the submillimeter emission of dust is still meager and it is obvious that observations with the COBE satellite, with new balloon and airplane facilities and with future submillimeter space observatories will have to fill up what is essentially the last major gap in our exploration of the electromagnetic spectrum.

In spite of their interest, for lack of space, I will not cover topics like infrared polarimetry (the best way to map the magnetic field in obscured regions), or the evolution of grains, a subject which will receive a strong impulse when the Hubble

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Space Telescope and hopefully LYMAN will provide us with new and better information on elemental depletions in the interstellar medium. I will not cover either the fast-growing subject of the interplanetary/cometary/interstellar connection , only to say that this is a domain of immense interest and that the interstellar dust community should support related space projects like the Comet Nucleus Sample Return mission and similar experiments.

Another field which is likely to experience a fast and strong development is that of grain surface chemistry. It has been speculated for a long time that grains should grow mantles through gas accretion inside molecular clouds, and that chemical reactions take place in these mantles, their products being ultimately released as interstellar molecules. We have been presented in this meeting with much better information from infrared spectroscopy on the composition of these mantles, and also with recent evidence that grain surface chemistry is indeed an important part of interstellar chemistry. This grain chemistry may well be of comparable importance to the much-studied shock chemistry.

Five years ago, convincing evidence was presented for the existence of very small grains (i. e. large molecules) which experience quantum heating to high temperatures by absorption of single photons. Soon after, it was proposed that at least some of these grains are the carriers of the infrared emission bands and are Polycyclic Aromatic Hydrocarbons (PAHs). We have learned at this meeting that these carriers are really ubiquitous: they are major constituents of the "cirrus" interstellar clouds, and are seen in most of the HII-region/neutral cloud interfaces, in the carbon-rich planetary nebulae and in most studied spiral galaxies. They are responsible in general for most of the 12 micrometer-band emission seen by IRAS and for a part of the 25 and even of the 60 micrometer emission, and may radiate as much as 40 per cent of all far-IR galactic emission. Some predictions of the PAH model have been recently met, in particular that of a new emission band at 5.2 micrometer which has been reported at this conference. PAHs also seem to be able to account for the red fluorescence discovered in reflection nebulae. However there are many remaining challenges for the future:

1. The competing HAC theory claims that local non-thermal spikes are possible in hydrogenated amorphous carbon mantles after absorption of single UV photons, and that infrared-band emission comes from these sites. This means that the thermal conductivity between these "hot spots" and the bulk of the grain must be very slow, on the order of at least a fraction of a second. The corresponding physics has not been worked out convincingly, and laboratory studies should demonstrate that this is indeed possible (conversely, the fluorescence emission of IR bands has recently been seen for a simple isolated PAH, azulene, excited by UV photons). The only likely situation in the HAC model might be that the band emission is due to PAHs attached to the HAC substrate by a single valence bond; their properties would not differ much from those of isolated PAHs but their rotation would be blocked. A search for radio rotational emission would be a good test for the models.
2. As the IR emission bands probably carry as much as 40 percent of the far-IR emission of the Galaxy, their carriers must absorb the same fraction of the UV interstellar radiation field and must show up accordingly in the far-UV extinction curves. For PAHs, recent UV absorption studies show that UV absorption occurs mainly below 2500 Å as a broad peak near 2200 Å and

a rise in the far-UV. It is somewhat distressing to see no absorption peak near 2200 Å in two protoplanetary nebulae showing the IR emission bands, HD 89353 reported at this conference and HR 4049. In any case, realistic interstellar dust models should include the IR emission band carriers: only the HAC model has made an attempt in this direction. This may have a bearing upon the distribution of carbon between carriers, graphite and gas. Observations of the abundance of gaseous carbon with the HST is a high priority to constrain dust models.

3. Observations of IR emission bands in protoplanetary nebulae suggest that they appear only when the exciting star is hotter than about 10,000K (spectral type A0-B9) in agreement with what we suspect of PAH excitation. This is apparently in contradiction with a study of the same bands in reflexion nebulae which suggests excitation by stars as cold as 5000K or less (after all, the radiation field might be intense enough to supply the required amount of far-UV photons?).

4. The formation of the IR band carriers in carbon stars has been extensively discussed at this meeting. The opinion seems to prevail that they are formed at a late stage as the IR bands are not seen in carbon stars. This is not too conclusive however as carbon stars lack the required UV photons. The only relevant observational case is that of a carbon star with a hot companion which does not show the IR bands. Further studies are clearly needed. In any case, the IR bands are seen in most of the carbon-rich planetary and protoplanetary nebulae and detection in novae has been reported at this Symposium. Are these sources sufficient to produce the large amount of ubiquitous carriers seen in the interstellar medium or do we need other sources? If so, what is the formation scheme? The destruction mechanisms for PAHs should also be explored further: double ionization is an established one, but what about sputtering in shocks? What are the destruction products? In particular, is the ubiquitous C_3H_2 molecule recently seen even in the diffuse interstellar medium formed in this way?

5. Very interesting observations bearing on the evolution of the IR band carriers have been presented at this conference: maps in various bands in planetary nebulae, HII region interfaces, etc., and also IRAS observations of variations in the 12/100 micrometer emission ratio at scales as low as 1 pc in relatively quiet interstellar filaments. These raise many unsolved problems. In particular, the latter variations seem hard to be attributed to variations in the UV radiation field and may correspond to variations in the mass spectrum of small grains. It is not easy to imagine any on-the-spot mechanism able to produce such changes, which may rather reflect the past history of a material that had not had time to mix with the surroundings.

6. The PAHs are possibly playing a fundamental role in the physics and the chemistry of interstellar matter. It has been suggested recently that they are efficient heating agents and that they may have deep implications on ion chemistry. This is clearly a very rich field for the future.

7. Are there other small grains than the IR band carriers? Why not? The only clear evidence is the non-stellar continuum sometimes observed in reflection nebulae at wavelengths shorter than the first strong IR band at 3.3 micrometers, at least if it is not due to fluorescence as observed around 6000 Å. Quantitative studies are going to be difficult however, especially as no very

clear emission features are expected beyond the well observed IR range (about 20 micrometers). The problem is worth attacking, however.

I will end by a few remarks on the 2175 Å absorption band and on the 3.4 micrometer band which has now been seen in emission in a few objects (comets and novae essentially) but is a major absorption feature in the direction of the Galactic Center. Both are major phenomena in terms of carrier abundances but are not yet well identified. There is no defined candidate for the 3.4 micrometer band which corresponds to an aliphatic $C - H$ stretch. Small graphite grains are still the best candidates for the 2175 Å band, but there are problems. One may be an abundance problem which is clear in the Small Magellanic Cloud (SMC). This galaxy has a very small gaseous carbon abundance (from studies of its HII regions) and 5 of the 6 stars yielding good extinction curves show no 2175 Å bump. But the last star has a bump as strong as the Galactic features, suggesting a high graphite abundance in this region of the SMC. The solution might be that the carbon abundance is in fact in large grains, due to the large number of carbon stars, and that we see vastly different amounts of processing of carbon grains into graphite. This must obviously be cleared up. The circumstellar absorption band sometimes seen in carbon-rich protoplanetary nebulae and in a few other objects near 2400 Å apparently corresponds to amorphous carbon, and a systematic study of possible intermediate objects showing the 2175 Å band or both should be very rewarding. Similarly, there might be evolutionary intermediates between the objects showing the 3.4 micrometer band (aliphatic $C - H$ bond) and those showing the 3.28 micrometer band (aromatic $C - H$): novae and comets may show both and the former in particular are choice objects for studies of the graphitization (or aromatization) of hydrogenated amorphous carbon compounds.

These are only a few examples of critical questions. Many of the participants have others in mind, and it is not difficult to predict that the next few years will bring other considerable advances in the field of interstellar dust.