FINAL REMARKS

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It would be very ungracious not to say a few words about this remarkable set of presentations, even though it would be cruel to the audience to try to review them at this late hour. I made sixteen pages of summary notes of the highlights. We have heard about enormous improvements in our knowledge of the behavior of complex molecules in space. May I remind you that the computations of chemical equilibrium presented by Professor Klemperer covered largely the diatomic molecules known many years ago. The radio astronomers, with incredible technical proficiency, have found many polyatomic molecules with molecular weights close to a hundred; in a solid particle that causes continuous absorption we must reach weights near 10^8.

There are hints from this new work concerning relations between optical properties of the grains and the molecules. For one, most of the molecules found are linear or flat. It seems to me that if nucleation and growth begins on these elongated molecules if they survive long enough in their hostile environment, one might very well produce the needle-like or flat shapes required for interstellar polarization. Wickramasinghe has advocated interstellar graphite, which is intrinsically flat and anisotropic, and could produce interstellar polarization very efficiently. There is still an enormous gap in weight between even the complex radiofrequency molecules and the solids. One might ask the very impolite question: is there any evidence at all that solids really do exist? I believe there are good arguments to the effect that solids do, in fact, exist, and that their size and optical properties are much as thought of three generations ago by myself, Schalén and Debye. (Some of the notations used on the blackboard here come out of papers by Debye in 1910 or thereabouts, or from my own doctoral thesis in 1937.) One must recognize that not only our conclusions, but the interstellar absorption and reddening have rather constant properties. The reddening law is very much the same throughout our Galaxy, except in a few H II regions like NGC 1976 where very hot stars are present. Even in other galaxies, the properties of the dust grains of the interstellar material are rather constant. It would be attractive to replace the solids by a numerous group of complex molecules capable of continuous absorption which would have small absorption edges which we see as the diffuse absorption bands. At the moment this seems somewhat implausible. So one still has the gap to bridge between the elongated or flattened solids and these very exciting polyatomic molecules found by radiofrequency techniques. The radiofrequency observers seem, to me, to be guilty of not looking often enough at pictures of the sky. May I point out that there is no such thing as a classic regular H II region? There is no place I have ever seen where you have a homogeneous ionized region with a neat boundary of fractional hydrogen ionization, bounded by a cool H I region of temperature 10 to 100 K. One of the exciting things about most regions containing molecules found by

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recent radiofrequency work is their extreme irregularity and the violence of internal motions. Mezger showed a picture of IC 1795, which I believe is typical. It has interfaces of instability, where cool material interacts with hot, in the so-called elephant-trunk structure, and bright rim structures. The Orbiting Astronomical Observatory showed that the well-known Horsehead Nebula is bright, not dark, in the far ultraviolet, although it is supposedly a cool region falling into a hot region, because of the Rayleigh-Taylor instability. Such an object suggests that the behavior of the short-lived molecules formed in H II regions and non-thermal sources like the Galactic center, are somehow connected, not only with the radiation and density fields, but perhaps with these motions. This has been implicit in the use of the shockwave heating model. Unfortunately, if one is going to include the dynamics, one must include the magnetic field and then, presumably, things become complicated. But I think that somehow one will get the molecule formation out of this more complicated picture.

There has been a large question at issue many times today, here. Do the molecules that we have laboriously built make the dust particles, or do the dust particles dissolve in radiation and make the molecules? This seems to me a difficult question. The relatively shortlived kinds of molecules dissociate or ionize and should not get far from the parent shockwave, if formed near an H II region. However, nature again, in its irregular profusion, gives us still another hint which I think should be taken seriously in the future. Shockwaves, such as normally occur in the expansion of a new H II region, after an O star has turned on its ultraviolet, are not terribly violent, although responsible for these pictures of violent and irregular density fluctuations. I do not know if most astronomers remember that the dust density fluctuates by a factor of 10^6 in these pictures, that there are regions where its opacity may be ten magnitudes per astronomical unit. Such enormous density fluctuation must be connected with some more violent instability than the expansion of a H II ionizing flash or shockwave into a vacuum, with associated cooling processes. The best visual examples are, I think, given by extragalactic objects of interest to radio astronomers: when they select a galaxy as a peculiar, strong radio source, it almost always has large amounts of dust in it, which it should not. Normal elliptical galaxies have little gas or dust, but those that are radio sources often do show dust structures. Seyfert galaxies also have nuclei with strong infra-red excesses, where dust acting as a photon converter, converts normal stellar into far infra-red radiation. Interestingly enough, stars in the process of formation have the same anomaly. The T-Tauri stars have gigantic, infra-red, continuum-emission tails on their energy distribution. For example, R Mon associated with Hubble's Variable Nebula NGC 2261, clearly shows shockwave structural patterns. It is a hundred times as bright in the infra-red as it is in the visible, either because of dust conversion of visible stellar energy, or from the gravitational energy of the cloud collapse, or from high-energy proton bombardment. The common rapid appearance of excess dust is beautifully shown in the explosion in M 82, a galaxy filled with dust; the Seyfert galaxy, NGC 1275, also has a peculiar fan of black dust across it. I have a strong feeling that at velocities somewhat higher than normal for an ordinary shockwave in an H II region, greater than 10 km sec^{-1} and certainly before one reaches 10^3 km sec^{-1}, the rapid formation of complex molecules may skip all the way to particles of typical dust sizes.

The stellar contribution to interstellar molecules is fantastically interesting. One can get water and graphite and silicon compounds which may be needed to account for the interstellar extinction curve, especially that from ultraviolet measurements. It is clear that one needs these refractories, because the dust and molecules in our Galaxy are unshielded from a generally destructive radiation field. Particles exist in low-density regions of interstellar gas, not only in the high-density regions here discussed, and one should have some refractory, dust-nucleation centers which can survive 10^9 yr. It may be that this is the major importance of stellar contribution, while the remainder of the gas is linked to the organic materials that we have been hearing about from radio observations. Solids are useful, also, for production of molecular hydrogen on their surfaces.

I wish that I could say that we seem near a solution of the problem of how the peculiar, radiofrequency interstellar molecular lines are produced. Maser and anti-maser action is required, as well as efficient cooling. The various pumping methods that have been suggested are very interesting. It was clear to me that the experts, rather fundamentally, did not agree, and perhaps did not even talk together very much. The detection of further molecules not subject to maser action is particularly important if we are to obtain reliable values for the space density of these peculiar polyatomic molecules, and attempt to obtain relative concentrations. The importance of the isotope ratios is enormous; saturation may give deceptively high abundance ratios of O^{18}/O^{16} and C^{13}/C^{12}. The ratio of O^{18}/C^{13} should be more easily derived, if the isotope features are weak. I should remind the radiofrequency spectroscopists that the terrestrial ratios O^{18}/O^{16} and C^{13}/C^{12} do not have a clear origin in current nucleosynthesis theory. The C^{13}/C^{12} ratio should either be near $\frac{1}{3}$ or very small ($\ll 10^{-2}$). If C^{13}/C^{12} is high, N^{14}/C^{12} should be higher than in normal stars, from the C–N thermonuclear rates. Abnormally high O^{18}/O^{16} can also occur by late stellar helium burning of the excessive N^{14} produced in the C–N cycle.

In conclusion, I know I speak not only for myself, but for the audience and the astrophysical community, in expressing my gratitude to the speakers, today, for their incredibly rapid progress in the study of the interstellar molecules.

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