INFRARED OBSERVATIONS AND INTERSTELLAR MOLECULES

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It has been common practice to separate the study of interstellar matter from that of stellar evolution. However, infrared astronomy deals mainly with observations of stars forming and stars dying. Interstellar matter represents a phase intermediate between these two stages, part of a cyclic process (Figure 1).

We find molecules in interstellar space and want to know how they came to be there. Molecules form most easily at high densities and moderately high temperatures. These conditions prevail both in envelopes around forming stars and also around evolved red giants. However, the matter going into star formation is mainly leaving interstellar space, while that from the red giants is going into space. Therefore the evolved red giants are potentially the source of interstellar molecules.

This paper will propose first that the chief interstellar solid molecules were formed in the atmospheres of red giant stars. Volatile solids that might condense in space do not seem to be a major constituent of the grains. Secondly it will be demonstrated that a major part of interstellar matter has probably come from the outer layers of red giant stars. Since the *solids* formed in these envelopes, it appears possible that less complicated *gaseous* molecules have also been ejected into space. Whether they are in fact the same molecules that are now observed is a question that cannot yet be answered.

Arrhenius first suggested that radiation pressure would drive small particles away from stars. Hoyle and Wickramasinghe noticed that the sizes of interstellar particles were such that they could have originated in this way. Also they pointed out that graphite is a refractory solid of potentially high cosmic abundance that could form in stellar envelopes. Gilman then showed that if chemical reactions went to completion, graphite probably would form in the atmospheres of carbon rich stars. However, in normal oxygen rich matter, silicates would be produced (Figure 2).

The infrared spectrum of silicates has two peaks of absorption or emission near 10μ and 20μ with a minimum between at near 13μ (Figure 3). Figure 4 shows infrared photometric measures of an M supergiant, the center of the Orion Nebula, and a comet. For the M star the usual arguments that show that emission features must arise in extended envelopes are appropriate. It is seen that the circumstellar emission peaks where silicates are expected to peak and is depressed where silicates have least emission. The Orion Nebula and the comet seem to show the silicate emission, with the addition of a cool black-body-like continuum. Figure 5, which shows the comet cooling as it moved away from the Sun, shows how the spectrum has become more like the Orion Nebula. Circumstellar emission resembling a cool black body has also been found. Figure 6 shows observations of R Cr B variables. Cool black-body-like envelopes also seem to appear around some N stars, R Lep, S Cep and V Hya;

De Jager (ed.), Highlights of Astronomy, 350–358.

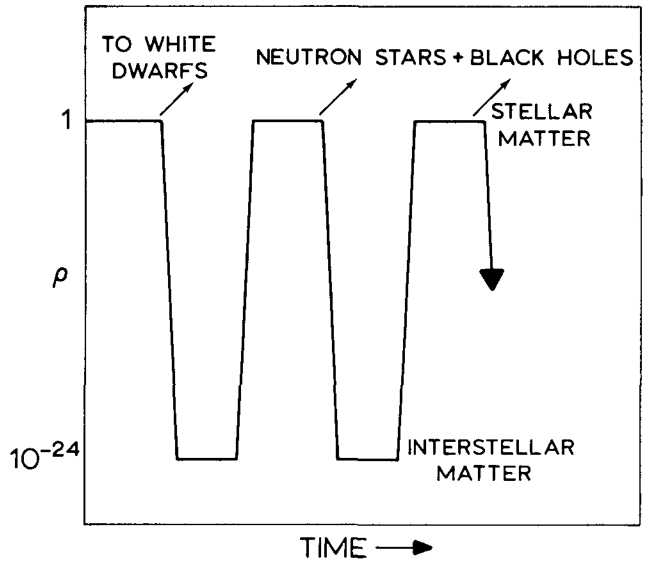

Fig. 1.

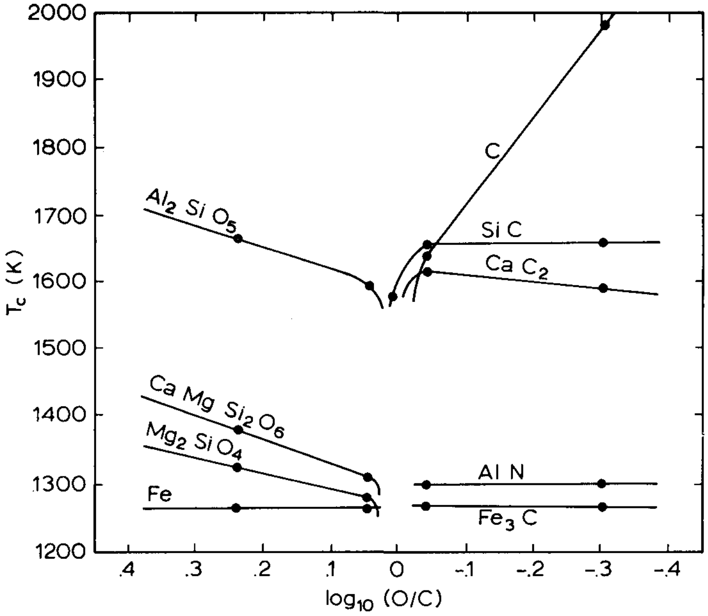

Fig. 2. Temperature of the onset of condensation, T_c, as a function of $\log_{10}(O/C)$ for the compounds named and for a total gas pressure of 50 dyn/cm^{-2}.

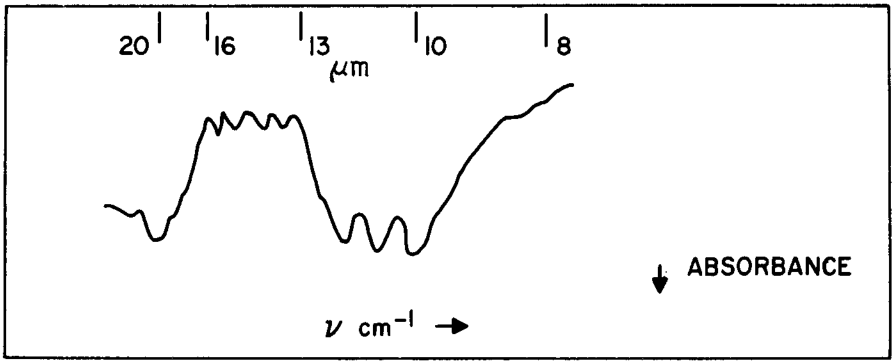

Fig. 3. Absorption spectrum of enstatite ($(Mg_{0.5}Fe_{0.5})SiO_3$).

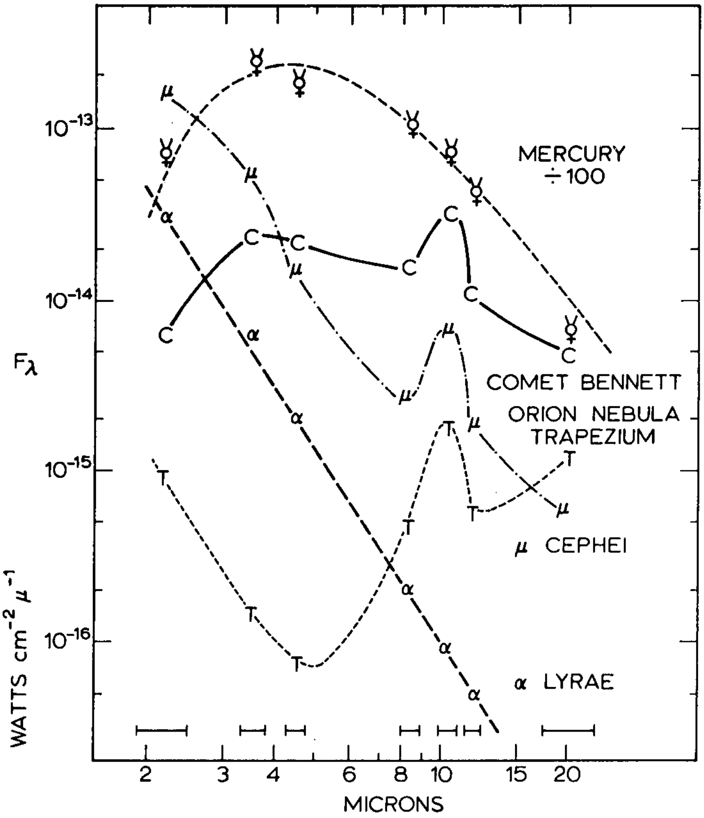

Fig. 4. Comet Bennett spectrum compared with the spectra of objects with a 10 μ emission peak, μ Cep and the Trapezium region of the Orion Nebula. Two objects without this peak, observed with the same instrument, are also shown. The 620 K blackbody curve drawn through the measures of Mercury is appropriate for the angular diameter of the planet, fraction of the disk illuminated, and emissivity of 1. The widths of the filter bandpasses are shown above the wavelength scale.

however, here there is confusion between the cool stellar continuum and the cool circumstellar continuum so that the black body character of circumstellar emission is less certain *. These objects are carbon rich stars. So the matter in the Orion Nebula and the comet has characteristics that can be interpreted as a mixture of carbon and silicates.

The circumstellar envelopes around cool stars have been observed by Deutsch, and interpreted as showing gaseous matter flowing from stars into interstellar space. The infrared observations can be interpreted as solid matter leaving the same stars and also flowing into interstellar space. The radiation pressure on the grains and the momentum transport to the gas seems to explain the existence of these envelopes.

The circumstellar visual absorption lines have been used to estimate mass loss rates for α Herculis and α Orionis. It is possible to use the infrared emission observations to place the ejection from other stars on the same scale. The total mass is

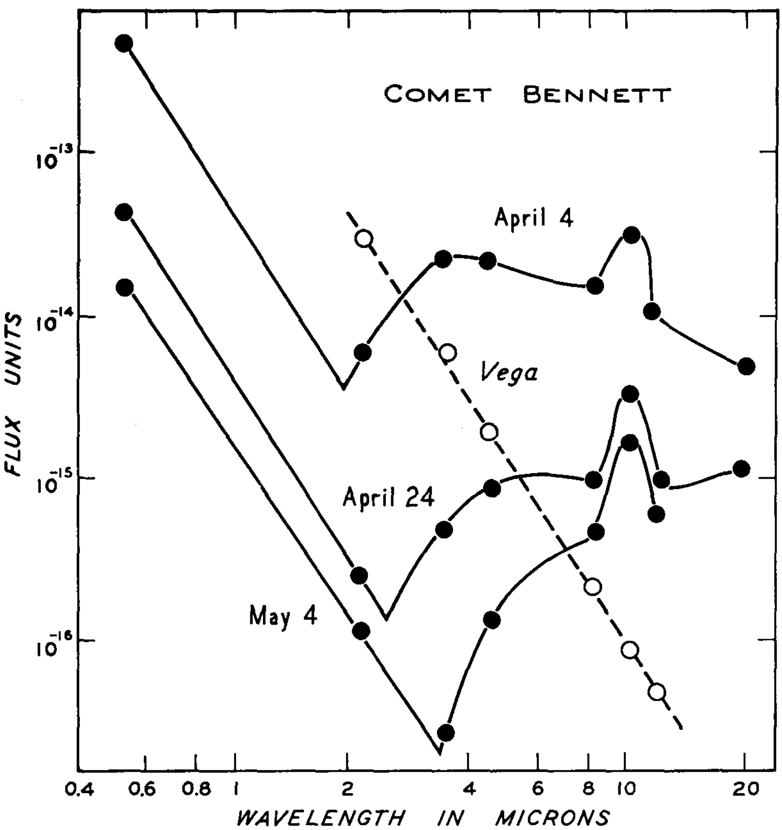

Fig. 5.

* Hackwell has discovered an emission peak near 11 μ in some of these stars, as compared with 9.75μ in the M stars.

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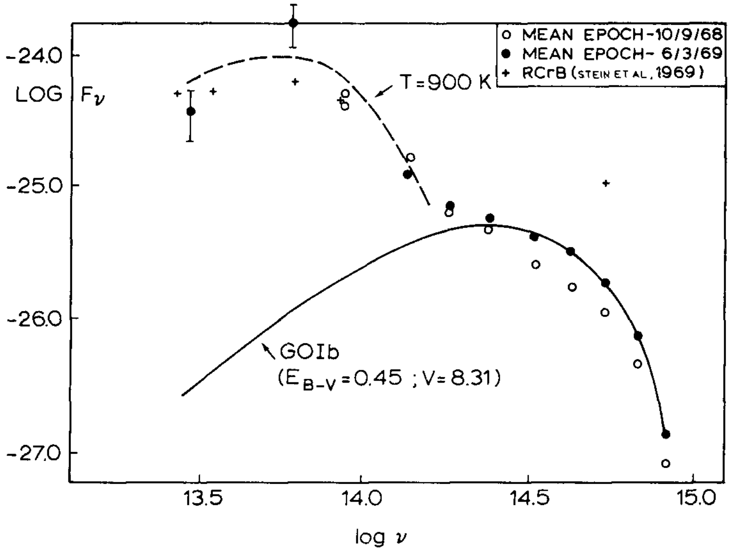

Fig. 6. Spectral energy distribution of RY Sgr. Filled and open circles refer to observations made at different epochs. Solid line represents a reddened G0 Ib star normalized to $V = 8.31$ mag; dashed line is the distribution of a 900 K blackbody. Crosses represent the observations of R CrB by Stein *et al.* (1969).

assumed proportional to the mass of silicates. Then the mass loss rate $\propto (L_{\text{envelope}}/L_{\text{star}}) \times L_{\text{star}})^{1/2}\, V$. Here V is the ejection velocity of the gas, assumed to be a constant. For a given height of circumstellar emission above a continuum, a cool star will have more ejection than a hot star, because its infrared continuum represents a greater proportion of its total emission.

Figure 7 is a color-color diagram for M type stars prepared with Robert Gehrz. Circumstellar emission can be measured either by the [11.5 μ]–[8.5 μ] color or the [8.5 μ]–[3.5 μ] color, but for large emission the envelope becomes optically thick at 11.5 μ and then only the [8.5 μ]–[3.5 μ] color is a good measure. It can be seen that α Her and α Ori are rather mild examples of circumstellar emission compared with typical long period variables. Further, the long period variables are cooler, while their bolometric luminosities are greater than α Her. We can estimate a typical mass loss rate of $\sim 6 \times 10^{-7}\, M_\odot\, \text{yr}^{-1}$. This rate is potentially significant as the mass loss is ~ 1 g per 6×10^{18} erg. Thus in a hydrogen shell burning phase, as much matter is ejected as is burned. Better mass loss statistics will become available when a photometric survey of red giants by Gillett *et al.* is completed.*

There are about 3×10^{-4} long period variable stars per pc^{-2}. of the galactic plane. This gives a total mass ejection rate of $\sim 1.8 \times 10^{-10}\, M_\odot\, \text{pc}^{-2}\, \text{yr}^{-1}$. The long period variables have a large Z motion, so that they are low mass stars. Deutsch has estimated that the entire mass loss from dying stars should total $4 \times 10^{-10}\, M_\odot\, \text{pc}^{-2}\, \text{yr}^{-1}$,

* Newer results indicating somewhat greater mass loss rates are being published by Gehrz and Woolf.

of which half should be from low mass stars. The two figures then are in agreement, though the uncertainty in both numbers must be very large. Although the large Z motions of the variables mean that this mass will flow in from large distances from the plane, the rate of mass flow is only about one tenth of that seen in the high latitude interstellar clouds. If these two rates are found on closer study to be similar, or if the clouds are a cycling of galactic matter, then a substantial fraction of interstellar matter has originated in cool stars. On the other hand if the rate of mass flow in the high latitude clouds is correct, and the matter comes from intergalactic space, then interstellar matter is mainly intergalactic and abundant molecules must have formed in space. In this case the high abundance of heavy elements found in the matter would be most surprising, and is an argument against this alternative.

The Orion Nebula solids in emission have been heated, and may not be typical of interstellar solids. To properly sample typical matter, spectral features must be sought in absorption. The Table shows cosmically likely solids, absorption bands, and band strengths.

Solid	Band	Central optical depth g^{-1} cm^2
H_2O	3.1 μ	1.4×10^4
	12 μ	4×10^3
NH_3	3 μ	$\sim 2 \times 10^3$
	9.4 μ	$\sim 2 \times 10^3$
H_2	2.4 μ	30
Silicates	10 μ	2.5×10^3
	20 μ	2×10^3
Graphite	2200 Å	$\sim 2 \times 10^6$

The wavelength of these features dictate the most sensitive tests for the presence of these materials. Thus the graphite band in the ultraviolet shows best against the spectra of reddened B stars. OAO observations show it very well. Unfortunately the band is so strong that the interpretation is confused by particle size effects.

The near infrared bands are best sought in reddened B stars, because cool luminous stars have their own confusing spectral features in this region. Searches in stars with up to 10 mag. of visual absorption show no features of ice, ammonia or solid hydrogen in the 3μ region. The maximum possible mixing ratios are then for solids to all matter, ice 7×10^{-4}, ammonia 1.5×10^{-3}, and solid hydrogen 3×10^{-1}. These ratios apply to the direction of VI Cygni No. 12. It can be estimated that about 10^{-2} of solid matter is needed to produce the interstellar absorption.

H. L. Johnson has reported that a band near 3.1 μ occurs in the spectra of about half the cool stars he has observed. The strength of this band is not apparently correlated with interstellar extinction and therefore seems to be of stellar or circumstellar origin.

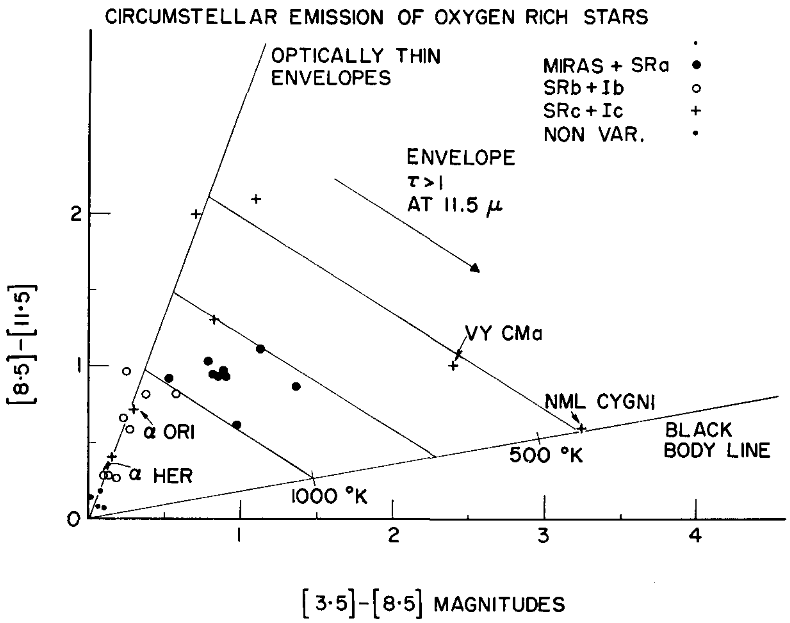

Fig. 7.

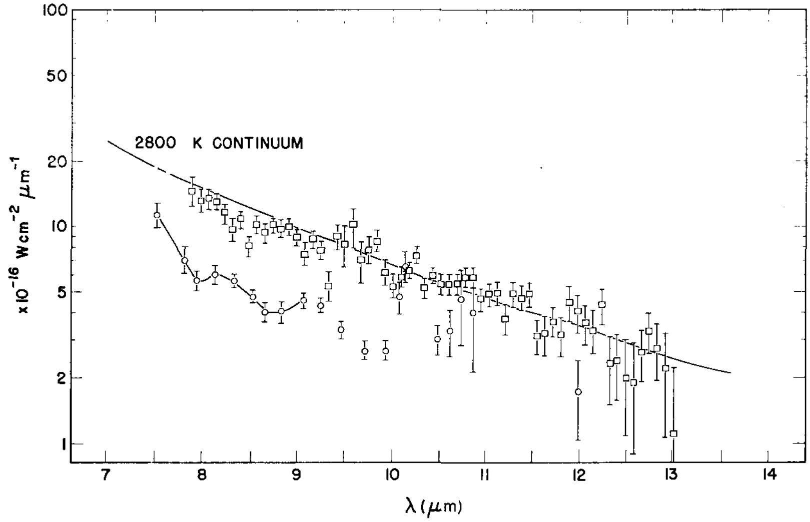

Fig. 8. Spectrum of 119 Tauri (M21b). □, Hackwell; —, Knacke *et al.*

At longer wavelengths, hot stars radiate little. Cool stars have stellar and circumstellar features that confuse the interpretation, and the only distant bright reddened source, the galactic center has an unknown intrinsic spectrum. An early search for silicate absorption compared the mildly reddened star 119 Tauri with α Orionis. The spectral types are M21b and M21ab. Further studies have revealed large luminosity effects on the circumstellar envelope at this spectral type. Also, the signal to noise ratio of the spectrum of 119 Tauri was rather low. An attempt by Hackwell to reproduce this observation has failed (Figure 8). Whereas the SiO absorption band near 8.2 μ still appears to be present, the points suggesting a lowering of the continuum near 10 μ do not repeat. Instead there seems to be a rather weak circumstellar emission just like that in other M stars. Two B stars suffering 4 mag. of visual absorption have been photometrically observed, and the continuum at 11.5 μ seems depressed with respect to 8.5 μ by perhaps $0\overset{m}{.}1$, giving a possible silicate mixing ratio $\sim 4 \times 10^{-3}$. Photometric observations by Low of the galactic center seem to suggest a peak at 13 μ in the continuum, with depressions near 10 μ and 20 μ. The average central optical depths are perhaps 0.7. The corresponding mixing ratio is also $\sim 4 \times 10^{-3}$.* This ratio is also the ratio expected on the basis of cosmic abundance of the elements. A more detailed spectral study of the galactic center in the 10 μ region is now under way. One interesting further point is that the 13 μ excess emission of the galactic center provides a further limit on the possibility of interstellar ice since the strength of the 12 μ ice band is similar to the strength of the silicate bands.

In summary, the refractory materials, silicates and graphite appear to be present in interstellar space in abundances adequate to produce the interstellar absorption between them. The gaseous molecules H_2O and NH_3 are seen in space; however, their volatile solids apparently do not make up any substantial fraction of the interstellar dust.

If we consider condensation conditions in the envelope of a star, it appears that the density where silicates can condense is more than 10^3 times greater than the density where ice can condense. Apparently the longer time scales available at low density conditions are not adequate to help grains form from volatile substances.

It is interesting to assume that similar behavior may govern the interstellar molecules found. Certainly CN, CH, CO and H_2O are found in stellar atmospheres as well as in space. The interstellar molecules NH_3 and CH_2O have not yet been found in stellar atmospheres, but the necessary infrared spectroscopic searches have not yet been made.

One chief worry about forming interstellar molecules in stars, is that the interstellar UV radiation field could rapidly disrupt them. Fortunately the grains that come off with the gas have a high UV opacity, so that molecules enter space with a protective shield. For the absorption, the matter would need to remain in dense globules. Such globules are indeed seen at high galactic latitudes, projected against globular clusters and external galaxies. Their presence provides tentative support for the suggestion that interstellar molecules originate as stellar molecules.

DISCUSSION

Zuckerman: When considering the question of whether the interstellar molecules, observed with

* Photometric observations by Hackwell *et al.* confirm the existence of the 10 μ absorption band.

radio telescopes, are formed in stellar atmospheres and ejected into the interstellar medium the following points are perhaps relevant. The lifetimes for H_2O, NH_3 and H_2CO in a 'typical' interstellar radiation field between the dark dense clouds is only 1000 yr. It is hard to understand, if these molecules are formed in stellar atmospheres, how they find their way into the interior of dark clouds without being destroyed in transit. Another point to consider is the C^{12}/C^{13} abundance ratio determined from H_2CO absorption spectra in directions away from the galactic centre. This ratio appears to be scattering around the terrestrial value of 89. This value is considerably larger than that found in many carbon stars. Therefore, if the H_2CO molecules are formed in these stars it is difficult to understand the observed isotopic ratios. This is true irrespective of whether the molecules are ejected from the stellar atmosphere in the monomer form or as particulate matter. Finally, concerning silicates, the $J=1 \rightarrow 2$ rotational transition of SiO has been searched for in many interstellar regions but without success.

Rank: SiO has been searched for (resolution $\frac{1}{3}$ cm^{-1}) in a number of IR stars at 8–9 μ. In particular the spectrum of 119 τ does not show SiO molecular absorption which indicates that absorption features around 8.5 μ are most probably solid material and not gaseous.

In the absence of the author, this paper was read by Dr. D. A. Allen. Replies to the above comments have been added in proof.

The visual extinction at the center of one of the high latitude globules has been estimated to be 5 magnitudes. If the matter coming from the cool stars holds together like this, the molecules would be adequately protected. With regard to the C_{12}/C_{13} ratio of formaldehyde, it is not obvious whether it should be expected mainly in the atmospheres of M stars or carbon stars. And as for SiO, its presence in α Orionis has been confirmed by Gaustad and Cudaback from observation of its first overtone absorption bands. It should not be expected in interstellar space since it appears to be used up in the formation of solid silicates.