INFRARED EVIDENCE FOR PANSPERMIA: AN UPDATE *

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Abstract. Recent infrared spectroscopy of astronomical sources, particularly over the 2–4 μm and 8–13 μm wavebands, is re-examined in relation to the hypothesis of biological grains. The most relevant new observations provide further support for this hypothesis.

1. Introduction

N.J. Woolf and E.P. Ney (1969) made the first detections of infrared emission by interstellar grains in the 8–13 μm waveband, with immediate follow-up investigations by the group of infrared astronomers at the University of Arizona. The grains responsible for the observed infrared emissions were quickly characterised as 'silicates', without it at first being considered necessary to specify what kind of silicate.

The instrumental improvements of subsequent years soon permitted an extended range of astrophysical objects to be observed in detail – late type stars, planetary nebulae, compact HII regions, the galactic centre, comets and the Trapezium nebula. Hot stars in this latter nebula were heating the interstellar grains to an unusually high temperature, about 175 K, much above the temperature of normal interstellar dust, thereby causing detectable infrared radiation to be emitted in the 8–12 μm band.

What was also important about the case of the Trapezium was that the emitted radiation experienced little self-absorption by the nebula itself. In these circumstances the flux of emission F_λ), at any particular wavelength is given by a simple formula

$$F_\lambda = \text{constant.}\ \tau(\lambda)\ B_\lambda(T). \tag{1}$$

Where $B_\lambda(T)$ is Planck function at the temperature T of the particles and $\tau(\lambda)$ is the opacity of grain material. What the opacity $\tau(\lambda)$ of a sample of a particular material means physically is that when radiation of wavelength λ is incident on the sample, a fraction $\exp -\tau(\lambda)$ penetrates through it. This function $\tau(\lambda)$ can be measured in the laboratory for any particular material. And in the astronomical case it can be obtained observationally to within a constant factor from Equation

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(1), once the temperature T is specified. So with the left hand side of (1) determined by astronomical observations at various values of λ, the observed opacity function $\tau(\lambda)$ is obtained by an easy calculation. Meaning that if we think the particles in the Trapezium nebula consist of a certain type of silicate we can readily verify our belief, or otherwise, by comparing the resulting observed $\tau(\lambda)$ with the $\tau(\lambda)$ obtained for the material in question in the laboratory. Two ways of obtaining $\tau(\lambda)$, one from astronomical observation, the other from a simple laboratory experiment, which must agree if our guess as to the nature of the silicate has been correct. Or to be more accurate, the two ways of finding $\tau(\lambda)$ must agree to within a constant factor, which necessarily must be expected because the amount of the sample in the laboratory is unlikely to be the same as in the Trapezium.

The point of this story is that when the comparison was tried for all silicates that anybody cared to try out in the laboratory the results were apallingly bad. Results were especially bad for crystalline silicates, where laboratory measures of $\tau(\lambda)$ gave sharp peaks and troughs as λ was varied through the 8–13 μm waveband. Whereas the $\tau(\lambda)$ obtained from observations of the Trapezium gave an unequivocally smooth curve with respect to λ.

So the buzz in the late 1970's was that crystalline silicates were out and amorphous silicates were in. The best of them have the effect shown in the top panel of Figure 1. Here the curve is calculated by using Equation (1) with a temperature of $T = 175$ K and the opacity values of silicates $\tau(\lambda)$ measured in the laboratory. The points are the actual flux observations for the Trapezium nebula. This was, not a result to cause one to fly into a paroxysm of joy. It would have required most of the radiation observed shortward of 10 μm to be generated by particles composed of some quite different substance. Then one would wonder how the two, the amorphous silicate and the unknown mystery substance X manage to join as smoothly together as do the observed points on Figure 1. This was the first important outcome of the birth of infrared astronomy in the late 1960's.

2. Identification of the 10 μm Feature

It was at this stage that we ourselves became mildly dissident by thinking that some effort should be made to identify X. And we became seriously dissident in most people's eyes by looking among aromatic organic substances, e.g. polysaccharides, to make the identification (Wickramasinghe, 1974; Hoyle and Wickramasinghe, 1977). Slowly but surely we were edging towards cosmic biology and inevitably to panspermia. We soon discovered that such substances as were connected with biology provided distinct improvements of fit to the observations of Figure 1 whilst also offering a promising explanation for the newly discovered ultraviolet interstellar absorption at 2175A (Hoyle and Wickramasinghe, 1977a,b).

Whether it was the distaste occasioned by this latter step or whether it was inherent ingenuity we do not know, but a remarkable resolution of the difficult was eventually offered by a number of astronomers. Using the observed points of Figure 1 on the left hand side of Equation (1), the astronomically required function $\tau(\lambda)$ was worked out, $\tau_{\rm obs}(\lambda)$ one can call it. Then instead of looking for an actual substance with $\tau_{\rm lab}(\lambda) = \tau_{\rm obs}(\lambda)$, such a substance was invented by hypothesis. And the proposed so called 'conservative' solution to the problem was to consider the hypothetical substance actually to exist.

Students, the editors of science journals, science writers and those who award money from the public purse to science were all persuaded that it really existed. After which it didn't matter whether there was such a substance or not. Nothing quite like it has been seen since the raising of Lazarus from the grave. Except of course Lazarus had actually been alive at one time. To give the same impression in this case the names of the inventors of this trick were attached to the non-existent substance, making the analogy to Lazarus seem closer.

As we have discussed in detail elsewhere the situation only got worse when the observations of the Trapezium were extended further into the infrared (see references in Hoyle and Wickramasinghe, 1991). The bottom panel of Figure 1 shows what happened for the best amorphous silicates that actually exist. Worse than bad. So it became even more important to most that they should put their trust in the imaginary silicate which didn't exist. Because of course the imaginary silicate could be extended without effort, *stans pede in uno*, as far out in wavelength as one wanted to extend it. Always giving perfect agreement with observations. All one had to do was to forget that it didn't exist.

Of course it could not be asserted that real silicates, amorphous or hydrated, did not exist anywhere in the Universe. It certainly exists on Earth and elsewhere in the solar system as well. All we could say from the Trapezium nebula data is that anything remotely resembling a real silicate cannot contribute any significant fraction to the mass of the dust that pervades the general interstellar medium.

As our thoughts began to turn in the direction of cosmic biology it occurred to us one day that there was a form of silica that nobody had yet taken a look at. The remarkable form of which gives the beautiful patterns of a class of algae known as diatoms when seen in a microscope, a class that appears to have made a sudden appearance on the Earth some 65 million years ago. One can spend an hour gazing at the chemical bond structure of diatom silica, marvelling at the subtlety of the alternating electron pairs which hold the structure together, a structure shown in Figure 2.

Dr Shirwan Al-Mufti, who was making the laboratory measurements for all manner of possible candidate substances, managed after some searching around, to obtain a mixed culture of diatoms taken from waters of the River Taff (Hoyle *et al.*, 1982; Al-Mufti, 1984). The headwaters of the Taff come from up in the hills of Garwnant Forest, where around 1250AD the Welsh invented the longbow, subsequently renamed the English longbow by the English!

Going back to Equation (1) and using this measured $\tau_{\rm lab}(\lambda)$ for $\tau(\lambda)$ on the right hand side of (1), together with the same temperature of 175 K as before,

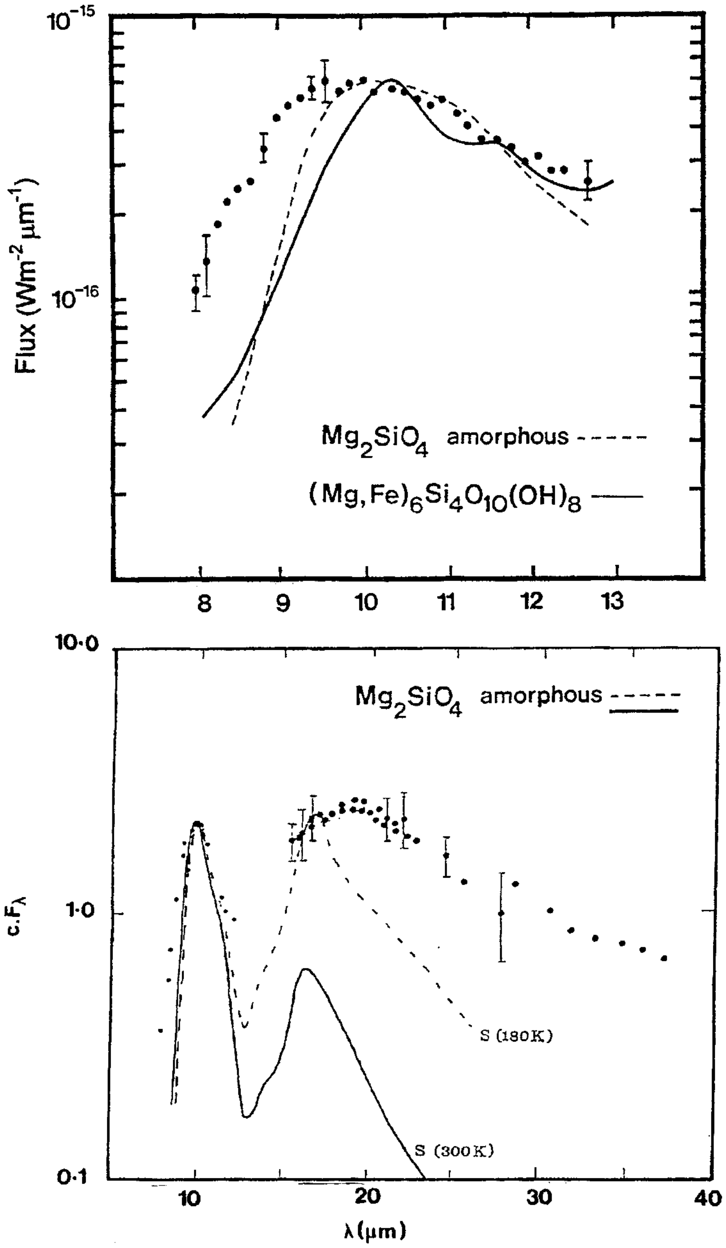

Figure 1. Top panel: The points are the flux measurements from the Trapezium nebula over the 8–13 μm waveband. The curves are the calculated behaviour of amorphous and hydrated silicates heated to 175 K. (Full references in Hoyle and Wickramasinghe, 1991.) Bottom panel: Trapezium nebula fluxes over the waveband 8–35 μm (points), compared with predictions for amorphous silicates heated to two temperatures.

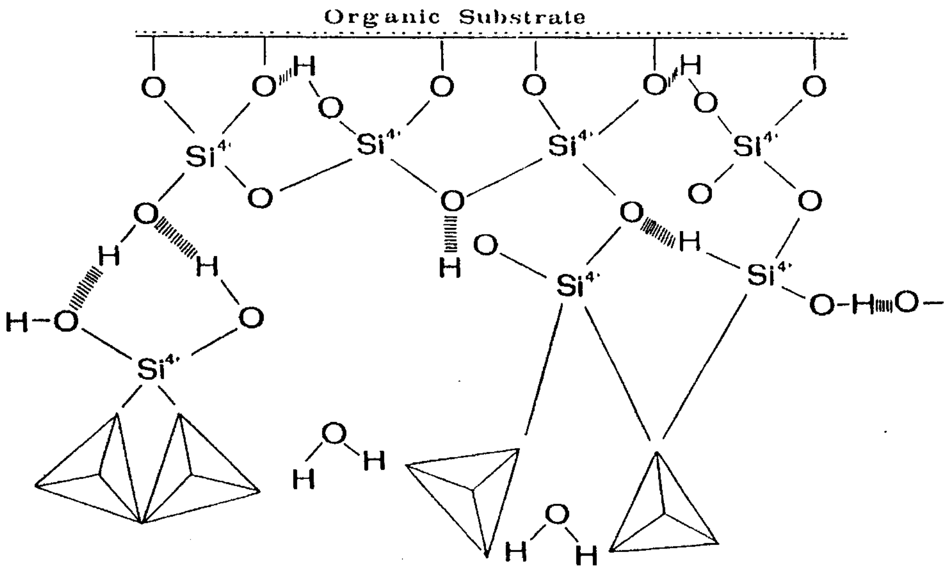

Figure 2. Schematic depiction of bond arrangements of diatom silica.

permits the expected emission of diatoms to be worked out at each wavelength λ. Permitting an expected curve for diatoms to be drawn (upper panel of Figure 3) as was done earlier for silicates in Figure 1. When this curve is compared with the observed points the agreement is seen to be most impressive indeed. And when the comparison was subsequently extended further into the infrared up to 40 μm, the agreement still remained good, as can be seen in the lower panel of Figure 3.

We have often been asked if we believe the particles in the Trapezium really are diatoms. From a scientific point of view this question is absurd, as absurd as it would be to ask an engineer who has produced some device if he believed in the device. Which either works or it does not. One might ask the engineer if he believes his device will sell to the world. But this is a sociological issue not a matter of engineering. Just as the question in the case of the Trapezium is sociological not scientific.

What one can say from the results to this point is first because of the mediocre fit of the best mineral silicates in Figure 1 that the particles in the Trapezium are not mineral silicates. That is a clear positive statement. No matter whose *amour propre* is offended by it, that is the way of the world. The second deduction that can validly be made from the good agreements in Figure 3 is that the particles in the Trapezium could be diatoms. Their being diatoms would be consistent with the evidence. But since there might be something else we haven't thought of that is also consistent with the evidence we cannot assert that the Trapezium particles definitely are diatoms. We have to see how things go as more evidence comes to light.

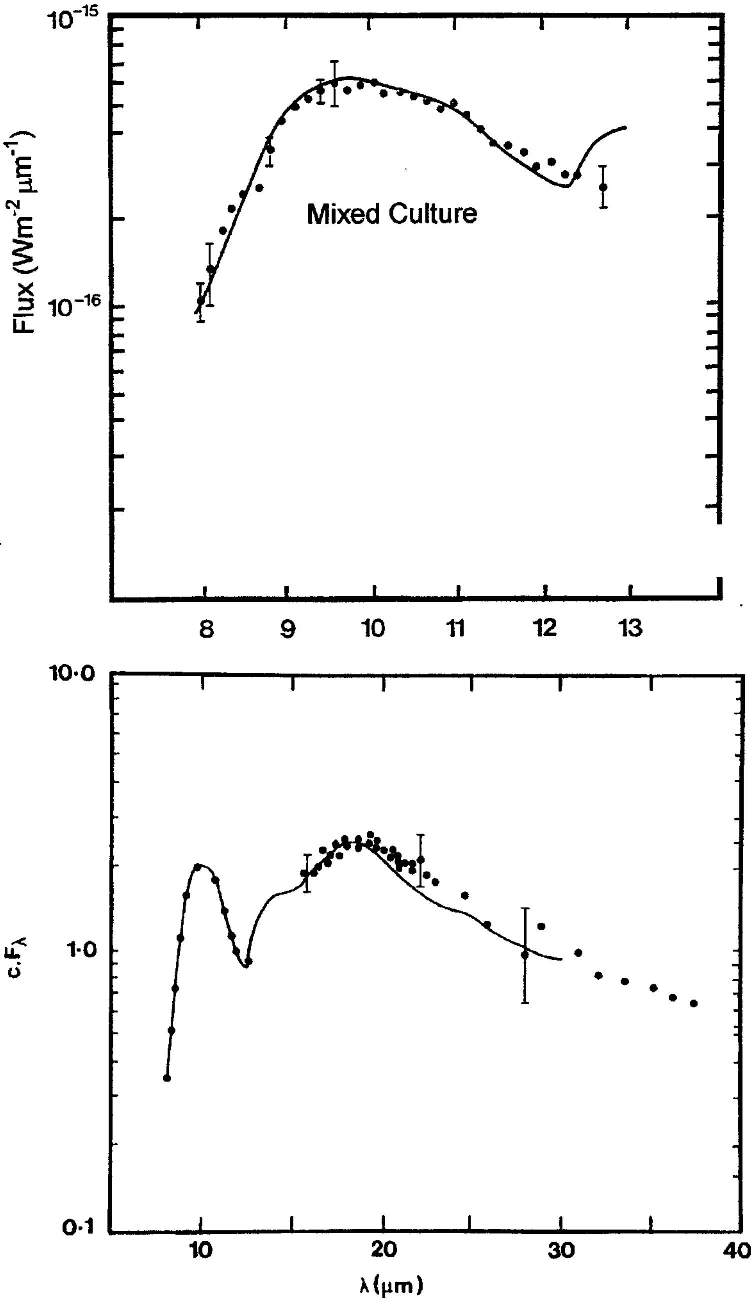

Figure 3. Points are the same as for Figure 1. The curves show calculated emission behaviour of diatom-type material heated to 175 K.

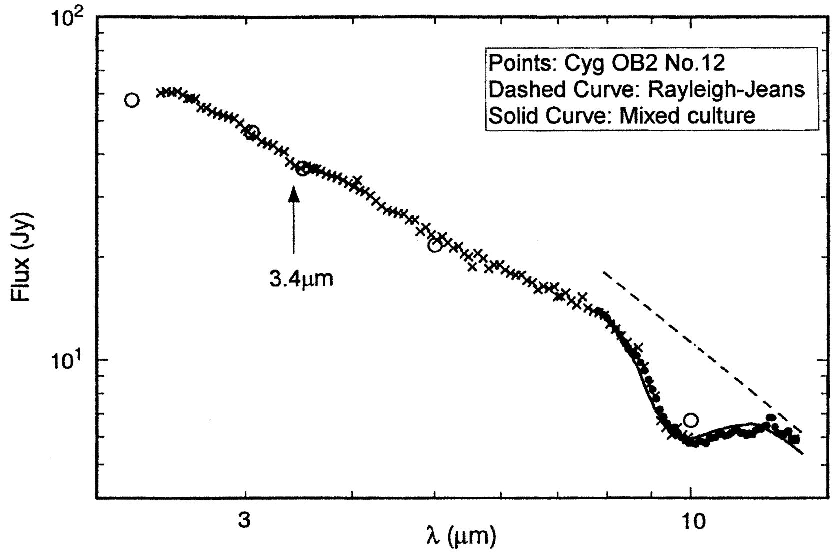

Figure 4. Spectrum of VI Cyg OB2 No. 12, combining ground based observations and satellite data (points) (adapted from Whittet and Tielens, 1997). The dashed line is the Rayleigh-Jeans tail of stellar emission. The segment of solid curve is calculated assuming extinction by diatom-type material.

3. Recent Observations of the 10 μm Feature

As with the introduction of every new observing technique the use of ISO (Infrared Space Observatory) launched by ESA on 17 November 1995 provided new opportunities for testing astronomical theory. Particulates in localised regions, for example, planet-forming regions around young stars, would be expected to contain a fair proportion of silicates, and this expectation was indeed borne out in some recent investigations. Spectral features near 19, 24, 28, and 34 μm that have been attributed to hydrated silicates have been observed in several such sources including HD100546 and also Comet Hale-Bopp (Crovisier *et al.*, 1997; Waelkens and Water, 1997). The uniqueness of these assignments is still in some doubt, and even on the basis of a silicate identification in the case of Hale-Bopp such material appears to make up only some few percent of the mass of the dust, the rest being Trapezium type grains (Hoyle and Wickramasinghe, 1997). In all cases where grains in the general interstellar medium or in extended regions of space have been studied the situation is exactly as we have discussed in the previous section – no real silicate can explain the observations over the 8–14 μm waveband.

An object that has recently been re-examined and one that is interesting in the present context is the highly reddened B star VI Cyg No. 12. This star has a normal interstellar extinction curve with a total visual extinction of some 10 mag. So it could be inferred that its reddening is due to dust over an extended path length in the diffuse interstellar medium. W.A. Stein and F.C. Gillett (1971) first examined this star to search for a 3.1 μm water ice band that was expected for the then popular ice grain theory. The results for the ice grain theory were disappointingly negative as it eventually turned out. Now the same star has been studied at high spectral resolution using both ground-based telescopes and satellite observations (Gezari *et al.*, 1993; Bowley *et al.*, 1996; Whittet and Tielens, 1997). This data is reproduced in Figure 4. The filled and open circles are ground-based data and the crosses represent SWS ISO observations. We note first that a hint of a feature occurs at 3.4 μm amounting when measured accurately to an extinction of $\sim$ 0.12 mag. This data is also seen to be consistent with the earlier data which implies that there is little or no evidence for water-ice absorption at 3.07 μm in the general interstellar medium.

The most striking feature of the spectrum of VI Cyg No. 12 is the broad smooth absorption feature over the 8–12 μm waveband, which must be due to grains in the general interstellar medium. The dip below a continuum level near 9.5 μm corresponds to an extinction of about 0.8 mag. The dashed curve displayed in Figure 4 corresponds to a Rayleigh-Jeans spectrum for the longwave emission from the star. The expected reduction of flux at the Earth due to absorption by interstellar dust is now given by the simple formula

$$|\Delta \log F_\lambda| = \text{const. } \tau(\lambda) \tag{2}$$

where $\tau(\lambda)$ as before, refers to the opacity of a candidate grain material as measured in the laboratory. With an appropriate choice of the constant scaling factor the resulting diminished flux, using $\tau(\lambda)$ for our mixed diatom culture model, is plotted as the solid curve in Figure 4. Figure 5 shows the same comparison in a slightly different way. The curve shows the normalised opacity function for diatom material compared with points for two astronomical sources – VI Cyg No. 12 and the young stellar object NGC 7538 IRS9 (Whittet *et al.*, 1996). For the latter case the normalised opacities were calculated adopting a flat underlying continuum emission over the 8–13 μm waveband as indicated by the heavy dashed curve of Figure 6.

4. The 3.4 μm Absorption Band

The earliest evidence of organic matter in a condensed form occurring in interstellar space had been greeted with strong scepticism from the mid-1970's through much of the 1980's. The first relevant data pointing in this direction turned up in spectra of protostellar sources such as the BN object as well as in dense clouds like the Taurus dust clouds (Whittett *et al.*, 1983; Merrill *et al.*, 1976). The evidence was in the form of a long-wave wing in the 3.1 μm absorption band due to water-ice. The circumstance that the 2.9–3.3 μm ice band with a mass absorption coefficient at its band centre of some 30 000 cm^2 g^{-1} could mask a very much weaker CH-stretching absorption band invariably left only a residual hint of a 3.4 μm feature

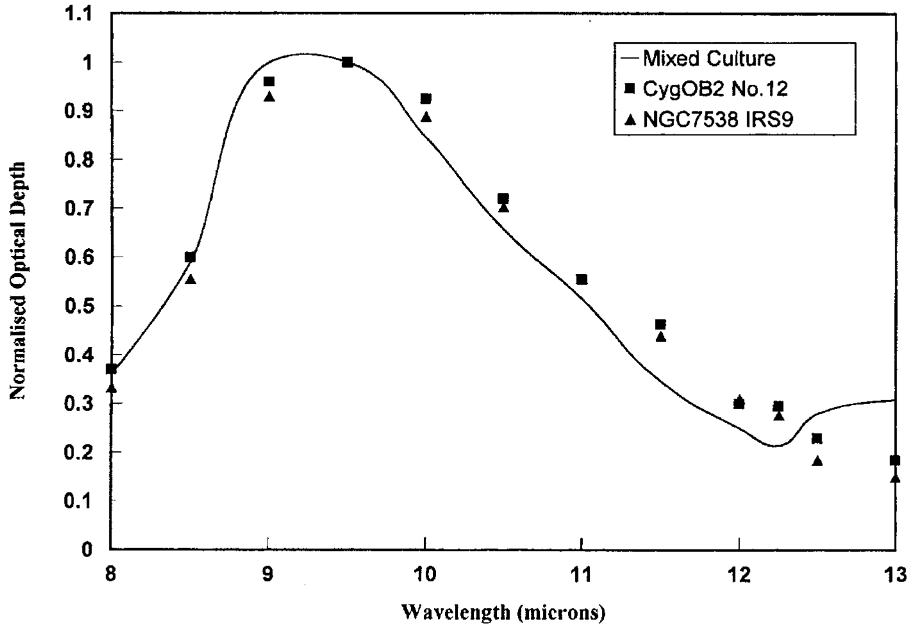

Figure 5. Normalised optical depth for diatom grain model compared with observations for VI Cyg No. 12 and NGC 7538 IRS9.

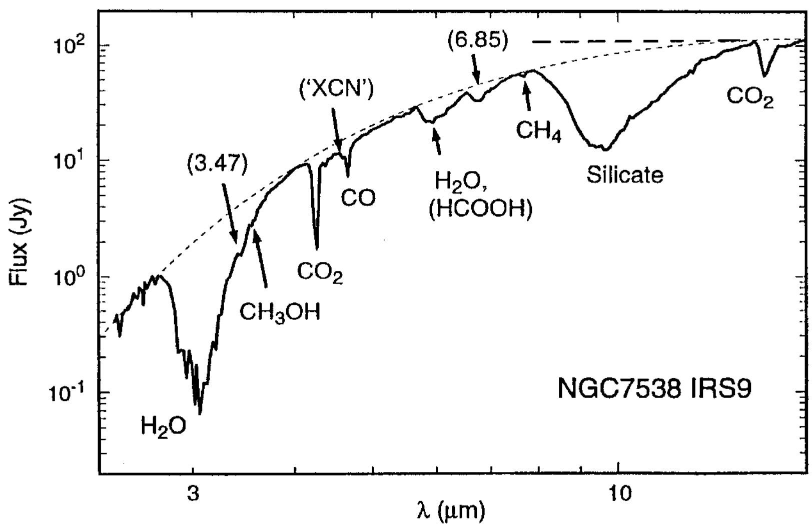

Figure 6. Spectrum of NGC 7538 IRS7 showing continuum level (long dashed line) for calculating optical depths.

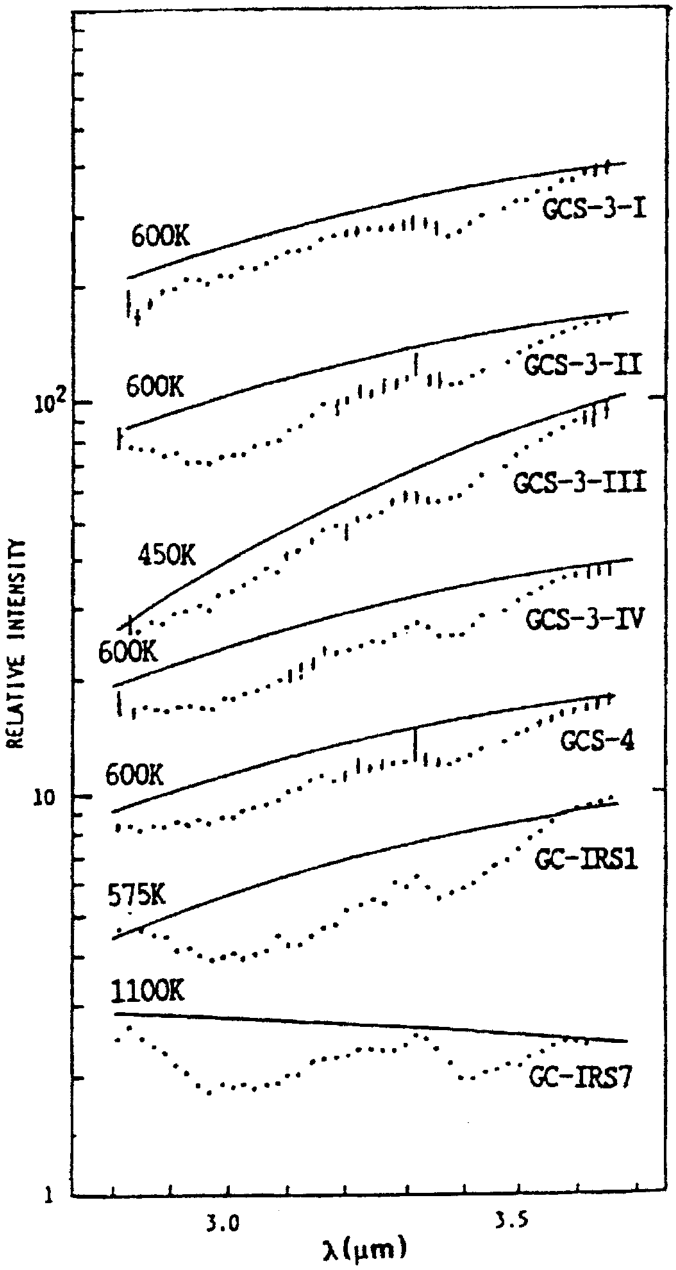

Figure 7. Relative flux data for several infrared sources in the galactic centre region (Okuda *et al.*, 1989).

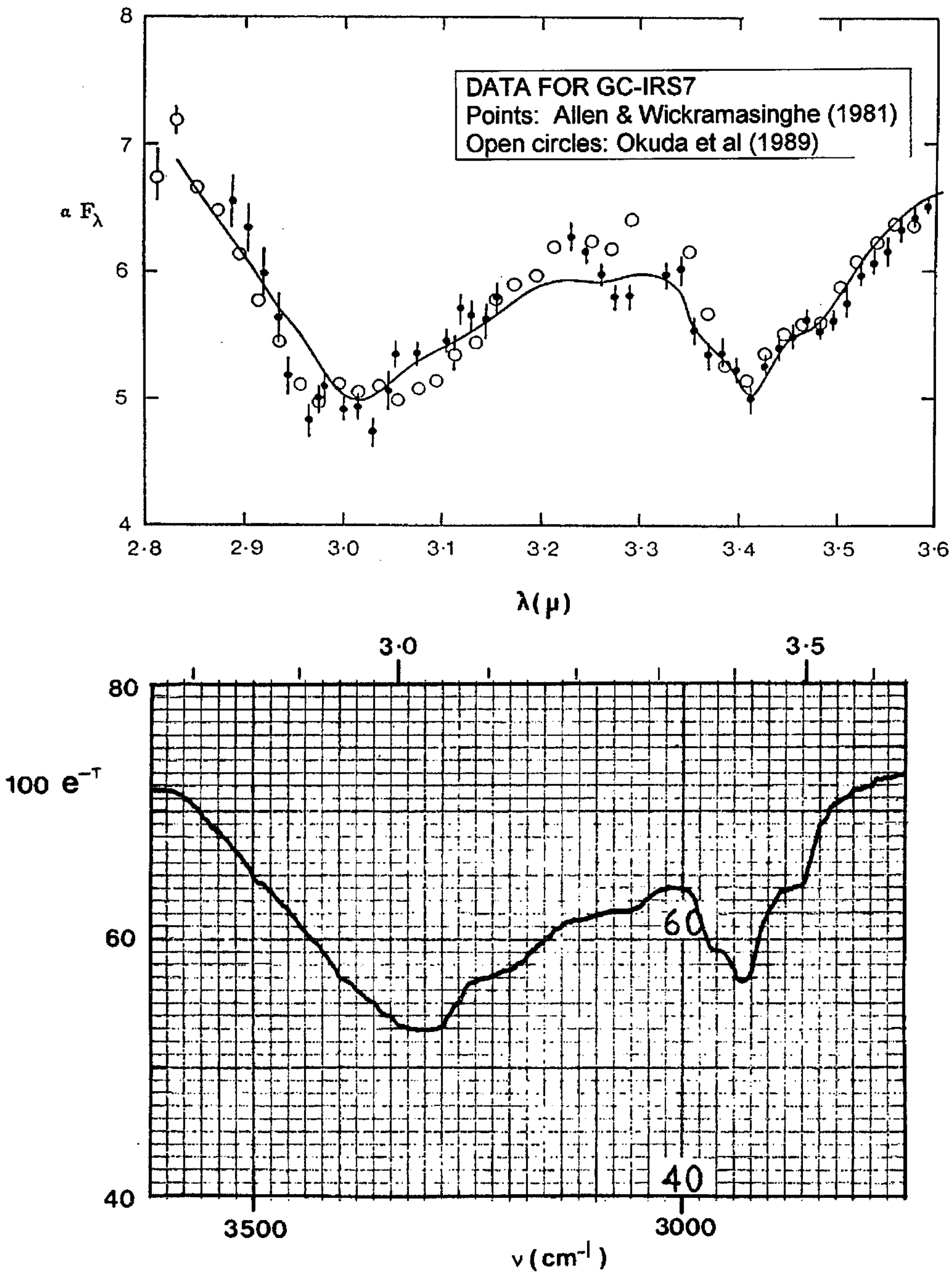

Figure 8. Top panel: Points show data of Allen and Wickramasinghe (1981) and Okuda *et al.* (1989) for GC-IRS7. The curve is the calculated behaviour of the *E. coli* model. Bottom panel: Transmittance data for dry *E. coli* (Al-Mufti, 1984).

to be seen. This was true wherever water-ice was able to condense on grains even in relatively small quantities. The present authors were the first to recognise this hint of 3.4 μm absorption in many sources such as the BN. It was pointed out that even in these instances the mass of organics exceeded the mass of ice by more than a factor of ten (Hoyle and Wickramasinghe, 1980a,b,c, 1983).

The first direct evidence of complex organic molecules associated with interstellar dust came with observations of the galactic centre source GC-IRS7 (Allen and Wickramasinghe, 1981). Their observations, using instruments on the Anglo Australian Telescope, with possibly optimal observing conditions, showed unequivocal evidence of a broad absorption band centred at about 3.4 μm that could be attributed mostly to CH stretching within a mixture of aliphatic and aromatic functional groups. The absorption was to be clearly detected against the background of thermal emission in a source radiating at a temperature of 1100 K. Quantitatively the absorption amounted to 0.3 mag at the centre of the 3.4 μm band. Figure 7 shows the spectra several similar sources distributed over an extended 3 cubic parsec volume around IRS7 which were subsequently observed by Okuda *et al.* (1989, 1990). The circumstance that all these sources display approximately the same central optical depth (0.3 mag) at the 3.4 μm band centre, relative to the underlying black-body continuum, makes it certain that most of the absorption arises from the diffuse distributed interstellar medium rather than from local circumstellar regions. It is therefore safe to infer that this C–H stretching absorption is characteristic of interstellar grains over an extended path length to the galactic centre of some 10 kpc or so. It is also clear from Figure 7 and from the original observations of Allen and Wickramasinghe (1981) that there is no ice band at 3.1 μm to any significant extent, at any rate none that exceeds the optical depth of the 3.4 μm band. This result is consistent with the ISO observations of VI Cyg No. 12 to which we have already referred.

The points in the upper panel of Figure 8 shows the detailed absorption profile in GC-IRS7, combining the data of Allen and Wickramasinghe (1981) with that of Okuda *et al.* (1989). The absorption occurs over wavelength ranges characteristic of OH stretching, CH aromatic and aliphatic stretching and NH stretching. It is immediately clear that a complex mixture of organic materials is involved, but the precise combination of functional groups within plausible models is difficult, perhaps impossible to specify. However, for any given organic substance, or mixture of organic substances, one could determine whether a fit to the astronomical data is possible or not. The general argument is exactly the same as that for the Trapezium nebula that we have discussed in an earlier section.

A laboratory sample of candidate material could give an experimentally measurable transmittance $T(\lambda) = 100 \exp[-\tau(\lambda)]$, whilst the spectrum of GC-IRS7 (e.g. Allen and Wickramasinghe, 1981) gives a flux

$$F_\lambda = A B_\lambda(\lambda) \exp[-\alpha\tau(\lambda)]. \tag{3}$$

A, α constants and $B_\lambda(\lambda)$ being the Planck function. Thus we can regard the astronomical observations as determining the quantity $\tau(\lambda)$ via Equation (3), at any rate to within a constant factor.

Historically, the first organic model that was considered, and found to match the data to a remarkable degree of precision, was the material represented by the common bacterium *E-coli*. A spectroscopic KBr disc was prepared with a carefully measured mass of 1.5 mg of dry *E-coli*. The KBr disc was then heated in an inert gas up to a temperature of 350C and the quantity $\tau(\lambda)$ for this system was measured using a standard Perkin-Elmer spectrometer. The raw spectrum showing $T(\lambda)$ for this case is displayed as the lower panel of Figure 8 (Al-Mufti, 1984). The mass absorption coefficient at the peak of the 3.4 μm absorption was found from this experiment to be close to 500 cm^2 g^{-1}.

The curve in the upper panel of Figure 8 shows the closeness of the fit that ensued with a choice $\alpha = 1.3$ used in Equation (3). To obtain this fit, which implies an extinction value of 0.3 mag at the centre of the 3.4 μm band, we require a distributed mass density of ‘bacteria-like’ organic dust grains amounting to about 10^{-26} g cm^{-3} – a large fraction of all the mass of interstellar dust.

Just as for the case of the 8–12 μm feature of the Trapezium one can now ask: what other chemical system besides biology can be invented to match the data for GC-IRS7? We can use Equation (3) to invert the relationship between τ and F_λ and obtain the $\tau_{\rm obs}(\lambda)$ curve just as was done for the Trapezium. In view of the closeness of the fit seen here $\tau_{\rm obs}(\lambda)$ should be considered to all intents and purposes as being necessarily identical to the *E-coli* opacity. This is of course true only we accept the observations represented by the points in Figure 8 as being substantially correct.

Since 1982 many attempts have been made to match the GC-IRS7 spectrum in the 2–4 μm waveband using abiotically generated mixtures of organic materials, an endeavour distinctly superior to that of raising Lazarus from the grave as was done for the case of the Trapezium nebula. Irradiation of suitably constructed mixtures of inorganic ices have been shown to result in organic residues possessing spectra that fitted the astronomical spectra to varying degrees (Tielens *et al.*, 1996). But all these arguments and comparisons have begged the important question as to how the precise conditions under which the laboratory experiments were conducted could be reproduced with such unerringly precision on a galaxy-wide scale. There have also been new attempts to measure the spectrum of GC-IRS7 using better instruments than before, although not necessarily at superior observing sites with regard to ambient atmospheric water. It should be noted in this context that even minute amounts of atmospheric H_2O would introduce a 3.1 μm feature in spectra that would be inconsistent with the original AAT observations of GC-IRS7 and also the ISO observations of VI Cyg No. 12. The generally favoured modern spectrum of GC-IRS7 appears to be one attributed to Pendleton *et al.* (1994) which is reproduced as the points in Figure 9. We see immediately that this spectrum differs from the original spectrum of Allen and Wickramasinghe (1981) (dashed line) to the extent of an excess absorption over the 2.8–3.3 waveband that is generally

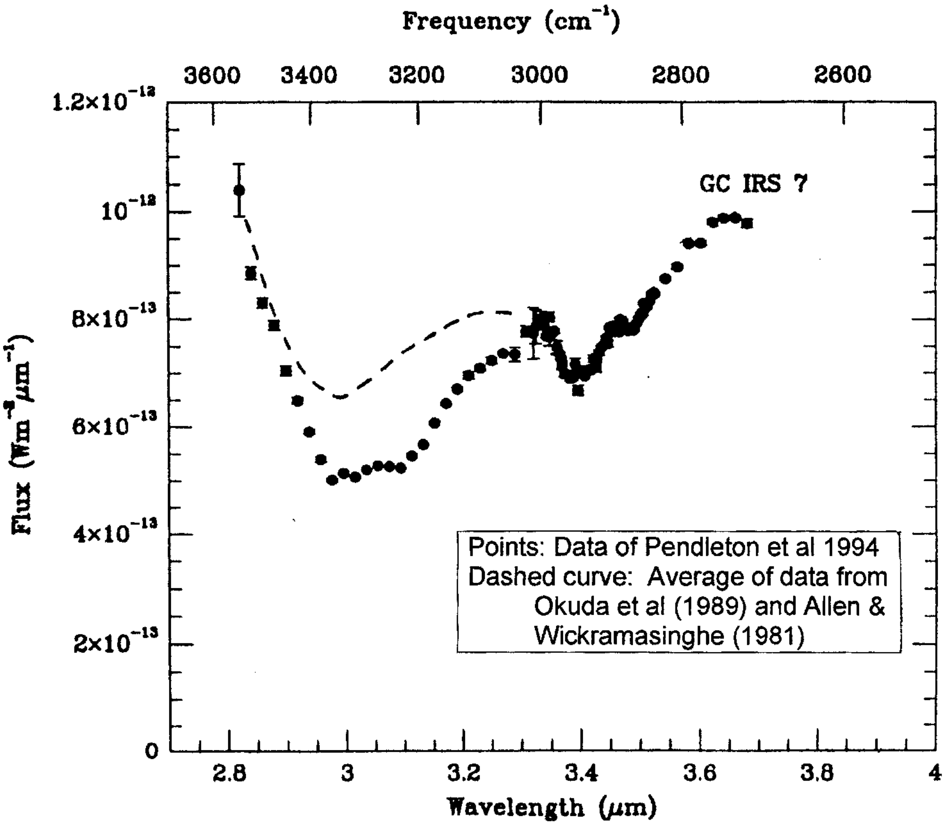

Figure 9. High resolution data for GC-IRS7 (Pendleton *et al.*, 1994) (points). Dashed curve is the average relative flux values from the data of Allen and Wickramasinghe (1981) and Okuda *et al.* (1989).

consistent with the presence of water-ice. Our original conclusion concerning the *E-coli* – GC-IRS7 opacity correspondence would remain valid provided we adopt one of the following two procedures:

(1) Subtract the excess absorption in this waveband, attributing it to spurious atmospheric water;

(2) Add a component of water-ice to our proposed bacterial grains, an amount as little as 2% of the bacterial mass density being sufficient for this purpose (Hoyle *et al.*, 1983).

Despite the astonishingly modest nature of requirement (2), we ourselves would prefer the former of these alternatives, option (1), and propose to adopt the relative flux curve of Figure 8 as having the correct overall shape, subject only to refinements of detail over the 3.4 μm band profile arising from improvements in astronomical spectroscopy.

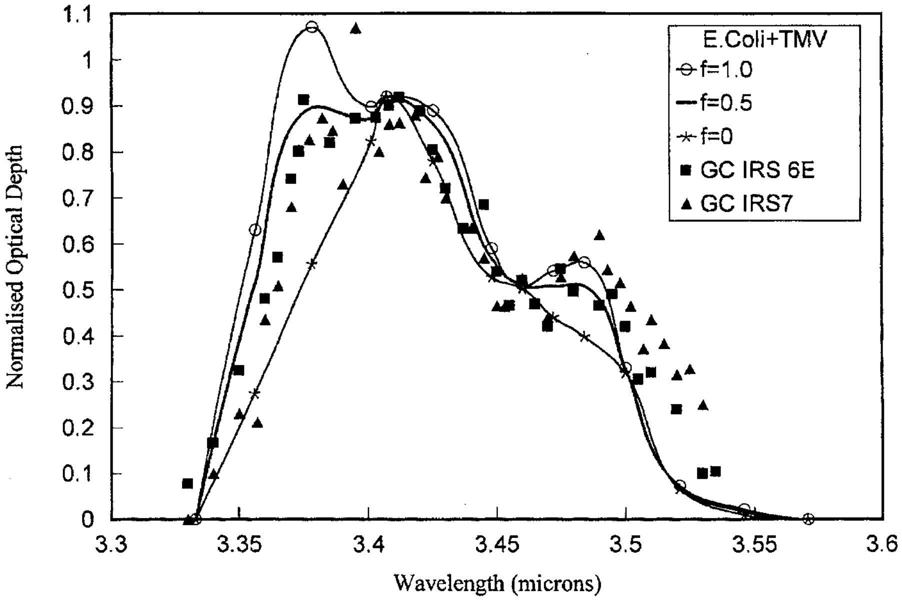

Figure 10. Normalised optical depths for *E. coli* – TMV mixtures over the 3.3–3.6 μm waveband (curves). The points are similarly normalised data for GC-IRS6 and GC-IRS7.

The points in Figure 10 show the optical depth profiles over the 3.33–3.55 μm wavelength interval for the sources GC IRS7 and GC IRS6 (Pendleton *et al.*, 1994; Whittet and Tielens, 1997). A background continuum defined by a straight-line joining the observational points at 3.33 and 3.55 μm is subtracted from the observed fluxes (on a logarithmic scale), thus giving optical depths $\tau(3.33\ \mu\text{m}) = \tau(3.55\ \mu\text{m})$. We use a further scaling factor to give the arbitrary optical depth $\tau = 0.9$ at $\lambda = 3.4\ \mu$m.

Finally we consider a mixture of optical depths derived from the laboratory data displayed in Figure 11. The solid curves in Figure 10 combine the effects of two types of biological material: viral type particles typified by the laboratory data for TMV (Tobacoa Mosaic Virus) and a desiccated bacterium represented by the data for *E-coli*. Average optical depths of such mixtures are computed according to

$$\{\tau(\lambda)\} = \tau_{\text{E-coli}}(\lambda) + f.\tau_{\text{TMV}}(\lambda) \tag{5}$$

so that the parameter f represents a relative weighting factor between the two biological types. The agreements with the observed points are found to be good, especially if one includes viral type material to the extent of contributing to an f value between the values 0.5 and 1.

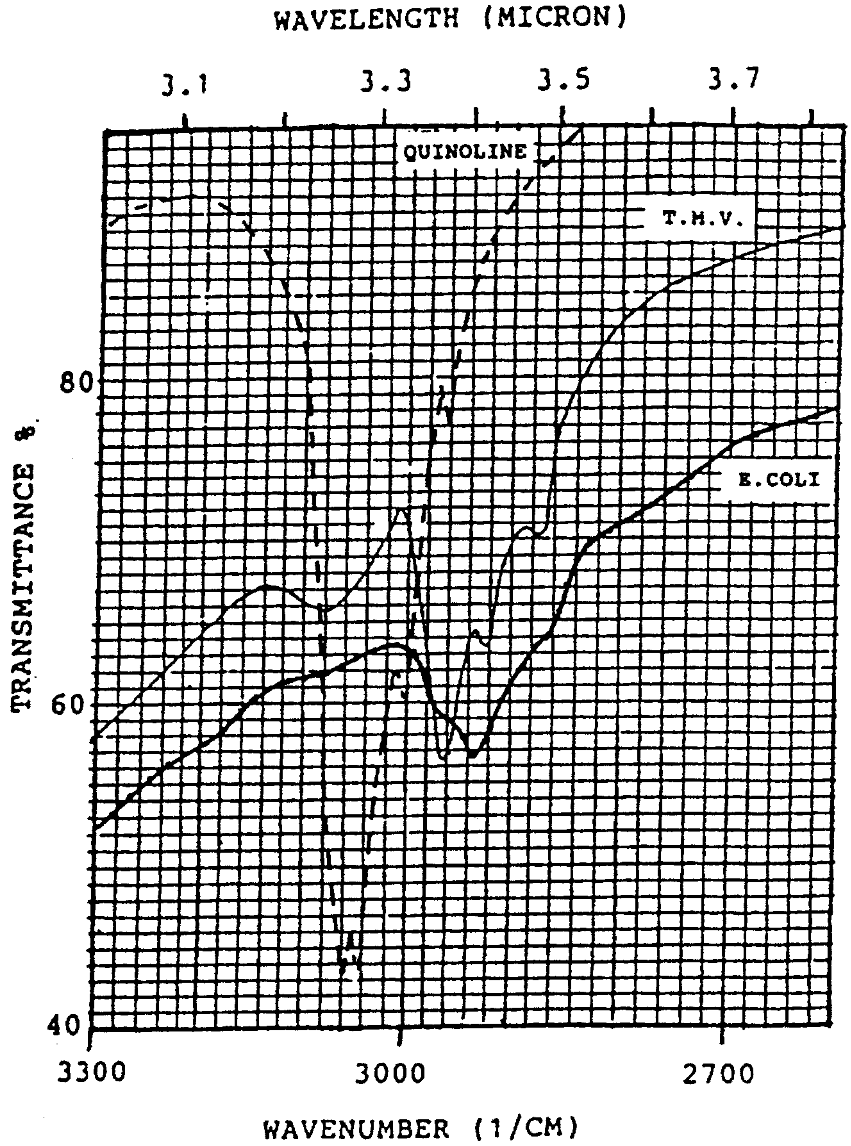

Figure 11. Laboratory transmittance curves for *E. coli* and TMV used for calculating the curves in Figure 10.

5. Conclusion

The idea of interstellar grains being a mixture of biologically generated siliceous and organic particles seems to have stood the test of time. New observational data over both the 8–13 μm and 2–4 μm spectral regions are fully consistent with panspermia theory. The challenge for non-biological models for interstellar and cometary dust is to account for the large-scale conversion of both C and Si into structures that are spectroscopically identical to biological matter. Highly contrived laboratory experiments producing esoteric mixtures of organics might well yield partial successes in fitting spectral data, but the problem remains to explain how identical mixtures are produced on such a vast cosmic scale: some 30% of interstellar carbon and 70% of interstellar silicon would appear to be tied up in structures that must essentially mimic biology. Non-biological processes are unlikely to approach anywhere near the efficiencies of conversion that biology can provide.

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