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INTERSTELLAR DUST, COMETS AND PANSPERMIA

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SUMMARY

A wide range of astronomical investigations that have been carried out over several decades is now converging on a model of both interstellar and cometary dust that is essentially organic in character. The hypothesis that cosmic grains contain freeze-dried bacterial cells, some in a viable form, is analysed in relation to both laboratory studies and relevant astronomical observations. A new model of cosmic organic grains is developed based on recent data from Halley's comet. The model involves a size distribution of clumps of hollow organic particles, as is found in Comet Halley, that are identifiable with bacteria together with components that result from their degradation. The correspondences between predictions of

this model and astronomical data is shown to be impressive to the point of giving credence to the view that comets carry, amplify and disperse life throughout the Universe.

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FIG I

1. Historical Background

The existence of obscuring matter between stars was not firmly established until the early 1930s. The most striking evidence for this matter is to be found in long-exposure photographs of the Milky Way. These show dark patches and striations which we now know are caused by clouds of gas and dust lying in front of distant stars. An example of such a photograph is shown in Figure 1. Visual recordings of these patches pre-date the advent of photography; Sir William

Herschell recorded their existence way back in 1785. But the recognition that the 'patches' are obscuring clouds rather than actual recesses between stars involved tests that seemed rather subtle even in 1930. The light from a distant star was shown to be reddened, as compared with a nearby star of the same spectral type. This effect is caused by scattering and absorption of starlight by sub-micron sized dust particles in interstellar clouds, blue light being absorbed and scattered more strongly than red light. About the same time as the existence of dust clouds was recognised interstellar gas atoms in the form of ionized Ca and neutral Na were discovered in the spectra of stars. Theoretical calculations of J.H. Oort, based on observations of instellar motions, gave a strong indication that there was close to an equal mass of uncondensed interstellar matter as of stars in the plane of the galaxy. The most abundant gaseous constituent of the interstellar medium - hydrogen - remained undetected until radio astronomers predicted, and subseqently observed a 21 cm absorption line corresponding to this material. The presence of dust clouds is by no means a phenomenon confined to our own galaxy. Most spiral and irregular galaxies show evidence of dust lines.

FIG. 2

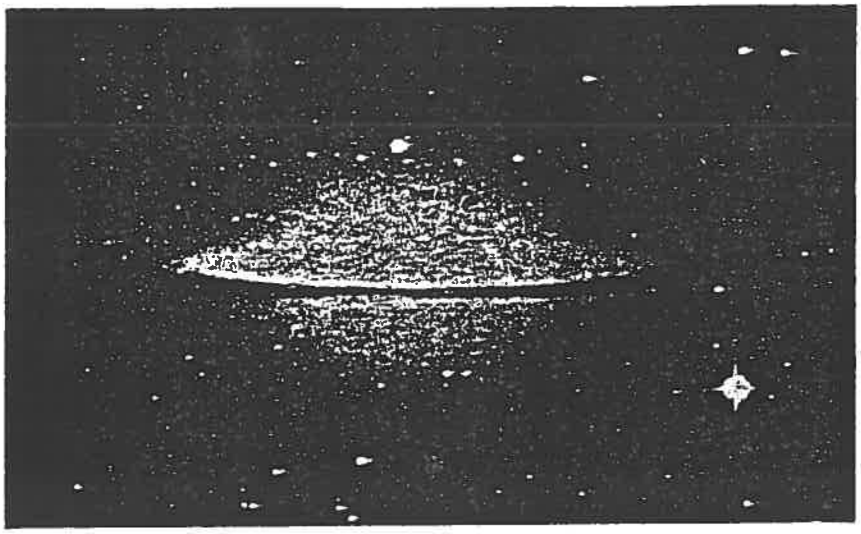
Spiral Galaxy in Andromeda, also called M 31, is about 2 million light years away and is the nearest of the large regular galaxies. It contains more than 10^{10} individual stars and has a diameter of about 125,000 light years (Courtesy of the Mt. Wilson and Palomar Observatories).

FIG. 3.

Spiral Galaxy also known as M 51 is probably like our own, except for its small companion (left). Lanes of dust delineate the spiral arms which contain the brightest and youngest stars along with gas and dust clouds. Photograph was taken with the 200" telescope on Mt. Palomar (Courtesy of the Mt. Wilson and Palomar Observatories.)

Figure 2 shows the Andromeda nebula, a nearby galaxy very similar to our own galaxy, consisting of some ten thousand million stars and gas and dust distributed along spiral arms. Figures 3 and 4 show two other galaxies which are also believed to be similar to our own galaxy, one viewed nearly face on, one edge on. The latter shows a conspicuous central lane of dust such as exists in our galaxy.

Fig.4



Spiral Galaxy NGC 4594, in Virgo viewed edge-on. This galaxy is 37 million light years away showing a conspicuous dust lane through central plane. (Courtesy of the Mt. Wilson and Palomar Observatories).

Interstellar matter tends to be clumped into irregular-shaped clouds of about 10-100 light years in dimension.

The clouds occupy a layer of thickness approximately 500 light years and a diameter 80,000 light years. For an average cloud the mean hydrogen density is about 10 atoms cm^{-3} and the kinetic temperature is 100 K. The mass of a typical cloud is about 1000 solar masses, and of this 20 solar masses would be in the form of solid particles. Such clouds could fragment and condense to make several hundreds of thousands of stars, and we believe that we are actually seeing this happening at the present time in many parts of the galaxy. The Orion nebula in our Galaxy is a striking example of a region of active star formation. Extremely young stars, which started to shine long after the first men walked on our planet, are buried in this mass of glowing hot gas and dust. Infrared astronomers are constantly detecting sources of infra-red radiation from hot dust in extended regions of such nebulae, as well as from point sources which are believed to be stars and planetary systems in the process of formation.

The first molecules to be discovered in interstellar space were the relatively simple radicals CH, CH^+ and CN during the years 1937-1941. Then, after a lapse of over 20 years, followed the discovery of the hydroxyl radical OH in 1963 using radio astronomical transitions at wavelengths close to 18 cm. Since then molecular spectroscopy has provided a major tool for exploring gas clouds between stars. By 1975 some 150 molecular lines had been observed, and these were identified with 45 terrestially known molecules and radicals. Since 1975 the discovery rate of molecules has slowed somewhat, mainly because of limitations in detection methods. The actual number of molecules discovered in space, however, continues to grow, and several trends may be seen to have emerged. Molecular hydrogen (H_2), carbon monoxide (CO), the hydroxyl radical (OH) and formaldehyde (H_2CO) are probably present in most clouds; but water, methane, ammonia and the more complex molecules are mainly confined to clouds with a hydrogen density in the range of 10,000 to a million atoms cm^{-3}. The predominance of organic molecles based on C has become amply clear. Several of the observed molecules have several carbon atoms linked into long chains, e.g. HC_9N. Two of the molecules actually observed in dense interstellar clouds, formic acid ($HCOOH$) and methanimine (CH_2NH) may be regarded as precursors of a simple amino acid. The presence of fairly complex organic molecules in interstellar clouds raises an important question: are interstellar clouds gigantic chemical factories as most astronomers have supposed, or could they be either the graveyard or cradle of life?

2. Early Ideas on Interstellar Dust

We shall show in the present article that a crucial component of the answer to this question may lie in the properties of the dust component of interstellar material, a component that was prophetically called "interstellar grains" by Lyman Spitzer, Jr.

Ideas on the composition of interstellar dust particles have undergone several changes since their effects were first observed. From 1930-1940 the dust grains were thought to be small iron meteorites. From 1940-1960 astronomers firmly believed that these solid particles condensed out of the tenuous gas clouds in space, and that they consisted mainly of H_2O ice with sub-micron dimensions. Difficulties relating to the growth of solid grains from single atoms in tenuous gas clouds led to the development of an alternative theory of grain formation in 1962. Fred Hoyle and the present author[1] argued that dust particles could be formed in the atmospheres of cool red giant stars, and that a major part of the interstellar dust could be particles blown off from such stars. The original idea was that this process occurred only in carbon-rich red-giant stars - the so-called carbon stars, and that the particles so formed were composed mainly of soot-like graphitic material. It was later argued that oxygen-rich red giant stars (the so-called Mira variables) could also produce dust in a very similar way, but that in this case the particles were composed of silicate-type material, rather than soot.

Astronomical observations carried out between 1965 and the present day have provided sensitive tests for contending models. The absence of a significant amount of interstellar ice was firmly established as early as 1965. In the same year a spectral feature of small graphite particles predicted theoretically to occur at 2200 Å was found in the spectra of most stars which were dimmed by dust clouds[2]. In 1969 infrared astronomers detected a broad spectral feature at ~10 μm in both carbon stars and oxygen-rich red giant stars[3]. In carbon stars this band is most likely to be caused by hydrocarbon molecules or impure graphite particles. In oxygen-rich red giants an identification with a silicate feature seemed at first sight to be likely. Although many astronomers believe that silicate particles could be the main component of dust, or at least be comparable in abundance with graphite, this would appear unlikely on account of the lower cosmic abundance of silicon relative to carbon, and also because of discrepancies that showed up between calculated profiles of the 10 μm silicate band and astronomical observations notably from dust in the Trapezium nebula. Astronomical data on the extinction of starlight at visual wavelengths (~2 mag/kpc) together with the elemental abundance ratios for material in space indicate that the elements C, N and O must provide the main contribution to the mass of interstellar dust. The cosmic abundance of Mg, Si are too low by at least a factor 5 to compete effectively with the CNO elements.

3. Shift towards Carbonaceous Polymers

By 1974 it was widely held that interstellar grains were a mixture of graphite particles of average radii 0.02 μm and silicate particles possibly carrying mantles of icy material[4]. The evidence for the former of these components seemed to be well founded in view of the fact that calculation[5] had shown a peak of extinction at 2200 Å for 0.02 μm sized grains, an effect that was subsequently found in the observed extinction curves of stars (Fig. 5). Although there was room for speculation as to the source of the carbon grains in space there seemed to be little doubt as regards their actual existence.

The claims for silicate grains in the general interstellar medium were based almost entirely on the shape of the 8-13 μm infrared flux curve observed for dust in the Trapezium Nebula. This data showed a broad emission peak arising from the heated dust centred on

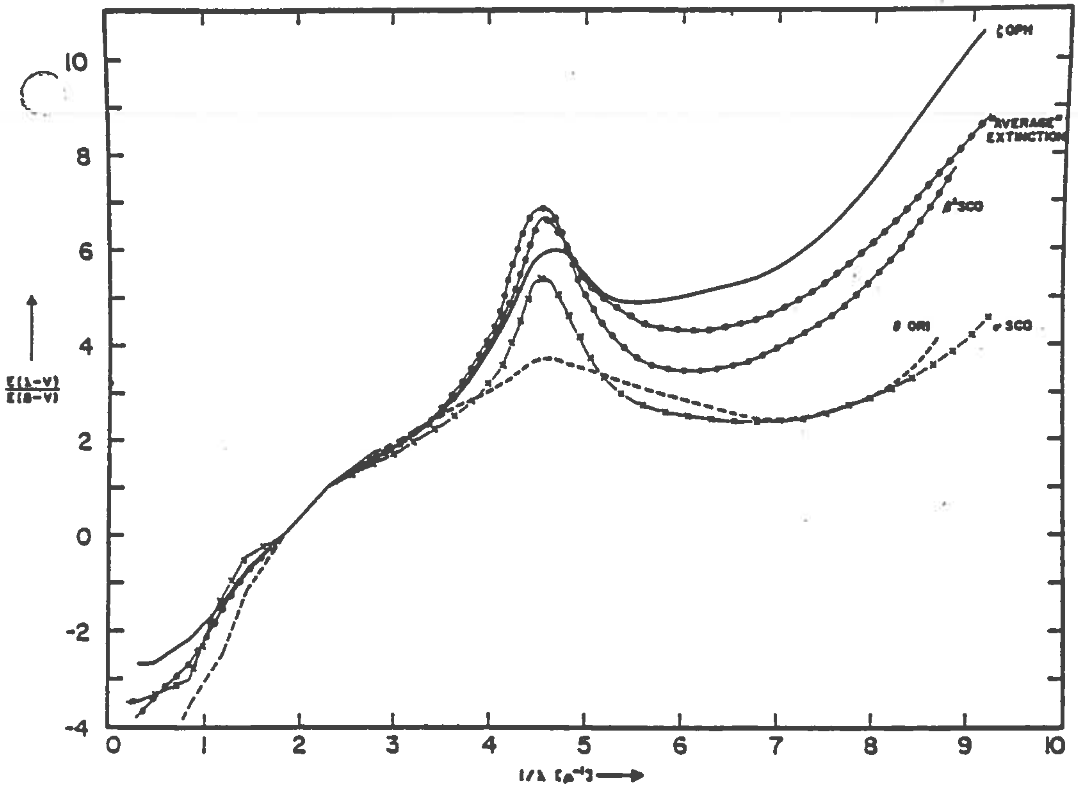


Fig.5

Extinction curves of several stars showing hump at 2200A

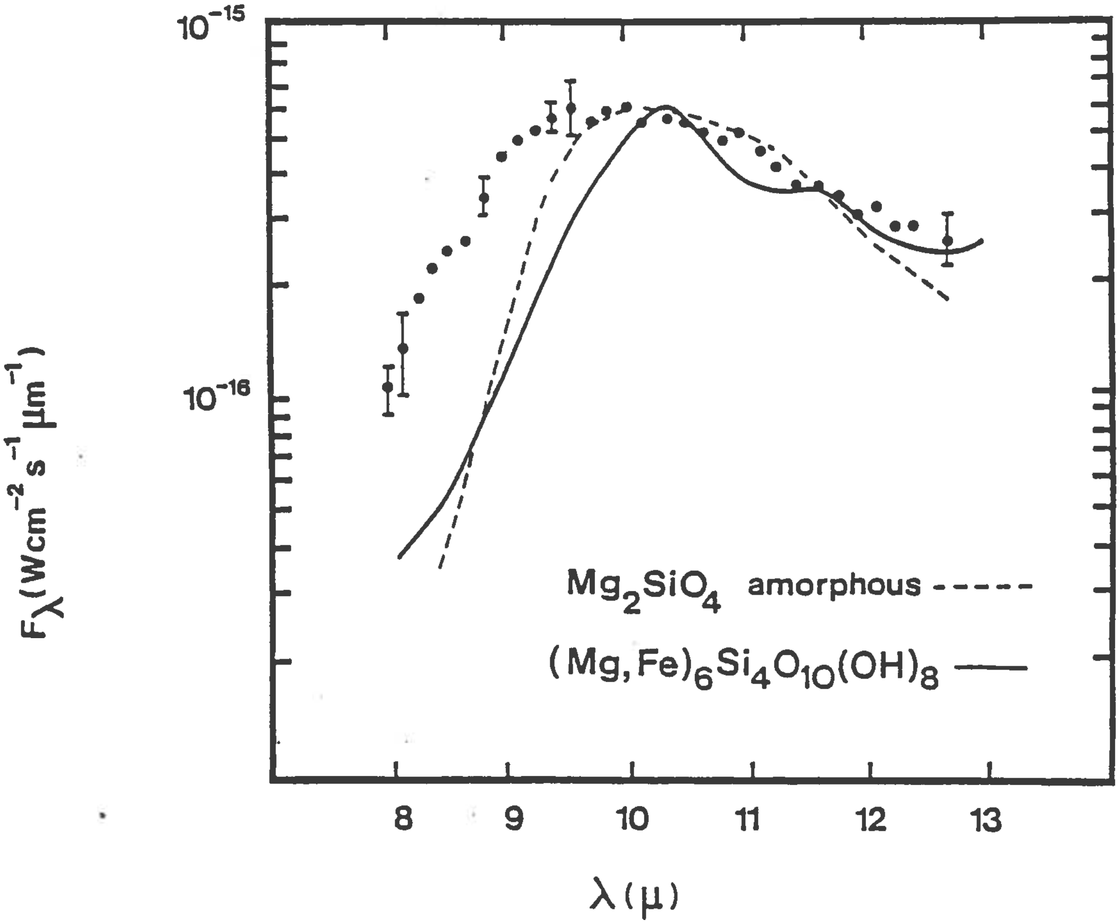


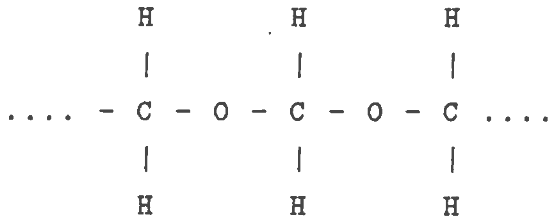
Fig.6

Comparison between the flux measurements for the Trapezium nebula (points) with the predictions for 0.1μ sized silicate grains (amorphous and hydrated) heated to 175°K. Observations and calculations are normalised to correspond at maximum value of flux.

the wavelength 10 μm[3]. Although Si-O linkages in silicates offered some possibility for such an emission, there appeared from the outset to be serious difficulties in obtaining detailed correspondences with astronomical data. Figure 6 shows the discrepancy between the flux curve for the Trapezium nebula over the 8-13 μm waveband and two of the best fitting silicate models where the dust is taken to be heated to 175 K. Although a tendency has developed to brush aside the discrepancies as appear in Fig. 6, and to call the material with Trapezium emissivity 'silicate', neither Fred Hoyle nor I could not allow ourselves to be deceived by this play of words. It was amply clear that inorganic silicates simply did not have the configuration of oscillators needed to yield satisfactory agreement with the Trapezium data.

Of course 8-12 μm absorptions are by no means unique to silicates. The fact that we experienced persistent failures with this model prompted us to look in new directions. The atoms C, N, O in combination with the more abundant element H can give rise to two broad classes of grain model: one class includes inorganic ices such as CH_4, NH_3, H_2O, the other includes organic polymers of a variety of types.

From 1973 onwards I began exploring this latter class of grain model, a model which was contemplated as having to exist in combination with small graphite spheres to which I have already referred. This model appeared all the more attractive in view of the discovery of large numbers of organic molecules in interstellar space. A molecule that first attracted my attention in this context was formaldehyde, H_2CO. It is evidently an ubiquitous molecule in the interstellar medium, and one that could also be readily polymerised into polyformaldehyde or polyoxymethylene. This model was discussed and probed in some detail during the years 1974-1976 (ref. 6, 7). Figure 7 shows the calculated flux for POM particles heated to 175 K compared with data for the Trapezium nebula. The polymers involved here have the empirical formula



$$\cdots\ - \underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}} - O - \underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}} - O - \underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}\ \cdots$$

and the 8-12 μm band arises mainly from C-O-C linkages along the chains. The agreement in Fig. 7 is not perfect, but at least it is indicative of the possible role of organic polymers in accounting for the data. Organics in general have several fundamental band configurations that can contribute to absorptions over the 8-13 μm waveband, including C = C, C - O, C - N. The possibility of improving the fit in Fig. 7 with

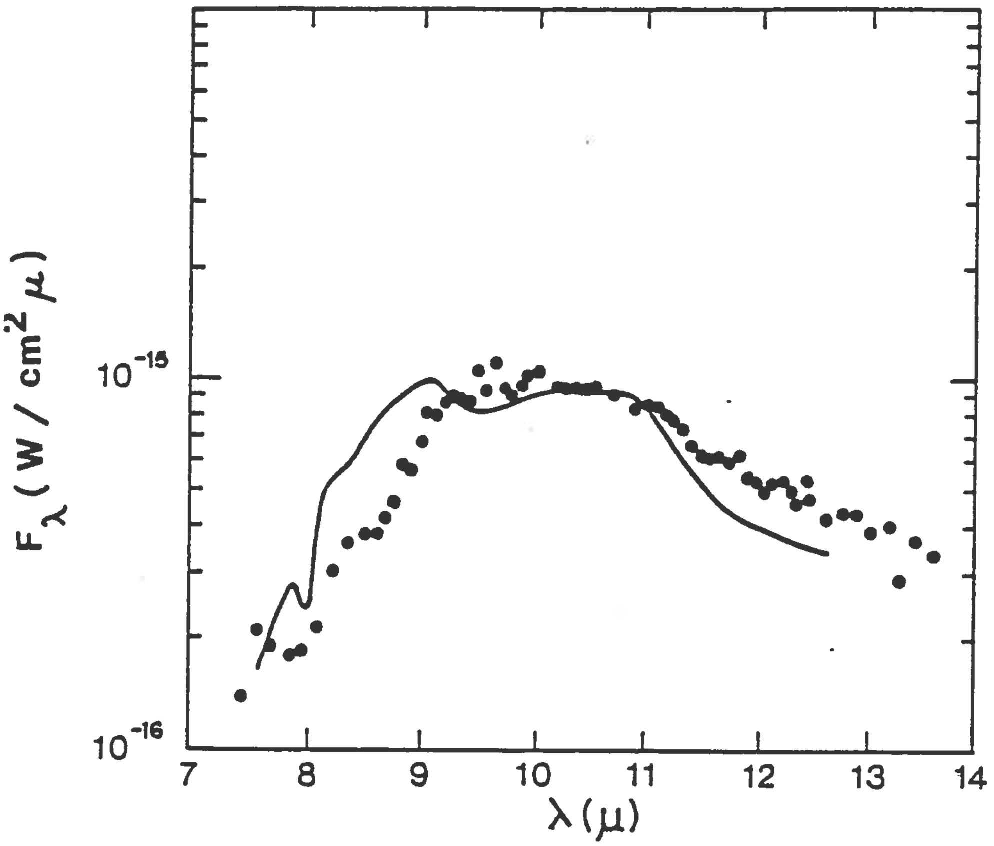


Fig.7 The infrared spectrum of the Trapezium nebula compared with prediction for a 445°K polyformaldehyde grain model.

other organic polymers therefore demanded further exploration. We considered a wide range of relatively simple organic polymers besides polyformaldehyde, but in all such cases the resulting agreements left much to be desired.

The spectrum of cellulose was one that we found quite early on offering scope for explaining much of the detail in the Trapezium spectrum. Slowly, but inescapably Fred Hoyle and I found ourselves moving away from inorganic dust towards organic particles, and thence eventually to biology. Cellulose, which gave an excellent fit to the Trapezium data, is of course a biopolymer, the main structural component of the cell walls of plants. From cellulose to fully-fledged biology was only a small step. The overall rationale for biological grains in space will not be discussed at any length in the present paper, but suffice it to state here that the overwhelming strength of our case depends on the prolific power of replication of cells under appropriate conditions. We shall now proceed to explore the hypothesis that interstellar dust grains are bacteria.

4. Infrared Implications of the Bacterial Hypothesis of Grains

From the point-of-view of elemental constraints bacterial particles in which C,N,O are combined with H fall well within the generally permitted class of organic grains. To test this model in detail, however, we require experimental data on the absorption properties of bacteria over relevant wavelength intervals. Laboratory spectra were first obtained by

S. Al Mufti from a mixed culture of diatoms and bacteria taken from a local river. In such a mixture a combined effect at $\lambda \sim 10\mu m$ could arise from C=C and C-O-C bonds as well as Si-O bonds. The latter arises from Si-O structures that are present in diatoms, which constitute a very wide class of micro-organisms present everywhere in lakes, rivers and streams.

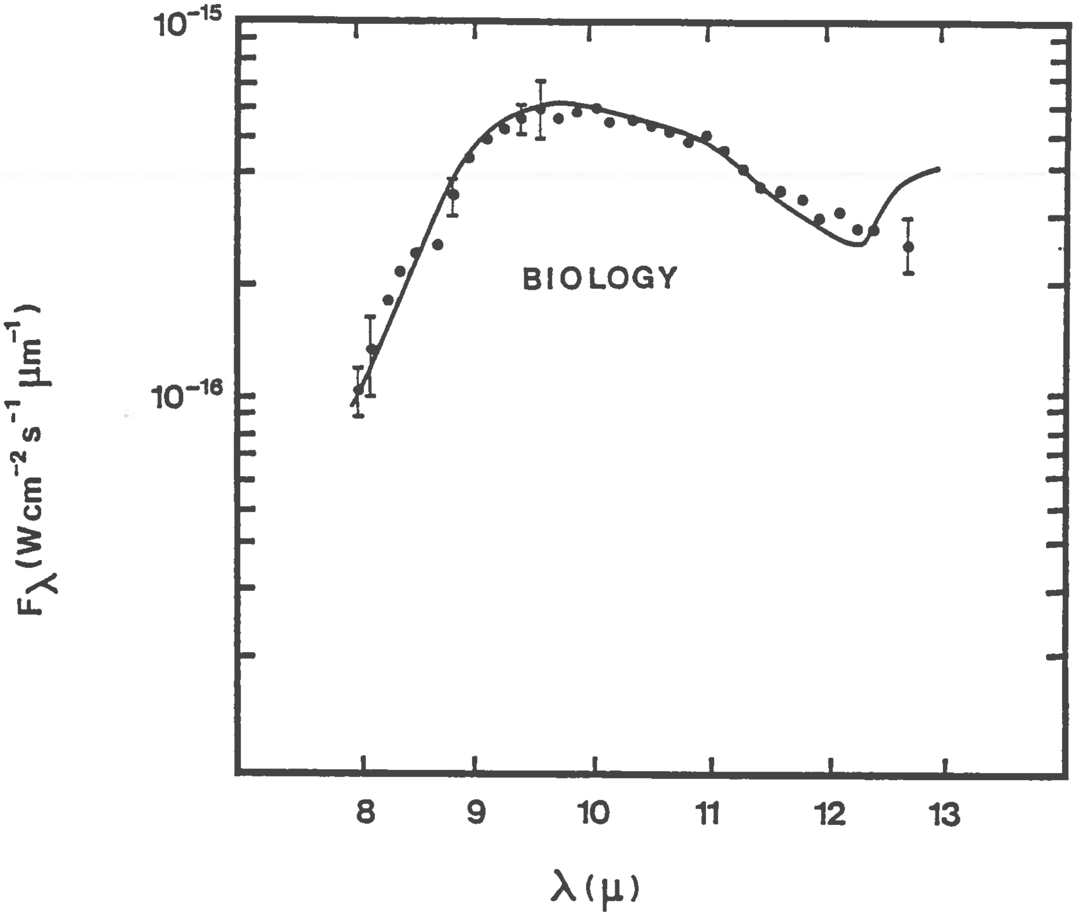
A milligram of a mixed culture of diatoms and bacteria was dried out in an inert gas at 350°C and pressed into a K Br disc. An infrared spectrum was obtained from such a disc and an opacity coefficient $\kappa(\lambda)$ was determined from the data. The infrared flux from such particles heated to 175 K can now be calculated according to the simple formula

$$F_\lambda \propto \kappa(\lambda)\ B_\lambda(175\ K) \qquad (1)$$

where B_λ is the Planck function.

Figure 8 shows a comparison of the normalised flux from the biological model with the data for the Trapezium nebula[8]. The agreement is essentially perfect. Similar data for a diatom-bacterial mixture extended to 30 μm by Q. Majeed shows that the predicted curve agrees not only with data in the 8-12 μm waveband, but also over the 15-25 μm waveband in the further infrared[9]. This agreement is shown in Fig. 9.

Fig.8



Comparison between the flux measurements for the Trapezium nebula (points) with the predicted curve for mixed diatom culture radiating at 175°K. Observations and theory are normalised to correspond at maximum value

Moving now to shorter wavelengths, bacterial spectra at high wavelength resolution were also obtained over the interval 2.5 - 4 μm, a few months before the first relevant astronomical data for comparison became available. We found that the spectra of all dehydrated micro-organisms over the 3.3 - 3.6 μm waveband were substantilly invariant, thereby confronting the bacterial grain hypothesis with a powerful discriminatory test. This invariant spectrum is shown in the upper panel of Fig. 10. The band arises essentially from CH linkages, but these linkages must be arranged in a highly specific way in order to get the correct relative strengths at different wavelengths in the interval 3-3 - 3.6 μm. If the bacterial hypothesis

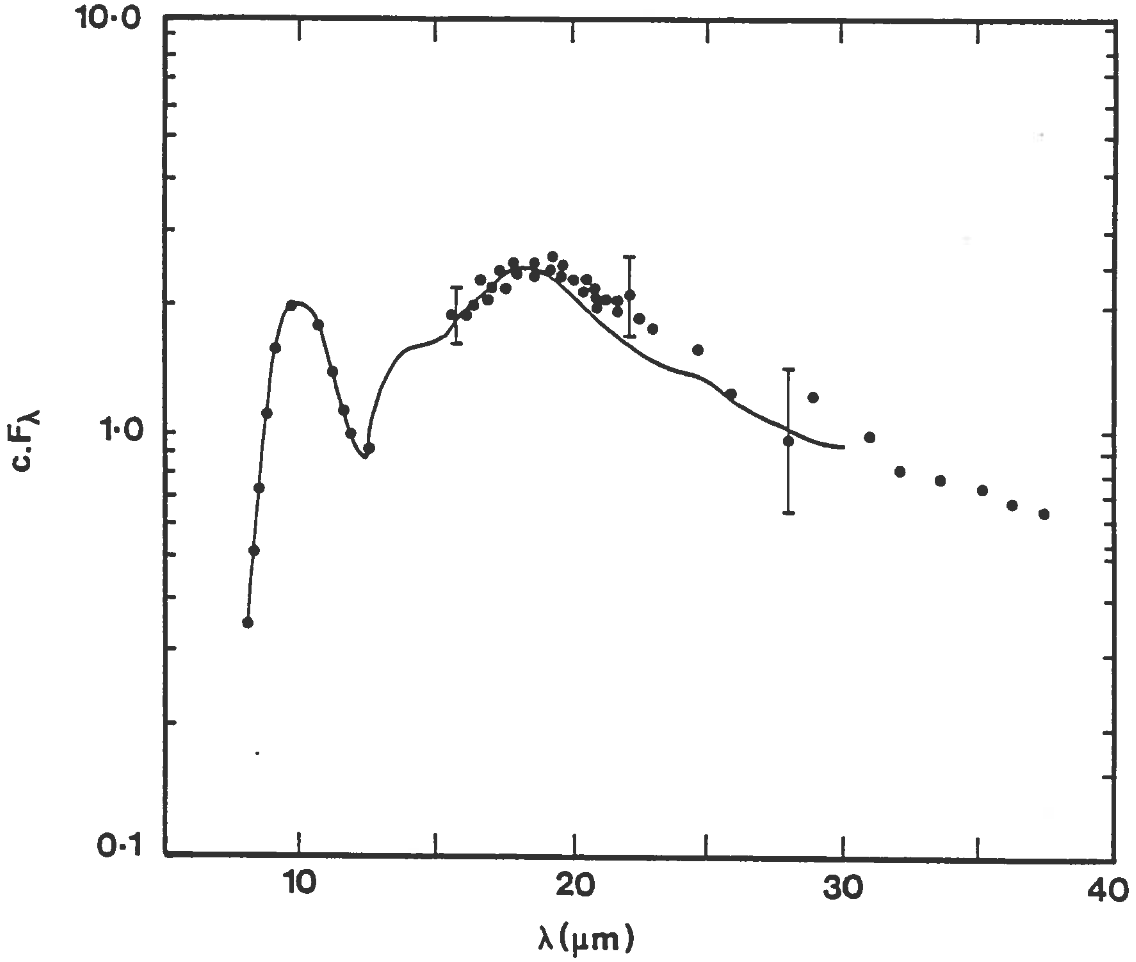


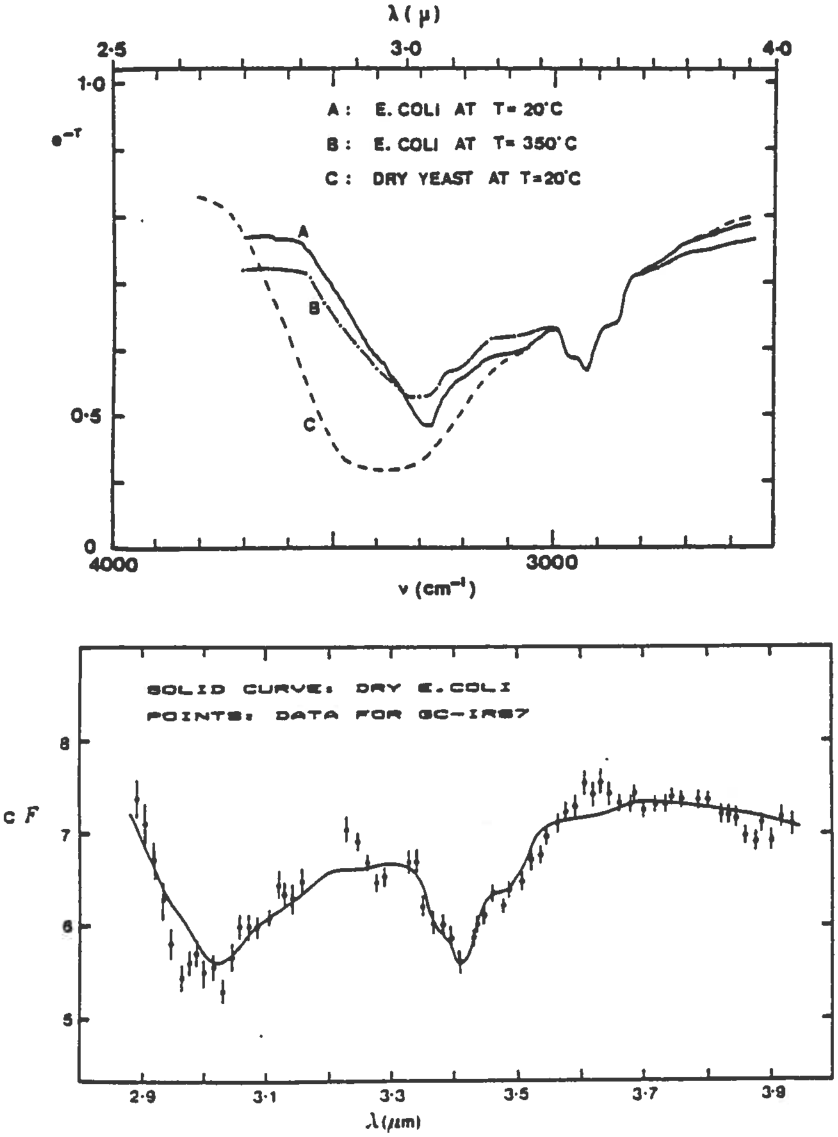
Fig.9

Same as Fig.8 but at longer wavelengths

were indeed correct the observed pattern of absorption over the 3.3 - 3.6 μm waveband would have to be matched to a precise degree in spectra of suitably chosen infrared sources in the galaxy. In terms of its absolute intensity the bacterial absorption at 3.4 μm is weak, amounting only to some 600 cm^2 g^{-1}. Since the visual extinction coefficient of interstellar grains of almost any type which arises from scattering is ~50,000 cm^2 g^{-1}, the expected extinction due to bacterial grains at 3.4 μm would be only about 1 percent of their visual extinction. The requirement for an astronomical source to display this absorption unambiguously is the existence of a long path length through cosmic dust. But for most ordinary stars such long path lengths would also mean a flux at infrared wavelengths that would be attenuated so much as to become too weak to detect. A possible class of candidate star are M Supergiants which in many cases have enough infrared luminosity to be detected even at great distances.

By a stroke of pure luck a supergiant of this type, surrounded by a local dust-cloud that absorbed the stars' radiation and re-emitted at a temperature of ~1000 K, presented itself as an ideal candidate located near the galactic centre at a distance of about 10 kpc. A high resolution spectrum of this source was obtained by D.T. Wickramasinghe and D.A. Allen[10] and it revealed a flux curve that yielded an exceedingly close correspondence with the predictions of the bacterial model[11] over the 3.4 μm band as shown in the lower panel of Fig. 10. The great distance of this source ensured that we were essentially sampling the bulk of interstellar matter in the Galaxy. Serendipity the reader might think, but it surely could not have served us better for the purpose of verifying the predictions from our model.

Fig.10



Upper panel: laboratory spectra of dry microorganisms

Lower panel: comparison of GC-IRS7 data with bacterial model

An earlier result that was also confirmed by the data points in the lower panel of Fig. 10 was the absence of any significant amount of water-ice associated with the interstellar grains. Water-ice, if it occurred, would show up as an absorption feature near 3.1 μm. Since the absolute strength of water-ice absorption at this wavelength is some 50 times or more higher than the CH absorption strength at 3.4 μm, even small quantities of such ice would have shown up as a considerable effect in Fig. 10. The lack of such an effect is decisive proof that the organic particles in space are essentially dry.

If one is not almost totally blinded by prejudice the detailed correspondence displayed in Fig. 10 would be taken as clear evidence for our model. If instead one believes that the model is inherently implausible, then it would be necessary to brush aside an impressive agreement as a mere coincidence. The CH linkages in a variety of different organic structures within the grains must, through pure chance and chance alone, have contrived to produce an extinction profile identical to that of a dried-out bacterium. The number of alternative systems that could produce the same profile and yet be considered plausible candidates for the composition of dust in the galaxy would be highly restricted indeed. Our own efforts to find such alternatives from potentially abundant organic and inorganic materials have led persistent failure.

5. Nature of Cometary Dust

Until the dust of Halley's comet was explored using direct space probes in 1986 comets were generally considered to be relatively simple objects, and almost certainly comprised of material that was inorganic. Recent observations have disproved many of these basic beliefs, although the necessary readjustments of thinking still tend to be accommodated within the framework of an old model that is rapidly moving towards obsolescence. Because of the impact that this earlier model has had on astronomical thought over several decades we shall describe its essential components in the briefest way.

In this model the nucleus is considered to be an object some 5-10 kilometres in radius made up of an assortment of ices including frozen water, ammonia and carbon dioxide, with mineral particles resembling household dust immersed within it. Molecules evaporate as the surface becomes heated by the Sun, and the evaporated gases when they are vigorously boiled off near perihelion are thought to drag along the dust particles so as to form the comet's conspicuous dust tail. A serious difficulty with this model (usually attributed to Fred Whipple) is that gaseous molecules such as cyanogen (CN) are found in comets at great distances from the sun, distances at which evaporation of ices would not normally occur. This original difficulty was circumvented in subsequent modifications to the model where water molecules were considered to form a beehive-like matrix within the cells of which other small molecules and radicals are loosely trapped. When the comet approaches the sun the matrix is disrupted at the surface due to the effect of sunlight, thus releasing trapped molecules, dust grains and also particles of ice that break loose from the matrix.

The first evidence that might have lent support to this old model came in the early 1970s with the discovery of large amounts of hydrogen atoms and hydroxyl radicals around comets. Although this data may at first sight have been thought to indicate a water-ice source, it is clear that water is by no means the only source of hydrogen atoms and hydroxyl radicals. There many other equally plausible sources, notably a whole range of organic molecules. The only direct measurements of ionised water (H_2O^+) when they later became available showed only the presence of small amounts of this molecule, and searches for cometary ice particles at both radio and infrared wavelengths have consistently led to negative results. In particular recent searches for the 3.1 μm ice absorption band in the comae of comets Cernis, Bowell and IRAS-Araki-Alcock were all conspicuously negative, thus casting serious doubts on the premise of a water-ice matrix long before the recent Comet Halley data became available.

Serious problems for the standard comet model first began to surface with observations of Comet Kohoutek in late 1973 and early 1974. Although this comet was a visual disappointment to millions of comet spotters the world over, the deployment of space-age technology in various ways led to many important results. The first clearcut detection of organic molecules HCN (hydrogen cyanide) and CH_3CN (methyl cyanide) came from this comet as also a broad emission feature centred on a wavelength near 10 μm. The latter feature was found to weaken in strength and effectively disappear when the dust became heated to above 300°C, indicating that it did not arise from mineral dust which would certainly have survived temperatures in excess of 1000°C. In 1974 Professor V. Vanysek and the present auther[12] argued that this emission signature must arise from particles comprised of organic polymers, thus setting in train a shift in opinion from icy to organic comets, exactly parallel to the story for interstellar grains that we have already described. Our idea was that many of the observed cometary radicals, e.g. C_2,C_3, CN, CH, OH must be regarded as the natural break-up products of organic polymers in comets.

The first studies of the elemental composition of cometary dust were carried out using instruments aboard Vega 1. Dust grains impacting the spacecraft at some 70 km/s were mainly atomised and a mass spectrometer had been set up to measure the distribution of atomic weights of the constituent elements. Preliminary results from Vega 1 came as a total surprise. They showed the elements, C,N,O to be dominant with very little evidence of heavier atoms. The expectations of most astronomers were that Mg, Si and O would be found in large quantity as break-up products of mineral particles and ice grains, but this evidence was embarassingly lacking. The results from Giotto confirmed the conclusions derived from the Vaga experiment. The dust particles collected in Giotto's instruments were also made up mainly of the elements carbon, oxygen, nitrogen and hydrogen with only trace quantities of other elements being involved. It was also found that the average bulk densities of the particles were significatnly less than 1 gm per cc, implying hollow or porous particles probably occuring in the form of loose clumps. Combined with the fact that most of the dust was at a temperature above that at which ices and simple organics, including methane would have boiled off, one is left inescapably with the conclusion that the cometary dust was comprised of high molecular weight organic polymers. Studies of positive ions in the coma gas also showed evidence of organic molecules with high molecular weight. Moreover, the sizes and densities found for the dust particles make them uncannily similar to freeze-dried bacteria and viruses. Hydroxyl radicals and water molecules have also been discovered to be plentiful in the gases around the comet, but the amounts found are not any more than would be associated with biological material. Water makes up some sixty persent by volume of living cells, and this is consistent with what has in fact been found.

A few days after the Giotto encounter dramatic support for the organic-biological theory of comets came from an unexpected source. Infrared observations of Halley's comet were made by Dayal Wickramasinghe and David Allen[12] on three successive nights using the powerful 154 inch Anglo-Ausgtralian telescope at New South Wales in Australia. They detected strong signals due to emission from heated organic dust over the 2-4 μm wavelength range. As we have noted earlier, basic structures of organic molecules involving linkages between carbon and hydrogen atoms (CH bonds) absorb and emit radiation at wavelengths near 3.4 μm, and for any assembly of complex organic molecules such as a bacterium this absorption band is in general very broad and takes on a highly distinctive profile. The infrared signals observed from Halley's comet shown in Fig. 11 were found to be almost identical to the expected behaviour of dessicated bacteria heated to 320 K, and closely similar to the signature of interstellar bacterial particles shown in Fig. 10.

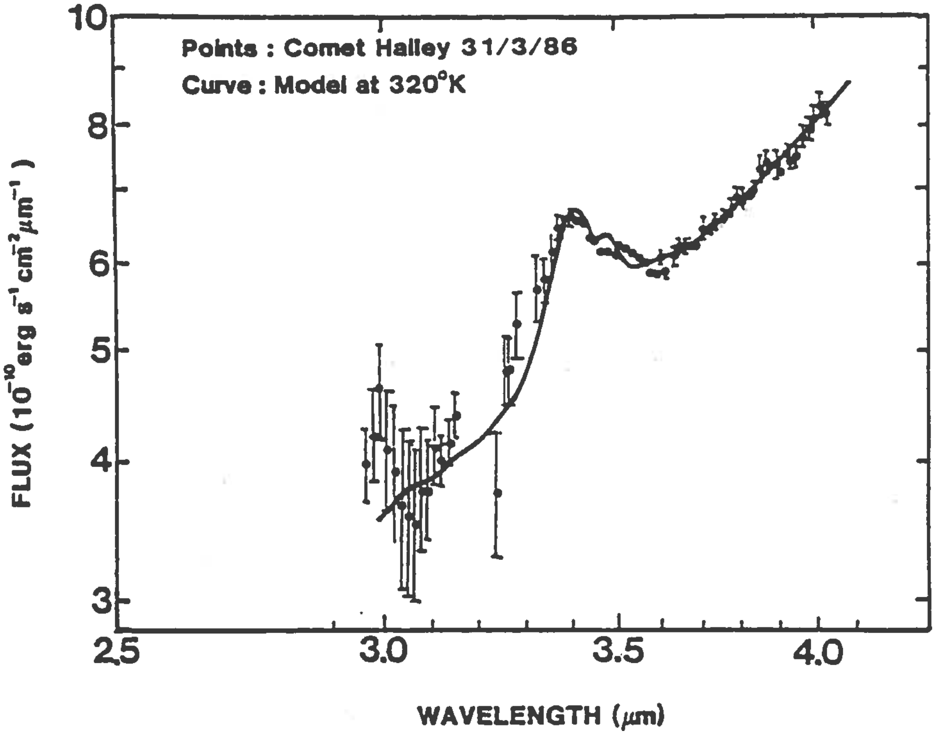


Fig.11

A fit of the cometary data in the 3-4 μm region with a bacterial grain model

The most startling conclusion to emerge from the 1986 observations of Halley's comet was that the previously-held view that comets are inorganic dirty snow balls must be abandoned. Although such conclusions are still being disputed as far as they possibly can the facts are cast-iron in quality and they have come to stay. Halley's comet, and by implication all comets, are organic in character. Finally, whether one likes it or not, the organic material of the comet occurs predominantly in the form of particles whose absorption properties at infrared wavelengths, sizes and densities are identical to the predictions of a bacterial model. The degree of perversity needed to ignore all these facts is in my view almost unimaginable.

6. From Comets to Interstellar Space

Comets are not likely to be a phenomenon that is confined to our solar system. Indeed to maintain such a point-of-view would be to revert to a distinctly pre-Copernican philosophy in relation to an evidently important class of celestial object that we find in our midst. Some four and a half billion years ago when the outer planets Uranus and Nepture were in the process of being accreted one could argue that cometary objects were much more plentiful than they seem to be in the present-day Oort Cloud. These outer planets themselves