# THE ULTRAVIOLET ABSORBANCE OF PRESUMABLY INTERSTELLAR BACTERIA AND RELATED MATTERS *

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**Abstract.** It is shown that the well-known 2200 Å peak in the extinction of starlight is explained by microorganisms. A mixed culture of diatoms and bacteria, which previously we found to give excellent fits to astronomical data in the infrared, has a peak absorption slightly shortward of 2200 Å, in very close agreement with the absorptions found in directions towards most early-type stars. The peak absorption is measured to be $\sim 35\,000$ cm$^2$ g$^{-1}$. This is in addition to a scattering component of the extinction which has an estimated value for dry microorganisms of $\sim 50\,000$ cm$^2$ g$^{-1}$. The scattering calculated for a size distribution of non-absorbing hollow bacteria with irregularities on the scale of 300 Å produces agreement with both the visual extinction law and the observed $\lambda^{-1}$ type extinction at the far ultraviolet. The contribution to the extinction from a pure scattering bacterial model is about 3.4 mag per kpc pathlength along the galactic plane at $\lambda = 2175$ Å. Absorption near this wavelength effectively adds $\sim 2.3$ mag per kpc, making up precisely the observed total extinction at the peak of 5.7 mag per kpc. The full range of the interstellar extinction observations is now elegantly explained on the basis of a bacterial model alone with no added components or free parameters to be fitted. Photolysis has little effect on the bulk refractive index of the particles and so does not change the scattering component appreciably. But photolysis due to sufficient UV in space can reduce the effectiveness of the 2200 Å absorption in comparison with the scattering, thereby decreasing the height of the absorption peak. An extreme example of this is the Large Magellanic Cloud, where UV emission from a profusion of early-type stars has reduced the absorbance of the particles to about one-quarter of its value for most of our galaxy. The 2200 Å absorption has generally been attributed to small graphite particles. We explain how this belief has come about and why in the past we have been swayed by it.

## 1. Laboratory Procedure

The object of our laboratory program was to determine the extinction properties of dessicated micro-organisms at ultraviolet wavelengths. For suspensions of bacteria in distilled water we had earlier found that the measured absorbance peaked at a wavelength close to 2050 Å. The fact that this wavelength was only about 150 Å short of the well-known interstellar absorption peak near 2200 Å led us to suspect that the true vacuum wavelength may have come to be displaced by this amount due to an interaction with ambient water. Because water is a polar liquid and ultraviolet absorptions in bacteria arise from polar chromophores, considerable wavelength shifts are indeed expected to occur. Thus water is a singularly poor choice of

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solvent for studying the wavelength positions of absorptions due to bacterial grains in space. For a non-polar liquid that would mimic a vacuum environment for bacteria, we chose 2-methylbutane (BDH product No. 29452), a liquid with an optical refractive index $n = 1.354$. A suspension of microbial cells is prepared by mixing 0.4–0.5 mg of dry cells in 15 ml of 2-methylbutane. The microorganisms are first ground using a clean mortar and pestle, and then drops of the solvent are added and ground together. More solvent is added and mixed thoroughly to make up a 15 ml quantity of suspension from which the sample cuvettes are to be filled.

If significantly more than 0.6 mg of dry micro-organisms were used in this way the suspension was found to become visually turbid due to excessive scattering by the dispersed particles.

Spectroscopic measurements were carried out using a Beckman Model 25 Double Beam Spectrophotometer which was balanced over the ultraviolet spectral region using quartz cuvettes filled with 2-methylbutane. The sample cuvette is then filled with the suspension under investigation, and the spectrum measured. For every measurement taken in this way we found it desirable to calibrate the instrument anew.

## 2. Results

The lowest curve in Figure 1 shows the absorbance spectrum measured for a blank run using two identical quartz cuvettes filled with 2-methylbutane. The absorbance is seen to be flat and nearly zero for $\lambda \cong 2100$ Å, whereas for $\lambda \leq 2100$ Å a jump occurs presumably due to a non-cancelled scattering effect at the quartz/liquid interface. In view of this discontinuity of slope and the consequent unreliability of our experimental technique, at shorter wavelengths we truncated all the spectra at a wavelength near $\lambda \approx 2100$ Å.

Figure 1 also shows our results for three cases: (a) *E. coli*, (b) diatoms, (c) a mixture of diatoms and bacteria in the ratio of $\sim$ 2:1. We note that in all cases the wavelength of the absorption peak is close to the astronomical extinction peak at $\lambda \approx 2175$ Å.

The most carefully determined mass estimate of 0.425 mg/15 ml was obtained for the case of *E. coli* shown in curve a of Figure 1. In this case a maximum absorbance of $A = 0.43$ was recorded, so that the optical depth through a 1 cm pathlength in the cuvette was $\tau = 2.302 \times 0.43 = 0.99$. If $\kappa$ is the mass extinction coefficient at 2200 Å and $\rho$ is the density of the sample in the cuvette

$$\kappa\rho = 0.99. \tag{1}$$

With $\rho = 2.83 \times 10^{-5}$ g cm$^{-3}$, we obtain an extinction coefficient

$$\kappa \cong 35\,000 \text{ cm}^2 \text{ g}^{-1}. \tag{2}$$

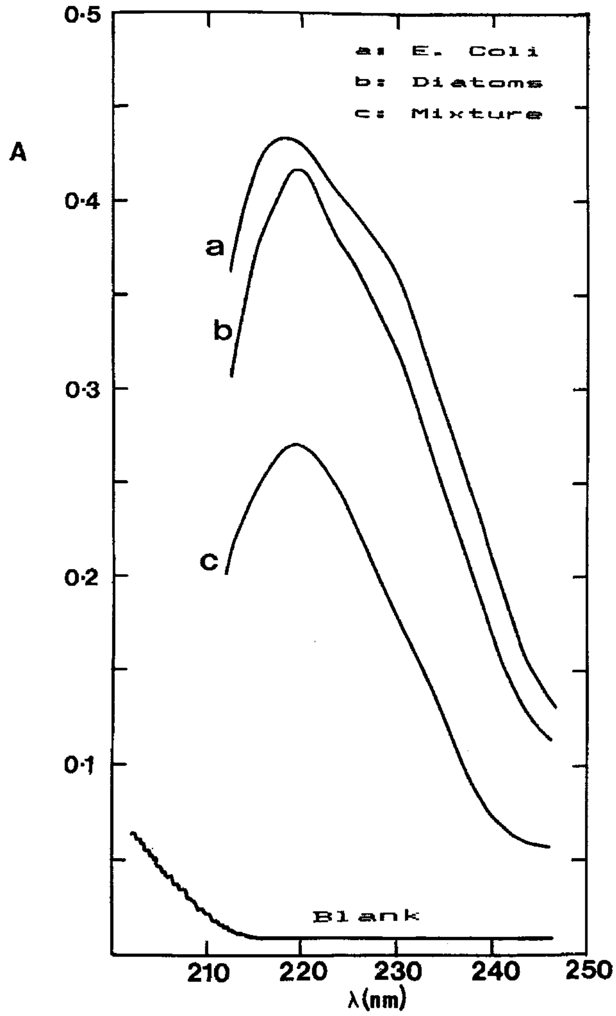



*Figure 1.* The absorbance spectrum of dry microorganisms in dimethylbutane. Curve (a) is for *E. coli*, (b) for diatoms, (c) for a mixture of (b) and (a) in the ratio 2:1. The lowest curve is for a blank run using two identical cuvettes filled with dimethylbutane. The mass of *E. coli* was measured accurately to correspond to 0.425 mg/15 ml.

This value strictly corresponds to both absorption and scattering. However, the refractive index of the suspended particle is close enough to that of the medium in which it is suspended so that scattering contributes only a small fraction to the measured effect at 2200 Å. We therefore take the mass absorption coefficient of *E. coli* and also of diatoms to be 35 000 $cm^2$ $g^{-1}$ at this wavelength.

We note from Figure 1 that the absorption profile is symmetrical near the peak, but tends to fall off a little more steeply on the shortwave side than on the longwave side. However, since our technique fails at a wavelength close to that at which we lose exact symmetry of the band, we consider that this effect is most probably spurious. To compare with observational data, we reflect the profile about the line defined by $\lambda = 2175$ Å, so as to obtain the shape of the spectrum down to $\lambda \cong 1950$ Å.* The curve in Figure 2 plots such a profile joined with experimental data obtained for longer wavelengths and normalised to give $\kappa = 35\,000$ cm$^2$ g$^{-1}$ at $\lambda = 2175$ Å.

## 3. Quantitative Determination of Amount of Absorption

In several earlier papers we have discussed the role of hollow bacterial grains in producing precise agreements with the interstellar extinction data at visual wavelengths (Hoyle and Wickramasinghe, 1979b, 1982; Jabir *et al.*, 1983). An example of such an agreement is shown in Figure 3. We have also shown that the observed scattering properties of grains over the wide waveband 0.3–9 $\mu$m$^{-1}$ could be satisfactorily explained by hollow grains of bacterial sizes combined with smaller spherical particles of an organic composition, the latter contributing to the scattering mainly in the far ultraviolet.

We now consider a more realistic scattering model comprised of hollow bacterial grains as before, but including also the effect of irregularities on the scale of macromolecular dimensions. A precise calculation of such a model goes beyond present techniques, so we consider here an approximate solution. If macromolecular irregularities of typical radius $a_o$ are distributed randomly within the shell of an evacuated hollow bacterium, their scattering effects in the far ultraviolet may be regarded, to a good approximation, as being uncorrelated within the grain. The total extinction cross-section of a grain of radius a at a wavelength $\lambda$ is then given by

$$\bar{C}_{\rm ext}(a, \lambda) = C^{(1)}_{\rm ext}(a, \lambda, \bar{m}) + nC^{(2)}_{\rm ext}(a_o, \lambda, m), \quad (3)$$

where $\bar{m}$ is the mean refractive index of the entire grain taken as 1.167, and $m$ is the refractive index of the organic matter comprising irregularities which are assumed to be spheres of radius $a_o$. $C^{(1)}_{\rm ext}$ and $C^{(2)}_{\rm ext}$ are the extinction cross-sections given by the Mie theory. The number $n$ refers to the effective number of irregularities in the grain.

A reasonable assumption would be that there are as many irregularities of scale radius $a_o$ as would effectively project onto a sphere of radius $a$. Thus we have

$$n = \frac{4\pi a^2}{\pi a_o^2} = 4(a/a_o)^2. \quad (4)$$

* We believe this procedure is justified both from general physical arguments and from our experimental results for *E. coli* suspended in distilled water which shows a symmetrical profile exactly as in Figure 2.

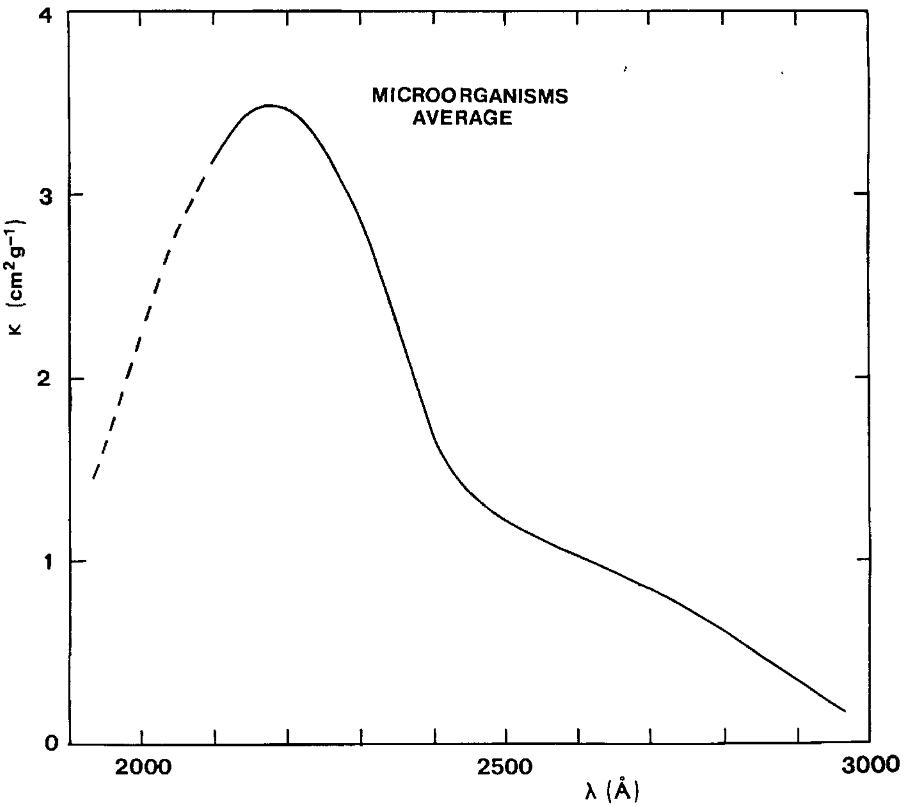



*Figure 2.* The extinction coefficient of a mixture of microorganisms. Direct laboratory measures for $\lambda > 2100$ Å are combined with an extrapolation for $\lambda < 2100$ Å involving reflection of the absorption profile about the central wavelength.

Adopting $a_o = 300$ Å as being a reasonable value, and $m = 1.5$, (3) can be written in terms of extinction efficiency factors $C^{(1)}_{\rm ext}$, $C^{(2)}_{\rm ext}$ as

$$\begin{aligned}\bar{C}_{\rm ext} &= Q^{(1)}_{\rm ext}(a, \lambda, \bar{m} = 1.167)\pi a^2 + 4(a/a_o)^2\, Q^{(2)}_{\rm ext}(a_o, \lambda, m = 1.5)\pi a_o^2 \\ &= [Q^{(1)}_{\rm ext}(a, \lambda, \bar{m} = 1.167) + 4Q^{(2)}_{\rm ext}(a_o, \lambda, m = 1.5)]\pi a^2.\end{aligned} \tag{5}$$

We can now use Equation (5) together with the Mie formulae to calculate the average extinction behaviour of a size distribution of bacterial grains in space. Thus we have

$$C_{\rm tot}\alpha \int_o^\infty N(a)\bar{C}_{\rm ext}(\lambda, a)da, \tag{6}$$

$N(a)da$ is the distribution function of grain radii. Using the empirically determined size distribution for spore-forming bacteria, we now compute the normalised extinction curve shown in Figure 4. The crosses are the average interstellar extinction values compiled by Sapar and Kuusik (1978).

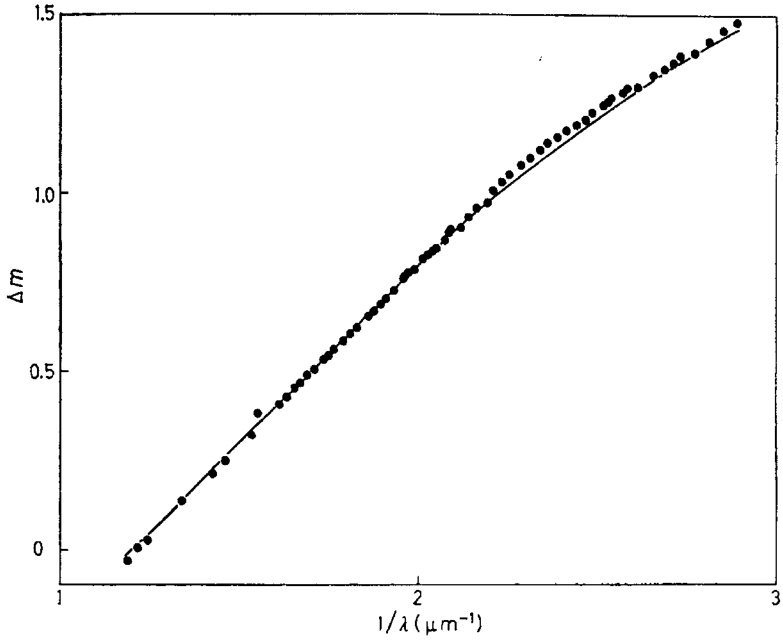



*Figure 3.* The extinction curve for non-absorbing, dessicated bacteria with a visual refractive index $n = 1.167$. The distribution of sizes used corresponds to laboratory distribution function of median sizes for a large number of spore-forming bacteria. The normalisation is to $\Delta m = 0.409$ at $\lambda^{-1} = 1.62\ \mu\mathrm{m}^{-1}$, $\Delta m = 0.726$ at $\lambda^{-1} = 1.94\ \mu\mathrm{m}^{-1}$. The points are observations of Nandy for Cygnus, similarly normalised.

Apart from the peak at $\lambda = 2175$ Å, the agreement for a pure bacterial model is found to be excellent, both in the visual spectral region as well as in the far ultraviolet. Over the intermediate waveband where a discrepancy exists, the difference shows up clearly in the enlarged display of Figure 5(a). The difference between the mean observations at $\lambda = 2175$ Å and our calculated curve for scattering by interstellar bacteria amounts to

$$\tau_{\mathrm{diff}} \cong 2.3 \text{ mag kpc}^{-1}. \tag{7}$$

Our laboratory measurements at 2175 Å gave a true extinction coefficient for bacteria in suspension, over and above a scattering background, of

$$\kappa_{\mathrm{diff}} \cong 35\,000 \text{ cm}^2 \text{ g}^{-1}. \tag{8}$$

The mass density $\rho_b$ of dry bacteria in space that would produce the observed excess of extinction above a notional scattering background is then given by the equation

$$\kappa_{\mathrm{diff}}\rho_b(3 \times 10^{21} \text{ cm}) = 2.3, \tag{9}$$

which yields

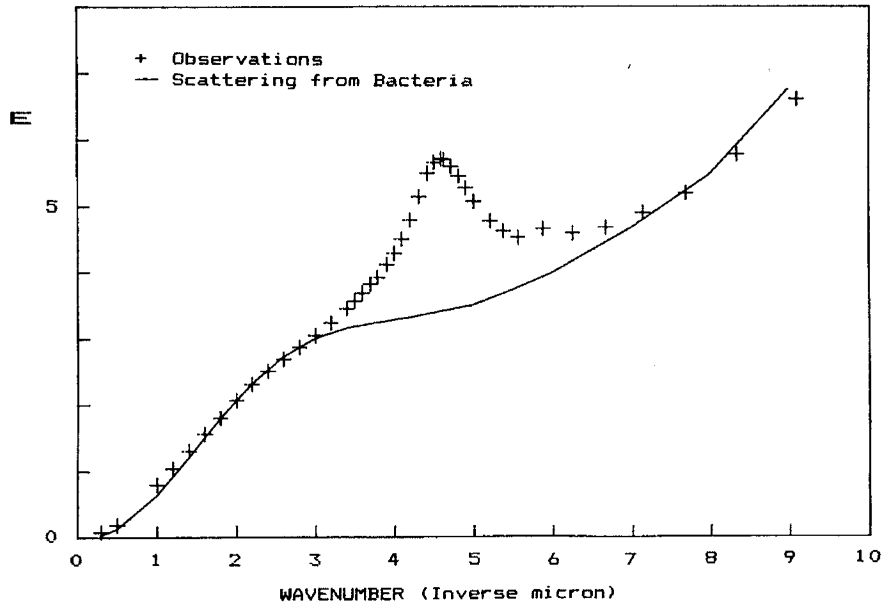



*Figure 4.* Theoretical extinction curve for bacteria assumed to be non-absorbing over the entire waveband shown here. The calculation takes account, in an approximate manner, of macromolecular irregularities on the radius scale of 0.03 $\mu$m. The normalisation is to $\Delta m = 1.8$ at $\lambda^{-1} = 1.8$ $\mu$m. The points are the average extinction data as compiled by Sapar and Kuusik (1978).

$$\rho_b = 2.2 \times 10^{-26} \text{ g cm}^{-3}. \tag{10}$$

This is almost precisely the mass density of dry bacteria that would produce the total visual extinction due to scattering alone of 1.8 mag kpc$^{-1}$ at $\lambda^{-1} = 1.8$ $\mu$m$^{-1}$. The wavelength dependence of the observed excess of interstellar extinction over the scattering background calculated from (6) is displayed as the points in Figure 5(b). The agreement is remarkably close, indicating that a bacterial model provides an essentially perfect agreement with the interstellar extinction law over the entire range of the available observational data.

## 4. The Curious Story of the Graphitic Misinterpretation of the 2200 Å Peak

It is interesting to see how the misinterpretation of the 2200 Å peak as arising from small graphite spheres with radii $\sim$ 0.02 $\mu$m came about. If one computes the absorption produced by such spheres according to Mie theory, there is no doubt that an absorption peak very like the observed astronomical peak can be obtained in special circumstances. Moreover, the mass absorption coefficient can be calculated to be remarkably large, $\sim$ 600 000 cm$^2$ g$^{-1}$ at 2200 Å, so that only a fraction of the interstellar grains (less than 10%) needs to be such graphite spheres in order

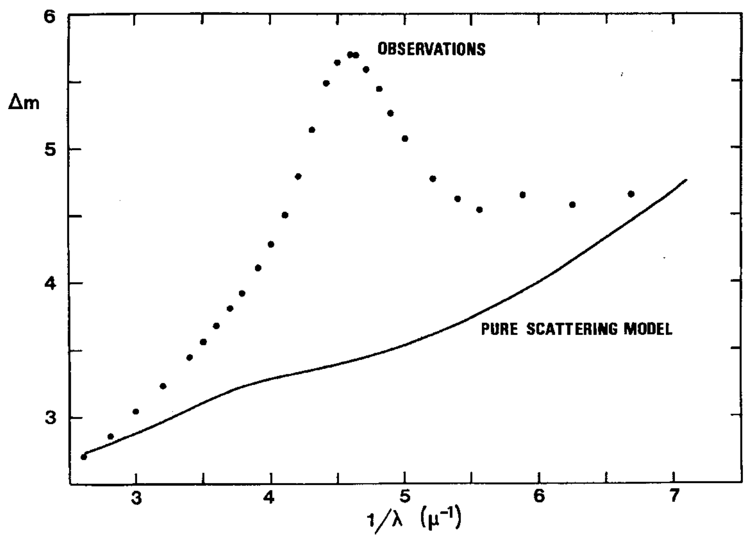



*Figure 5a.* A portion of Figure 4 enlarged to show excess astronomical extinction over and above scattering calculated for non-absorbing bacterial model.

to explain the amount of the observed absorption. So what is wrong with graphite spheres as an explanation of the 2200 feature?

Figure 6 shows the extinction coefficient $Q_{ext}(\lambda)$ for graphite spheres of radii 0.01 $\mu$m, 0.02 $\mu$m, 0.03 $\mu$m, and 0.04 $\mu$m. It will be seen that the peak value of $\lambda$ shifts as the wavelength increases, with $\lambda_{peak} = 2110$ Å for radius 0.01 $\mu$m, $\lambda_{peak} = 2190$ Å for radius 0.02 $\mu$m, $\lambda_{peak} = 2305$ Å for radius 0.03 $\mu$m, and $\lambda_{peak} = 2415$ Å for radius 0.04 $\mu$m. Since, taken from star to star, the observed absorptions actually have maxima consistently within the very small range $2175 \pm 20$ Å, the radii of graphite spheres can be permitted almost no spread about the value 0.02 $\mu$m. Only if a strong physical reason could be found for this particular radius alone would it be possible to feel comfortable with the graphite theory. No such reason having emerged, it was with a sense of unease that we suggested some years ago that the explanation of the 2200 Å peak might lie elsewhere. Indeed the composite absorption curve we then obtained from a mix of biomaterials, shown here as Figure 7, has turned out to be very like the absorption now measured for *E. coli* (Hoyle and Wickramasinghe, 1979a).

A rotating particle of irregular shape tends to behave with respect to the scattering of electromagnetic radiation like a non-rotating particle having the shape of the swept-out volume. Since a swept-out volume often has a less irregular shape than the rotating particle itself, the effect is usually to produce an averaging effect that tends to make particles act more like spheres than one might at first sight expect. Another circumstance tending to make one 'sphere-minded' is that long rods of circular cross-section scatter nearly as spheres of the same diameter. So a perception has become widespread that the Mie theory for spheres gives a satisfactory

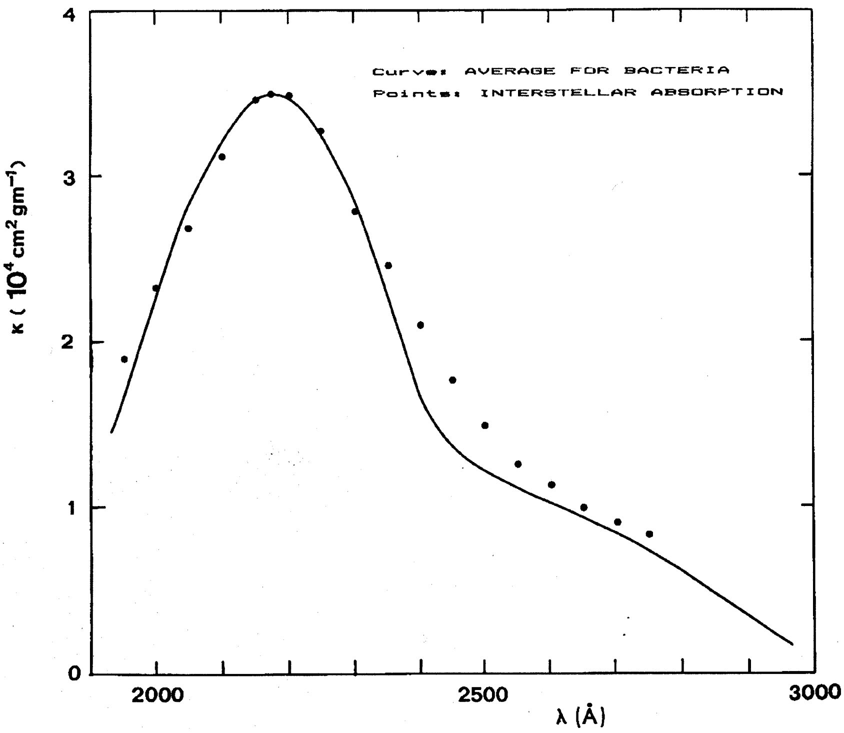



*Figure 5b.* The points are astronomical extinction excesses above pure scattering level as defined in Figure 5(a). The curve is the same as in Figure 2.

approximation even for particles that are non-spherical, provided equivalent sphere diameters for particles are approximately chosen, and provided equivalent sphere diameters are not large compared with $\lambda/\pi$ – otherwise an irregular particle behaves like a conglomerate of smaller particles, a situation we saw became important for microorganisms in the farther ultraviolet beyond the 2200 Å peak.

This is for scattering. The situation in most cases is much the same for absorption. The important exception is graphite (Gilra, 1972; Wickramasinghe and Nandy, 1974). If one calculates blindly from Mie theory, without examining the detailed physics of what goes on, it is easy to be misled into thinking that the very large absorption of 600 000 $cm^2$ $g^{-1}$ obtained for small graphite spheres arises from 'true' absorption. By 'true' absorption we mean the following. A plane electromagnetic wave of free-space wavelength $\lambda$ propagates in bulk material of refractive index $n(\lambda) - ik(\lambda)$ with a phase factor $\exp(-2\pi inx/\lambda)$, and with an attenuation factor $\exp(-2\pi kx/\lambda)$. Such an attenuation, determined by the complex part of the refractive index, is what we mean by true absorption. The absorption produced by microorganisms is 'true' in this broad sense. The situation for graphite spheres is otherwise, however, with the attenuation in bulk graphite being $\sim$ 40 000 $cm^2$ $g^{-1}$,

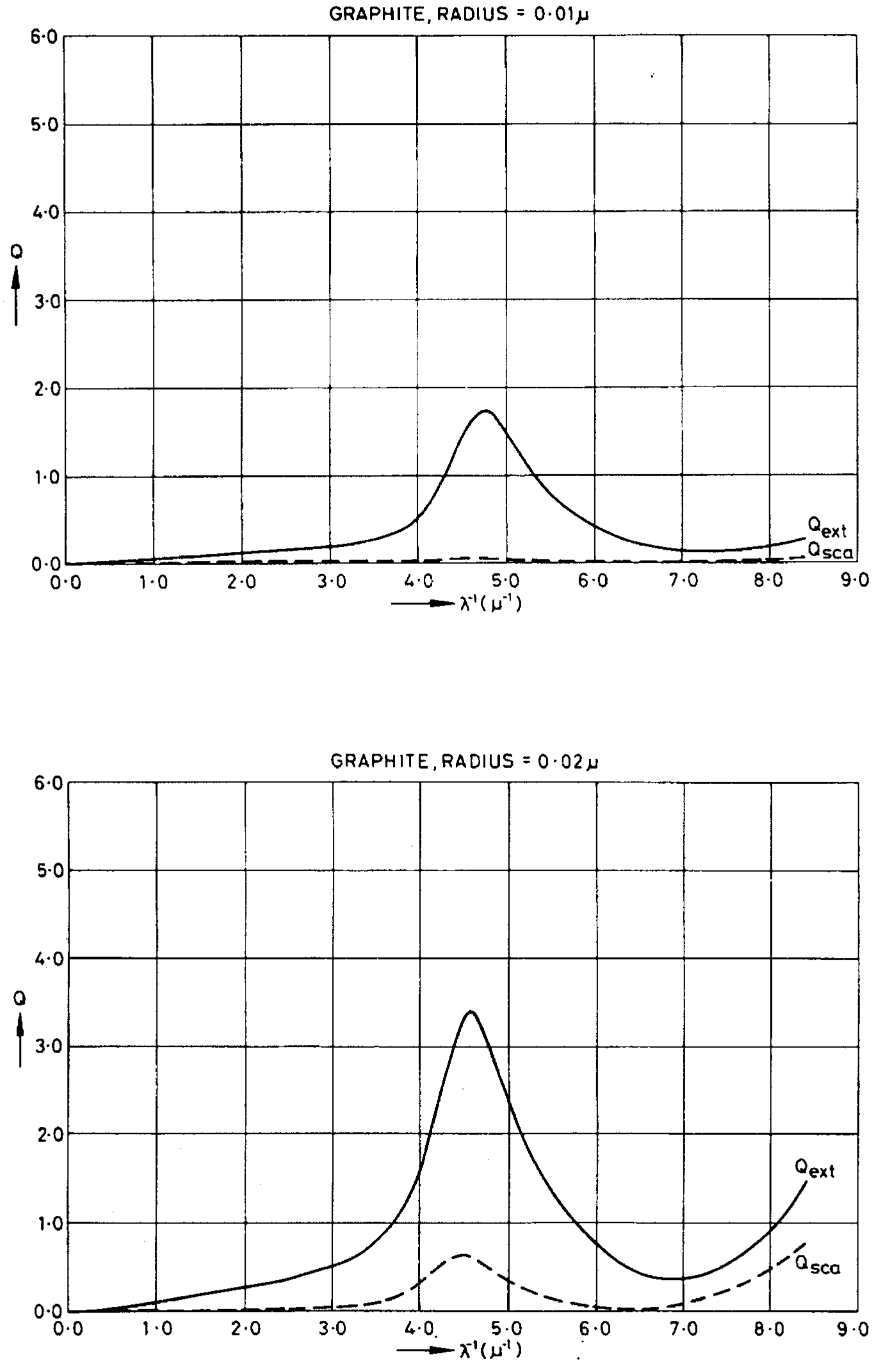
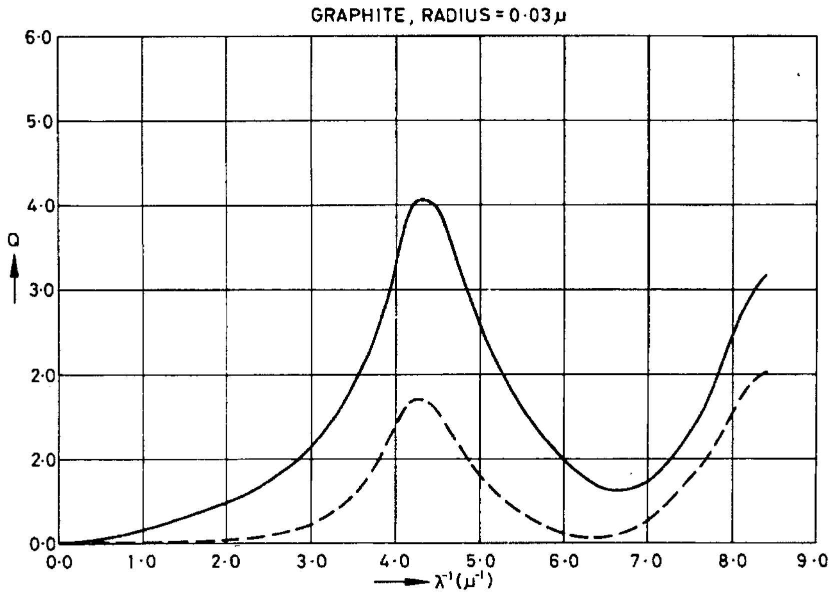



*Figure 6.* Extinction and scattering efficiency factors for graphite spheres of radii 0.01 $\mu$m, 0.02 $\mu$m, 0.03 $\mu$m and 0.04 $\mu$m.



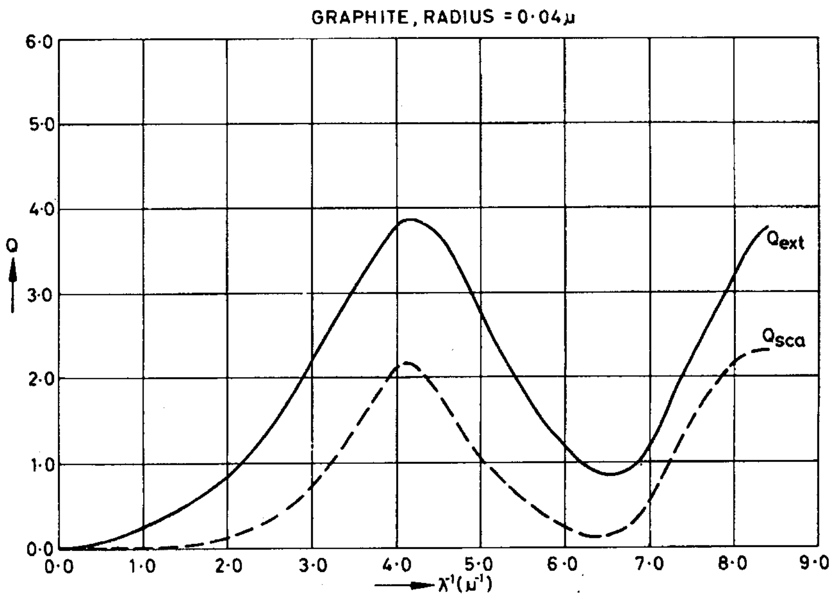




*Figure 6.* (continued)

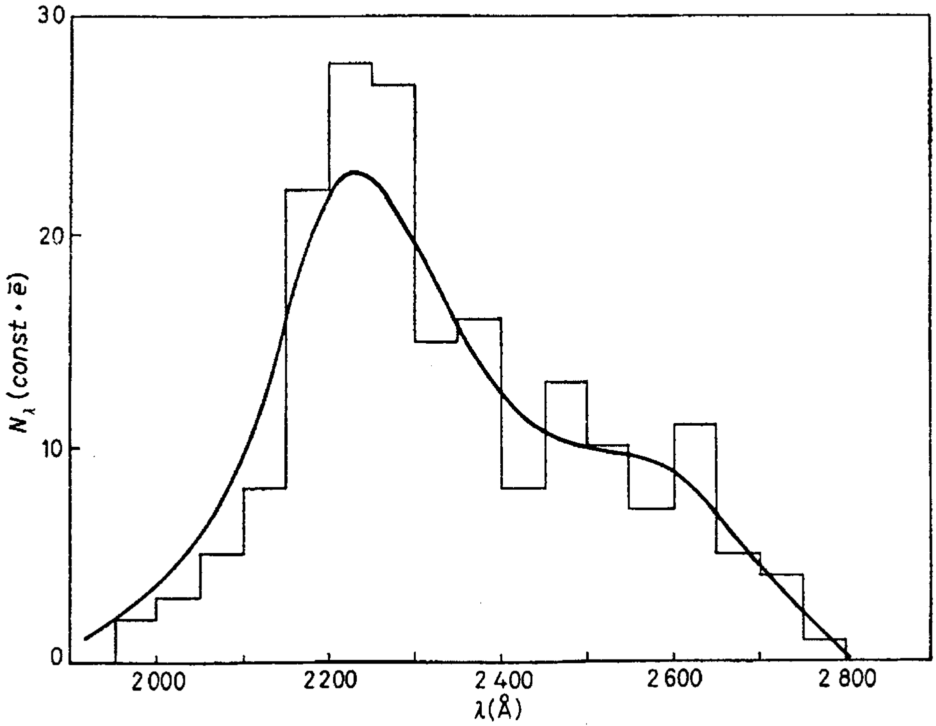



*Figure 7.* Histogram showing distribution of main absorption peaks for chromophores (see Table I) in 186 biomolecules. Solid curve is the computed average absorption curve due to this ensemble.

rather than the much larger $\sim$ 600 000 cm$^2$ g$^{-1}$ yielded by the Mie theory for small spheres. Where then does the difference arise?

A sphere of dielectric constant $K$ placed in a uniform electric field $E_o$ contains a uniform field $3E_o/(K+2)$, a result that appears as a trivial exercise in electrostatics. The internal field would become infinite if $K = -2$, a possibility not contemplated in electrostatics, however, because for static fields K is positive for all materials. But the situation can be different when the electromagnetic field is oscillatory, as may be seen from Figure 8, which gives $n(\lambda)$, $k(\lambda)$ for both iron and graphite. Remembering that the dielectric constant $K$ and the conductivity $\sigma$ are related to $n(\lambda)$, $k(\lambda)$ by

$$K = n^2 - k^2, \quad \sigma\lambda/c = nk, \tag{11}$$

it can be seen for graphite that $K = -2$ for $\lambda$ a little longward of 2000 Å, which is just where the Mie theory gives the exceptionally high absorptivity of small spheres.

From electrostatics one knows that the infinity of $3E_o/(K + 2)$ at $K = -2$ is a property only of spheres. A similar result is obtained for a right circular cylinder with its axis perpendicular to the external field, but with $K + 1$ in the denominator

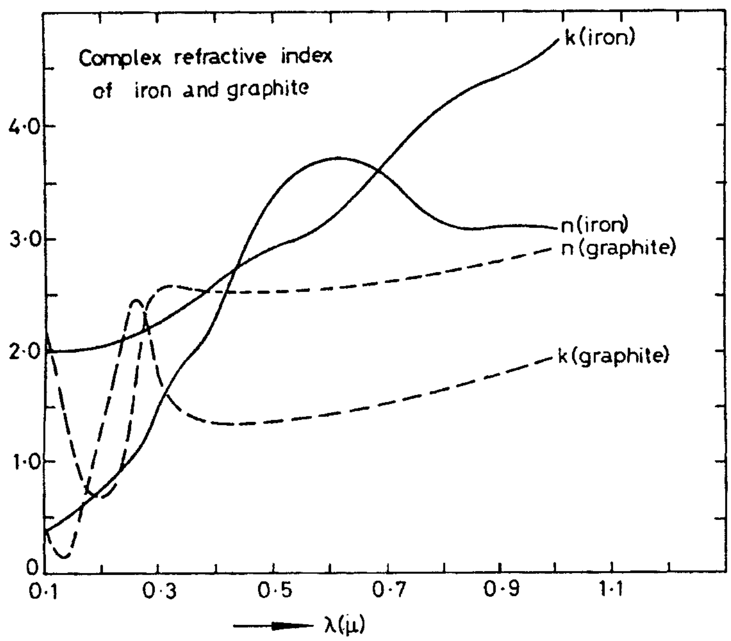



*Figure 8.* Laboratory measurements of optical constants for iron and graphite.

instead of $K + 2$. Thus for right circular cylinders of small diameter, one would have high absorptivity for graphite, but for $\lambda$ such that $K = -1$, which according to Figure 8 occurs shortward of 2000 Å. Also from electrostatics one knows that these infinities are artifacts of the shape of the material. In geometrical optics a paraboloidal mirror produces infinite focussing of a parallel beam – this is a similar artifact of shape that is soon destroyed when the shape of the mirror is distorted. So it is for small graphite spheres. Small graphite particles which are not spheres, which may differ only a little from spheres, lose the shape effect and the absorptivity not only falls by an order of magnitude but the central wavelength is no longer at $\lambda = 2200$ Å. Laboratory experiments on small graphite particles formed under laboratory conditions, consistently produce a peak displaced from this wavelength and significantly broader (Day and Huffman, 1973; Huffman, 1976).

The essential requirements of the graphite theory are therefore dual. To a high degree of approximation graphite grains must be spheres, and the spheres must all have effectively the same radius, 0.02 $\mu$m. One could reasonably be sceptical of either of these requirements. Taken together, they seem just too much to swallow.

## 5. The End of a Controversy

We were led to consider the hypothesis that interstellar grains are microorganisms through attempts to understand the extinction of starlight in the visual spectrum, a problem which can be carried to a high level of quantitative precision. After much effort it became apparent that the real part of the refractive index of interstellar grains had to be so low at visual wavelengths that the grains must be hollow, as indeed dry microorganisms are. When we also noticed that the size distribution of bacteria agreed closely with what we know the size distribution of the interstellar grains must be (sphere diameters or rod diameters mostly in the range from 0.5 $\mu$m to 1 $\mu$m) an explicit parameter-free calculation suggested itself. Take the known size distribution of bacteria, together with the known volume-averaged refractive index of dried bacteria, and compute what visual extinction such a system of small hollow particles would give. The outcome as in Figure 3 was a result very close indeed to the observed astronomical situation, a considerably better result than we had obtained otherwise in ten years.

The natural impulse on first hearing the hypothesis that interstellar grains are bacteria is to reject it immediately as ‘obviously absurd’. But why is it obviously absurd? Nobody is born with *a priori* knowledge of what interstellar grains are, or what they are not. The only valid way to find out is to examine the facts, which is what we have done from the outset.

Unfortunately for critics, it was all too easy to rely on the apparent absurdity of our hypothesis. By leaning on prejudice it seemed that victory could be won by no effort at all, whereas any critic competent enough to have repeated even our first calculation should have realised there was no hope at all of refuting the hypothesis. Wrong theories do not fit a quite substantial body of facts unless they contain many adjustable parameters, whereas our hypothesis fitted the many facts without any disposable parameter at all, and it went on doing so as new facts were discovered, in one notable case predicting what the facts would be ahead of their discovery (Hoyle *et al.*, 1982). The clear inference was that although the hypothesis might be ‘obviously absurd’ it was correct. This is now demonstrable beyond doubt, since any tolerably equipped physics laboratory anywhere in the world will be able to verify that the properties of dry microorganisms (including diatoms) fit a very large amount of astronomical data over an extensive wavelength range going from 13 $\mu$m in the infrared down to 1100 Å in the ultraviolet. There are many physics laboratories in the world and it is inconceivable that prejudice will prevent all of them from doing straightforward experiments whose consequences are wide and which will undoubtedly be profitable from the point of view of further research cutting across many disciplines.

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