ON THE NATURE OF INTERSTELLAR GRAINS *

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Abstract. Data on interstellar extinction are interpreted to imply an identification of interstellar grains with naturally freeze-dried bacteria and algae. The total mass of such bacterial and algal cells in the galaxy is enormous, $\sim 10^{40}$ g. The identification is based on Mie scattering calculations for an experimentally determined size distribution of bacteria. Agreement between our model calculations and astronomical data is remarkably precise over the wavelength intervals $1\ \mu^{-1} < \lambda^{-1} < 1.94\ \mu^{-1}$ and $2.5\ \mu^{-1} < \lambda^{-1} < 3.0\ \mu^{-1}$. Over the more restricted waveband $4\,000$–$5\,000$ Å an excess interstellar absorption is found which is in uncannily close agreement with the absorption properties of phytoplankton pigments. The strongest of the diffuse interstellar bands are provisionally assigned to carotenoid-chlorophyll pigment complexes such as exist in algae and pigmented bacteria. The $\lambda 2\,200$ Å interstellar absorption feature could be due to 'degraded' cellulose strands which form spherical graphitic particles, but could equally well be due to protein-lipid-nucleic acid complexes in bacteria and viruses. Interstellar extinction at wavelengths $\lambda < 1800$ Å could be due to scattering by virus particles.

Ever since the existence of interstellar grains was first recognized over half a century ago, astronomers have striven unceasingly to understand their properties – sizes, shapes and composition – and how they might be formed. These questions have assumed a growing importance over the past decade mainly from a conviction that grains play a crucial role in controlling many astrophysical processes. A vigorous effort on the part of many astronomers has led to a welter of new observational data, to much theorizing and heated controversy, but little in the way of agreement or understanding. The nature of interstellar grains remains to this day a major unsolved problem in astronomy (see, for example, Hoyle and Wickramasinghe, 1962; Wickramasinghe, 1967; Martin, 1978).

The wavelength dependence of interstellar extinction is perhaps the most direct observational test of interstellar grain models. The observed interstellar extinction at visual wavelengths has an average value of ~ 2 mag kpc^{-1} in directions close to the plane of the galaxy. This datum combined with other scattering and polarization observations leads to the result that grains are strongly dielectric, with radii $\sim 10^{-5}$ cm, and that they make up a few percent by mass of all interstellar matter. With an overall composition of interstellar matter similar to the composition of the Sun's outer layers, we thus find that a significant fraction of all C, N, O atoms in interstellar clouds is in the form of grains. About 10^{40} g of interstellar grains exist throughout the galaxy. Since the typical turnover time of interstellar matter into stars is $\sim 10^{9}$ yr, grains must be re-supplied at an average rate of $\sim 10^{31}$ g yr^{-1}.

The requirement that $\sim 3\%$ by mass of the interstellar material is in the form of dielectric grains imposes stringent constraints on the composition of grains. Cosmic abundances of Mg and Si are too low by a factor of ~ 5 for the bulk of grains causing visual extinction to be in the form of either silicates or metallic oxides. Graphite particles, which are electrically conducting for electric vector parallel to the basal planes, cannot make up more than $\sim 10\%$ of the mass density of grains so as to be consistent with data on the diffuse galactic light and interstellar polarization – both observations requiring predominantly dielectric grains.

A wide range of materials involving the abundant CNO elements in various combinations with H remains in the field of possible grain compositions. There are two distinct types of such material that we shall need to consider: icy inorganic grains, made up mainly of H_2O, and organic grains which are made up of a mixture of organic molecules and/or biochemicals. Grains comprised of H_2O ice do not seem able to fit the astronomical data. For a size distribution of ice grains that result from growth and destruction processes of the type considered by van de Hulst (1949), model calculations of interstellar extinction are at variance with astronomical observations in the waveband $1 \, \mu^{-1} \leq \lambda^{-1} \leq 3 \, \mu^{-1}$. The curve in Figure 1 (van de Hulst No. 1) is the calculated curve for such a distribution of ice spheres with a size parameter $r_1 = 0.34 \, \mu$. The theoretical extinction curve is normalized to $\Delta m = 0.409$ at $\lambda^{-1} = 1.62 \, \mu^{-1}$, $\Delta m = 0.726$ at $\lambda^{-1} = 1.94 \, \mu^{-1}$, to correspond with Nandy's (1964) observations for the Cygnus region. The disagreement shown in Figure 1 is endemic to all pure ice grain models. Although a smaller value of the size parameter r_1 could produce a higher value of the relative extinction at $\lambda^{-1} = 3 \, \mu^{-1}$ (see Figure 1), the extinction curve then departs markedly from the observed $1/\lambda$ law in the waveband $1 \, \mu^{-1} < \lambda^{-1} < 2 \, \mu^{-1}$. Attempts to rectify this defect have involved arbitrarily adding an absorptive component, $k \cong 0.1$, to the complex refractive index ($m = n - ik$) of ice, and attributing this absorption to the effect of metal-ion impurities. Alternatively, composition grains with graphite or metal cores and ice mantles could help to remedy the mismatch illustrated in Figure 1 (Wickramasinghe, 1967). The arbitrary nature of these refinements, in our view, makes this model unsatisfactory. Moreover, recent data on galactic infrared sources show that grains causing both emission and absorption must persist at temperatures well above 400 K, thus ruling out a volatile icy composition for these grains. Organic polymers have distinct advantages over ices for the main constituents of interstellar grains. Under astrophysical conditions organic polymers would be expected to persist up to temperature of ~ 900 K, and polymers with infrared absorption properties similar to cellulose could be shown to account for all the observed features of galactic infrared sources (Hoyle and Wickramasinghe, 1977a,b). While it is true that many organic polymers have absorption bands at 3, 3.4, 10 and 18 μ, similar to cellulose (Wickramasinghe *et al.*, 1977; Sagan and Khare, 1979), a proper consideration of the detailed shapes of these bands as well as the slopes of the underlying absorption continua outside these bands point strongly – we think uniquely – to cellulose, or to some very closely related polymer.
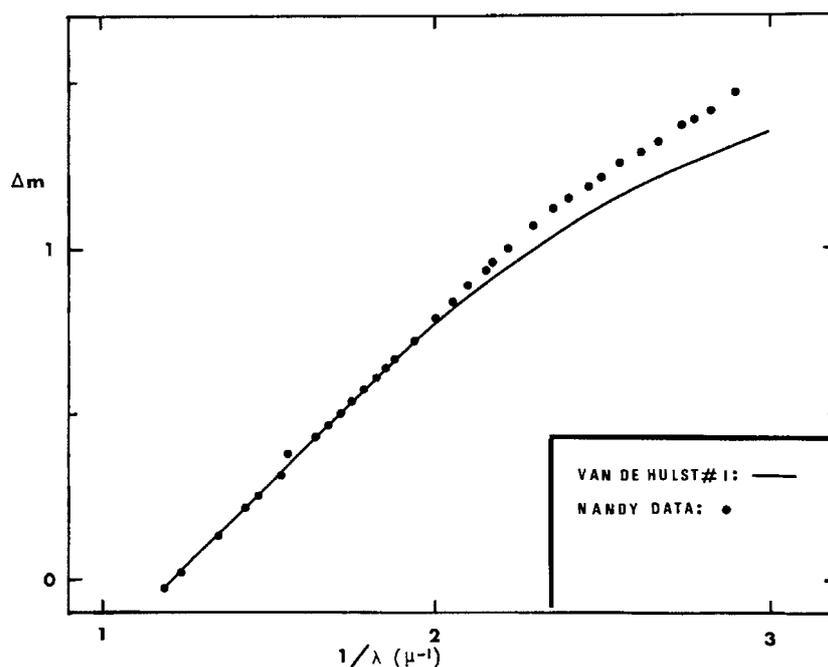
Figure 1. Points represent Nandy's (1964) extinction data for stars in the Cygnus direction. Curve is the normalized extinction calculated for a size distribution of ice spheres of refractive index $n = 1.33$, The distribution function is van de Hulst's (1949) distribution (1) with a size parameter $r_1 = 0.34\ \mu$. Normalization is to $\Delta m = 0.409$ at $\lambda^{-1} = 1.62\ \mu^{-1}$; $\Delta m = 0.726$ at $\lambda^{-1} = 1.94\ \mu^{-1}$.

Duley and Williams, (1979) have recently claimed that the non-detection of a 3.3–3.4 μ band in the extinction curves of stars militates against the dominance of organic molecules in grains. Their argument is unreliable, however. For early-type stars, such as those used for interstellar extinction studies, the stellar continuum in the 3.3–3.5 μ waveband is a Rayleigh-Jeans spectrum $\propto \lambda^{-4}\ d\lambda$. The stellar flux at 3.5 μ is therefore 0.26 mag fainter than at 3.3 μ. Against such a steeply falling spectrum it would clearly be futile to look for any 3.4 μ band due to organic molecules which had a band centre absorption of much less than 0.2 mag. Where a differencing technique is used for pairs of stars, a likely contribution due to circumstellar infrared emission would further complicate matters.

We have argued elsewhere that cellulose-like polymers – or at least their backbone structure – could form abiogenically in mass flows from stars (Hoyle and Wickramasinghe, 1977c). Such a non-thermodynamic mass-flow chemistry would lead to the production of one main polymer type by a logic that is strikingly similar to biology. A more powerful and inevitable logic for producing a wide range of biochemicals, is, of course, to be found in biology itself. Living systems can replicate whole ensembles of complex molecular structures.

A photosynthetic bacterium of typical mass $\sim 10^{-12}$ g supplied only with H_2O, CO_2, visual light plus a few inorganic nutrients might, under terrestrial conditions, replicate in about one hour. The number of bacterial replications required to convert 10^{40} g of CNO nutrients into bacteria is $\sim$ 173. Thus, in situations that are not nutrient or energy limited, the total mass of interstellar grains in the galaxy could be produced in about seven days. One week is thus the *integrated* time over which replicative biology needs to operate in order to supply a mass of bacteria equal to the mass of interstellar grains. The actual timescale needed for replenishing a total bacterial mass of $\sim 10^{40}$ g would, of course, be very much longer. On individual sites where replication is feasible – such as in dense protostellar shells, planetary surfaces and in cometary interiors – growth of the bacterial mass will be restricted by the availability of nutrients. However, the circumstance that bacterial cells escaping from a stellar-planetary system can be propelled by radiation pressure of starlight to the next nearest similar system leads to the possibility of galaxy-wide regeneration of bacteria in a manner not too dissimilar to that envisaged by Arrhenius (1909). Arrhenius's arguments concerning the low-temperature resistance of spores could be combined with more recent data concerning the effects of ionizing radiation on bacterial or algal cells. Significant transfers of cells from one planetary abode to another would occur in timescale $< 10^6$ yr. A slow flux of soft X-rays over such a length of time would produce a large-scale massacre of cells, but there would nevertheless be a non-negligible viability of cells that are transferred from one galactic abode to another. Even a minute number of surviving, radiation resistant strains, would quickly become amplified by astronomically large factors until available nutrients are exhausted. On a timescale that is essentially determined by the mean access time of interstellar matter to appropriate 'abode' conditions (protostellar, cometary or planetary environments) a large fraction of all the CNO elements in the galaxy would be turned into bacterial cells. We estimate that an efficient gas to bacteria conversion occurs over a typical turnover time for star formation $\sim 10^9$ yr.

Encouraged by the strength and inevitability of this logic, we now turn to astronomical data in search of evidence for interstellar bacteria. We first note that bacteria possess the requisite dielectric properties and have a range of sizes and shapes that already provide a *prima facie* case for considering their candidature as interstellar grains. Spore-forming bacteria on the Earth could be either spherical or rod-shaped with a distribution function of radii that we deduce from microbiological literature to be well represented by the histogram in Figure 2. The non-aqueous component of vegetative bacteria and algae has a bulk refractive index at $\lambda 5\,000$ Å that we estimate to be $n \cong 1.5$. Expulsion of such cells into space conditions would in general lead to freeze-drying with the consequent evaporation of unbound water. Evaporation of water would lead to microporosity and to a lowering of the mass density of the particle as well as of the quantity $|m - 1|$.

In the argument that follows we assume that a large fraction (some 80% or more) of the interstellar carbon is tied up in the form of bacteria. The evaporation of water
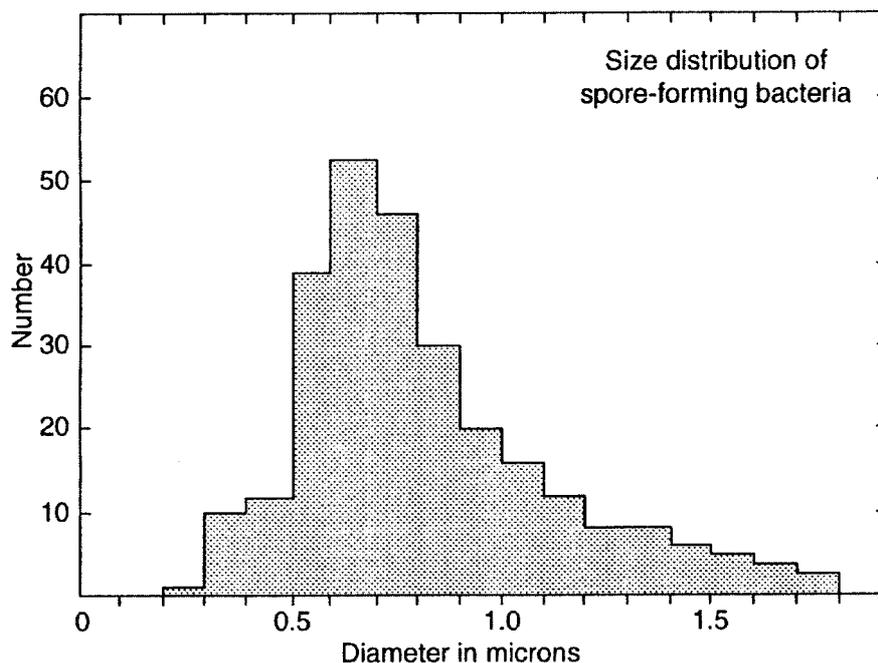
Figure 2. Size distribution of endospore-forming bacteria estimated from tabulated microbiological data (Buchanan and Gibbons, 1974). When a given diameter range for a particular bacterium spanned an interval greater than 0.1 μ (e.g. 0.7–0.9 μ) it was assumed that bacteria were found with equal probability per radius interval throughout this range.

from bacteria occurring under interstellar conditions would be constrained by the requirement that an overall value of O/C within individual bacteria is maintained close to the cosmic value ~ 2. For this requirement to be satisfied we find that the average volumes of water and of biological material in cells must be nearly equal. Since the initial volume distribution in vegetative cells must have been 80% water and 20% biological material, the evacuation of water would amount to 75% of the total present in vegetative cells. With cells that have rigid walls such water loss results in internal porosity. Thus a freeze-dried cell in interstellar space is made up of three volume components with different refractive indices: 20% in the form of biological material with $n = 1.5$, 20% in the form of water-ice with $n = 1.3$ and 60% in the form of vacuum with $n = 1$. The average volume-weighted refractive index is therefore:

$$\bar{n} = 0.2 \times 1.5 + 0.2 \times 1.3 + 0.6 \times 1.0 = 1.16. \tag{1}$$

For bacteria freeze-dried under interstellar conditions we shall assume an overall refractive index close to $\bar{n} = 1.16$, with a probable range $\bar{n} = 1.15 - 1.17$. We now proceed to calculate the theoretical extinction curve for spheres of refractive index in this range and with a diameter distribution as prescribed by Figure 2. Since

$\bar{n} - 1$ is less than unity we consider it a good approximation to use the asymptotic formula

$$Q_{\text{ext}} = 2 - \frac{4}{\rho} \sin \rho + \frac{4}{\rho^2} (1 - \cos \rho), \qquad (2)$$

with $\rho = 4\pi a(\bar{n} - 1)/\lambda$, where a is the radius of the bacterium and λ is the wavelength (van de Hulst, 1957). An average extinction efficiency was calculated from

$$\bar{Q}(\lambda) = \int \pi a^2 N(a) \left[2 - \frac{4 \sin \rho}{\rho} + \frac{4(1 - \cos \rho)}{\rho^2} \right] da, \qquad (3)$$

with $N(a)\, da$ taken from the histogram of bacterial diameters in Figure 2, and for various values of $\bar{n}$ in the range 1.17–1.15. A normalized extinction efficiency was then obtained as

$$\Delta m = A + B \bar{Q}(\lambda) \qquad (4)$$

with the coefficients A and B so chosen as to give $\Delta m = 0.409$ at $\lambda^{-1} = 1.6\ \mu^{-1}$ and $\Delta m = 0.726$ at $\lambda^{-1} = 1.94\ \mu^{-1}$.

The best agreement with Nandy's data for stars in the Cygnus direction was obtained for the case $\bar{n} = 1.163$, remarkably close to the value we calculated above (see Equation (1)). The theoretical $\Delta m(\lambda)$ values for this case are tabulated in Table I and plotted together with Nandy's (1964) astronomical data in Figure 3.

The fit shown here over the wavebands $1\ \mu^{-1} < \lambda^{-1} < 1.95\ \mu^{-1}$, $2.5\ \mu^{-1} < \lambda^{-1} < 3\ \mu^{-1}$ is superior to that found previously for any *pure* dielectric grain model. The close agreement with observations follows quite naturally from the actual size distribution of bacteria which is used (which approximates closely to $N(a) \propto a^{-3}$, $a > 0.35\ \mu$) and the lowered refractive index of bacteria caused by dehydration. There is no arbitrariness in the model and essentially no free parameters whatsoever. A slight variability of n in the range 1.15–1.17 in the galaxy could lead to a variability in the extinction curve such as is found in several different galactic regions (Nandy, 1965). We propose to investigate the effect of nonsphericity of grains (bacteria are often rod-shaped, with diameters distributed as in Figure 2), as well as the role of non-uniform porosity caused by freeze-drying. Our preliminary results show these to be negligible effects with regard to the properties we consider here.

Over the waveband $1.95\ \mu^{-1} \leq \lambda^{-1} \leq 2.5\ \mu^{-1}$ the observed interstellar extinction curve shows a sharp discontinuity of slope at $\lambda^{-1} = 2.3\ \mu^{-1}$ (Nandy, 1964, 1965; Harris, 1969). It has been realized for over a decade that this feature cannot be explained with Mie scattering curves for simple materials such as ices, silicates or graphite. The same result is clearly true for the scattering curve calculated here for bacteria. The observational points over the waveband $1.95\ \mu^{-1} \leq \lambda^{-1} \leq 2.5\ \mu^{-1}$ are seen in Figure 3 to lie slightly above our calculated extinction curve.

TABLE I

Normalized extinction values for an empirically
determined size distribution of bacteria. The ef-
fect of dehydration due to natural freeze-drying
is taken into account by a lowered refractive
index $n = 1.163$

$\lambda^{-1}(\mu^{-1})$	Δm	$\lambda^{-1}(\mu^{-1})$	Δm
1.19	–0.019	2.06	0.838
1.22	+0.010	2.08	0.856
1.25	0.038	2.09	0.865
1.35	0.147	2.10	0.874
1.43	0.217	2.12	0.892
1.47	0.257	2.15	0.919
1.54	0.328	2.17	0.936
1.56	0.348	2.2	0.962
1.62	0.409	2.22	0.979
1.64	0.429	2.25	1.004
1.66	0.449	2.26	1.012
1.67	0.460	2.30	1.044
1.70	0.490	2.32	1.06
1.71	0.500	2.35	1.084
1.74	0.530	2.37	1.099
1.75	0.540	2.40	1.122
1.76	0.550	2.41	1.130
1.77	0.560	2.44	1.152
1.79	0.580	2.46	1.166
1.80	0.590	2.48	1.180
1.82	0.609	2.50	1.194
1.83	0.619	2.53	1.215
1.87	0.658	2.54	1.221
1.88	0.668	2.55	1.228
1.90	0.688	2.59	1.254
1.92	0.707	2.60	1.261
1.94	0.726	2.62	1.273
1.97	0.754	2.67	1.303
1.98	0.764	2.70	1.321
1.99	0.773	2.72	1.332
2.00	0.783	2.74	1.343
2.02	0.801	2.78	1.365
2.03	0.811	2.82	1.385
2.04	0.820	2.86	1.405
2.05	0.829	2.90	1.423
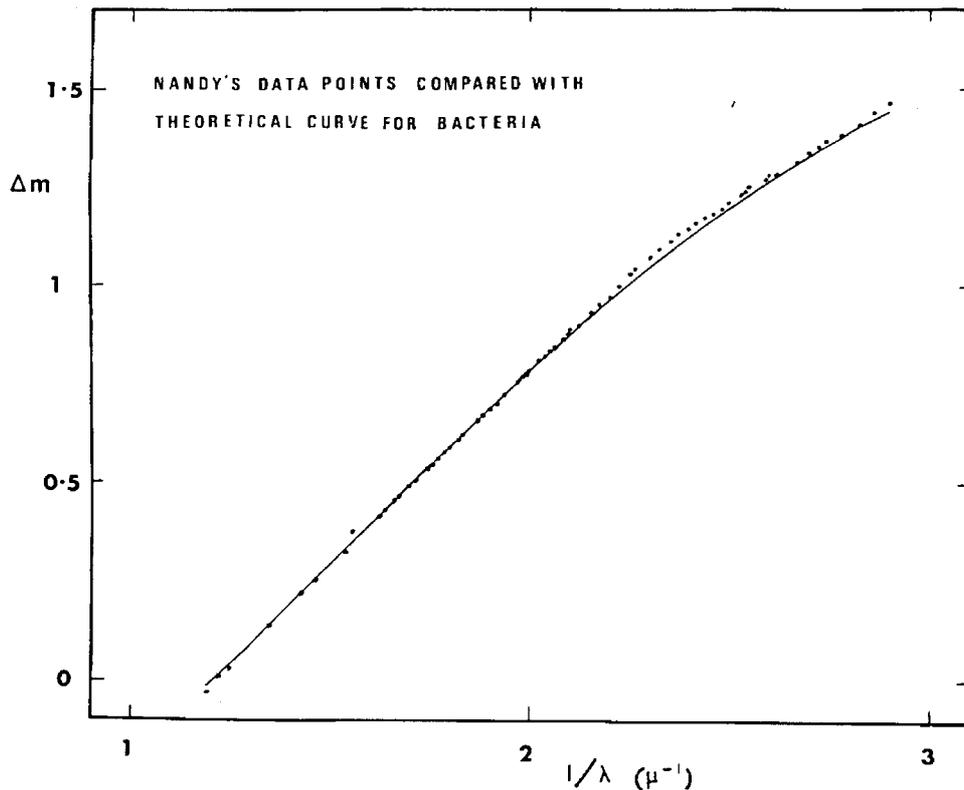
Figure 3. Calculated extinction curve for size distribution of bacteria prescribed by the histogram in Figure 2. The average refractive index of dehydrated bacterial material is taken as $n = 1.163$. Normalisation is to $\Delta m = 0.409$ at $\lambda^{-1} = 1.62$ μ^{-1}; $\Delta m = 0.726$ at $\lambda^{-1} = 1.94$ μ^{-1}. Points are the mean extinction data of Nandy (1964) for the Cygnus region.

An absorption band centred on the wavelength $\lambda 4\,350$ Å possessing a width of ~ 800 Å would be required to be superposed upon a smooth extinction curve that arises primarily due to scattering. Inorganic candidates have been sought, for instance, involving colour centre effects (Nandy *et al.*, 1968) but no specific transitions have been found. Spectra of organic molecules are known to have absorption bands in the visual and ultraviolet spectral regions (Scott, 1964). However, it would seem that individual organic molecules, particularly if they are simple, inevitably produce bands which are too narrow and which have an unwanted amount of fine structure. To seek an ensemble of such molecules whose spectra might average to produce the observed extinction excess would also be unprofitable. Such an arbitrarily chosen ensemble would almost certainly be irreproducible over any wide range of astronomical conditions. In an attempt to find a naturally reproducible ensemble of organics we are led again to consider biological systems. We found that a ready-made composite absorption band peaking at $\lambda^{-1} = 2.3$ μ^{-1} and with the correct width occurred in the pigments of phytoplankton (Figures 4 and 5)
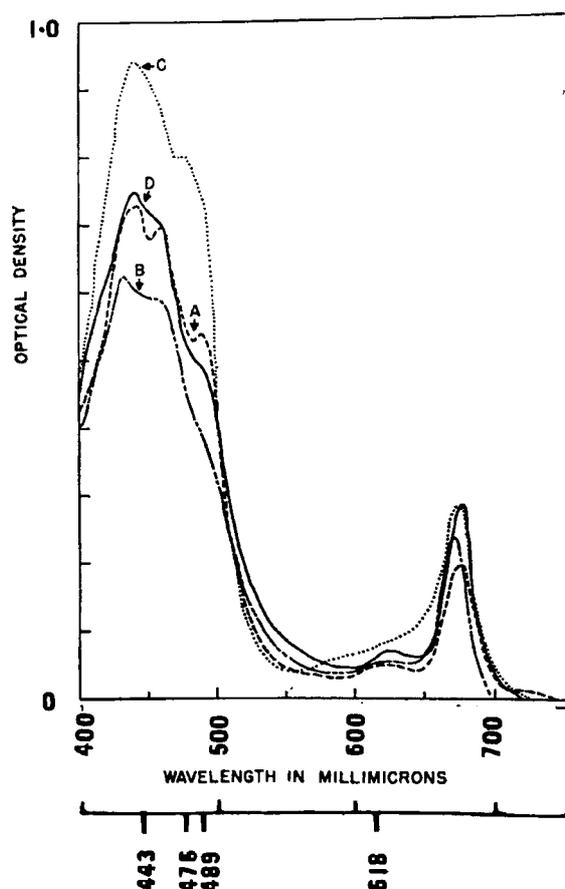
Figure 4. Absorption spectra of pigments extracted from planktonic algae: (A) a diatom, (B) a dino-flagellate, (C) a green flagellate, (D) a natural population taken from Woods Hole Water (Deutsch, 1960).

(Deutsch, 1960; Whittingham, 1976). Phytoplankton, which includes unicellular algae as a predominant subset, represent the ultimate in the food chains of aquatic biology. Along with photosynthetic bacteria, they could be regarded as the most primitive group of microorganisms, structurally relatively simple, and able to synthesize biochemicals using only CO_2, H_2O and inorganic minerals. Such organisms must figure prominently in any galaxy-wide proliferation of biology. The smallest algae have radii of the order of 1–2 μ, but in a sporing state they could shrink to $\sim 0.5 - 1 \mu$.

The points in Figure 6 represent the excess interstellar extinction in the waveband 4 000–5 000 A above that appropriate to our best-fitting bacterial extinction curve. The excess astronomical extinction is normalised to $\Delta m = 0.1$ mag at $\lambda^{-1} = 2.3 \mu^{-1}$. The agreement of the astronomical data with the predicted excess

due to phytoplankton pigments* (curve in Figure 6) is uncannily close (cf. Figures 4 and 5) reproducing the shape of a shoulder in the laboratory data at $\lambda \sim 4\,800$ A. The phytoplankton absorption in the $4\,000$–$5\,000$ A waveband arises due to a mixture of several carotenoids and chlorophylls, with the carotenoids dominating at $\lambda^{-1} = 2.3\ \mu^{-1}$ (see Figure 5).

Carotenoids have a molar extinction coefficient at the centres of their visual absorption bands

$$\varepsilon \sim 10^5 \ (\text{gram-mol per litre})^{-1} \ \text{cm}^{-1}, \tag{5}$$

(Scott, 1964).

Remembering the usual definition of ε given by

$$\log_{10}(I_0/I) = \varepsilon C l,$$

where I_0, I are, respectively, the initial and final intensities, C is the concentration of absorbing molecules in gram-mol per litre, and l is the pathlength in centimetres through the absorbing medium, we obtain the extinction coefficient κ at the band centre in the form

$$\kappa \sim 7.5 \times 10^{24} \frac{\rho}{M} \varepsilon \ \text{mag kpc}^{-1}, \tag{7}$$

where ρ is the smeared-out mass density of absorbing molecules, M is their average molecular weight and ε is the molar extinction coefficient. Using $\varepsilon \sim 10^5$, $M \sim 10^3$ appropriate for carotenoids, we obtain

$$\kappa \sim 7.5 \times 10^{26} \rho \ \text{mag kpc}^{-1}. \tag{8}$$

The observed value of κ at $\lambda^{-1} = 2.3\ \mu^{-1}$ from the astronomical data is ~ 0.1 mag kpc^{-1}, requiring a density $\rho \sim 10^{-28}$ g cm^{-3}. Thus we require a fraction of $\sim 1\%$ of all the interstellar carbon in the form of such pigment material.

We note from Figures 4 and 5 that phytoplankton pigments in grains should also produce a slightly less pronounced extinction excess in the waveband $6\,000$–$7\,000$ Å. Such an effect is not inconsistent with Nandy's extinction data. The presence of a very broad absorption band at wavelengths longward of 6280 Å has also been observed by York (1971) in the spectra of several stars.

The well-known diffuse interstellar features occurring at well-defined wavelengths in the optical region (the strongest of which is centred on $4\,430$ Å), might be considered as 'fine structure' in the interstellar extinction curve (York, 1971). Despite an intensive search of candidate transitions, mainly in inorganic systems, these thirty or so diffuse bands are yet unidentified. We consider here their possible connection with biological pigments. In addition to producing the very broad absorption band centred on $\lambda^{-1} = 2.3\ \mu^{-1}$ and possibly one on $\lambda^{-1} = 1.5\ \mu^{-1}$, we

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* The curve plotted in Figure 6 represents a normalised absorption excess due to *Nitzchia Closterium* (cf. Figure 5). The spectrum of Figure 5 is better calibrated for our purpose than the spectra in Figure 4.
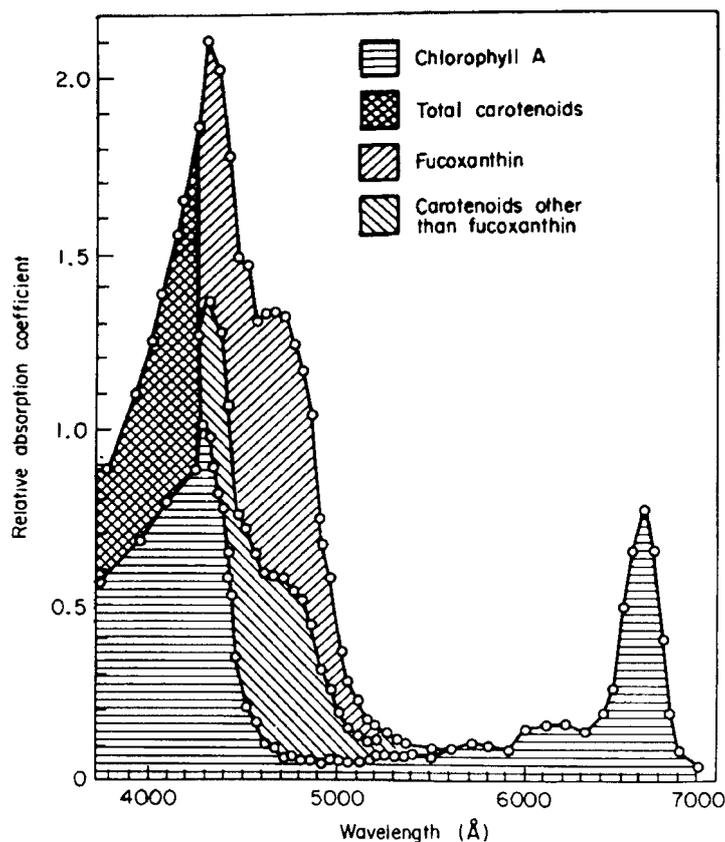
Figure 5. The contribution of different pigments to the absorption spectrum of the diatom *Nitzchia Closterium* (Whittingham, 1976).

see from Figures 4 and 5 that there are several narrower ripples at well-defined wavelengths which are superposed upon the more general background absorption curve due to phytoplankton pigments. Because the spectral resolution achieved in this data is only about 100 Å we cannot determine the central wavelengths and heights of the ripples to an accuracy that permits identification with any diffuse bands. However, it could be significant that the three strongest diffuse interstellar bands which have widths in excess of 20 Å (York, 1971) and central wavelengths at λ = 4430, 4890, 6180 Å fall within the resolution of the main ripples in Figure 3. The wavelengths 4430 Å, 4890 Å could correspond closely to the main absorption maxima of certain carotenoids measured in a light petroleum solvent (Davies, 1976), while the wavelength 6180 Å may be assigned to chlorophyll B. A higher resolution spectrum of phytoplankton pigments is obviously needed for seeking to confirm these provisional identifications. A combination of carotenoids and chlorophyll-type pigments (Johnson, 1967) may well provide the long-awaited solution to the problem of the diffuse interstellar bands.
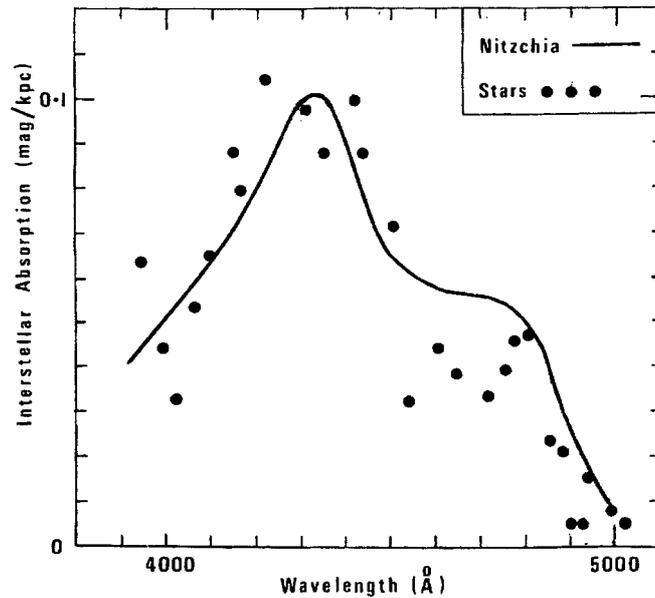
Figure 6. Points represent the excess interstellar extinction over the waveband 4 000–5 000 A differenced against our theoretical calculation for scattering by freeze-dried bacteria (Figure 2 and Table I). Normalisation is to $\Delta m = 0.1$ mag at 4 300 A. Curve is the expected absorption excess by phytoplankton pigments taken from Figure 5 with normalisation to $\Delta m = 0$ at $\lambda = 5\,100$ A, $\Delta m = 0.1$ at $\lambda = 4\,300$ A.

In the ultraviolet region of stellar spectra a broad interstellar absorption feature is centred on $\lambda^{-1} = 4.6\,\mu^{-1}$ ($\lambda \sim 2\,200$ Å) (Bless and Savage, 1972). This band has a symmetrical profile with a band-centre absorption coefficient which may be estimated as $\kappa \sim 1.5$ mag kpc^{-1}. The 2 200 Å band is widely attributed to absorption by spherical graphite particles of radii less than $\sim 3 \times 10^{-6}$ cm and with an overall mass density amounting to $\sim 10\%$ of the total interstellar carbon density. The requirement for strictly spherical shapes (Gilra, 1972) would seem at first sight to present some difficulty, since spherical graphitic particles are not known to be formed by any inorganic processes. We do not think that interstellar graphite particles could form in any appreciable quantities by inorganic processes, however. Rather would they form as a result of the reduction and degradation of organic polymers under interstellar conditions.

If cellulose can form in stellar mass flows in the manner we have proposed elsewhere (Hoyle and Wickramasinghe, 1977c), the degradation of polymers involving the stripping-off of side chains and weak bonds could lead eventually to the formation of small graphitic spheres. The process could be analogous to the 'balling up' of cotton fibres during combustion. An organic or biochemical origin of the $\lambda 2\,200$ Å interstellar absorption feature remains a distinct possibility, however (Hoyle and Wickramasinghe, 1977d; Wickramasinghe *et al.*, 1977). Whilst

polysaccharides together with an admixture of carotenoids and chlorophylls would probably make up a major mass fraction of bacterial and algal cells in the galaxy, other biochemicals would also be present in equally vast quantities. These include proteins, lipids and nucleic acids which are directly associated with cells, and which are also present in viruses and bacteriophages. It is of interest in this context to note that the ultraviolet spectrum of the tobacco mosaic virus shows a steep rise of absorption towards $\lambda 2\,200$ Å, the ultraviolet absorption being dominated by nucleic acids and proteins (Fraenkel-Conrat, 1969). A very large class of basic biochemical structures have ultraviolet absorption spectra peaking at wavelengths close to 2 200 Å. The combined absorption properties of such molecules might well reproduce the observed $\lambda 2\,200$ Å interstellar absorption feature.

Virus particles could play a crucial role in contributing to interstellar extinction at far ultraviolet wavelengths $\lambda < 2\,000$ Å. The steep rise of the extinction curve in the wavelength interval $2\,000$–$1\,000$ Å, arising mainly from pure scattering, indicates the presence of a population of very small dielectric particles with cross-sectional radii less than 0.03 μ. These properties are characteristic of some viruses. While the scattering efficiency of bacteria begins to fall off at wavelength $\sim 2\,500$ Å, smaller-sized viral particles would have a steeply rising scattering efficiency at wavelengths shortwards of $\sim 1\,800$ Å and so make a dominant contribution to interstellar extinction at far ultraviolet wavelengths. On the basis of scattering by dielectric 'viral' spheres of radius 0.02 μ and refractive index $n = 1.4$, we estimate that the observed average interstellar extinction of ~ 6 mag kpc^{-1} at $\lambda \sim 1\,000$ Å is achieved with only $\sim 5\%$ interstellar CNO in the form of viruses. The contribution to visual extinction by such a density of viral particles will be totally negligible.

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