A MODEL FOR INTERSTELLAR EXTINCTION *

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Abstract. From an analysis of the interstellar extinction we conclude that interstellar grains are of three main kinds: graphite spheres of radii $\sim 0.02\ \mu$m making up $\sim$ 10% of the total grain mass, small dielectric spheres of radius about 0.04 μm making up $\sim$ 25% of the mass, and hollow dielectric cylinders containing metallic iron with diameters of $\sim 2/3\ \mu$m making up $\sim$ 45% of the mass. The remaining $\sim$ 20% consists of other metals and metal oxides. The main dielectric component of the grains appears to be comprised of organic material.

1. Introduction

In this article we present a first-order solution to the long-standing problem of the nature of the interstellar grains. The immediate reason for our confidence in this solution is the agreement shown in Figure 1 between the observed interstellar extinction of starlight plotted as a function of inverse wavelength and the calculated effects of the particle distribution discussed below. The observations represented by the points of Figure 1 were taken from standard sources (Sapar and Kuusik, 1978; Bless and Savage, 1972; Jamar *et al.*, 1976), and the calculations shown by the continuous curve were done using accurate Mie formulae. Both observations and calculations were normalized to an extinction of 1.8 magnitudes at $\lambda^{-1} = 1.8\ \mu\text{m}^{-1}$, which is the extinction produced by the grains when starlight traverses a path length of 1 kiloparsec through the interstellar medium in the solar neighbourhood of the galaxy.

There is little variability in the observations at visual wavelengths taken from star to star in the solar neighbourhood of the galaxy, but there is considerable variation in the ultraviolet. The observed points for the ultraviolet are averages for a number of stars. Even so, the U.S. and the European results still show appreciable differences, as can be seen from the distinctively displayed points in the figure.

Although the calculations which have hitherto been published have not agreed nearly as well with the observations as the curve of Figure 1, because the definition of our particle distribution contains certainly three and perhaps four parameters, it is not possible from Figure 1 alone to invert the logic, and to say the agreement proves the model. For this, a further strong argument is needed. Such an argument,

* 1982, *Astrophys. Space Sci.* **86**, 321–329.

Astrophysics and Space Science is the original source of publication of this article. It is recommended that this article is cited as: *Astrophysics and Space Science* **268:** 263–271, 1999.

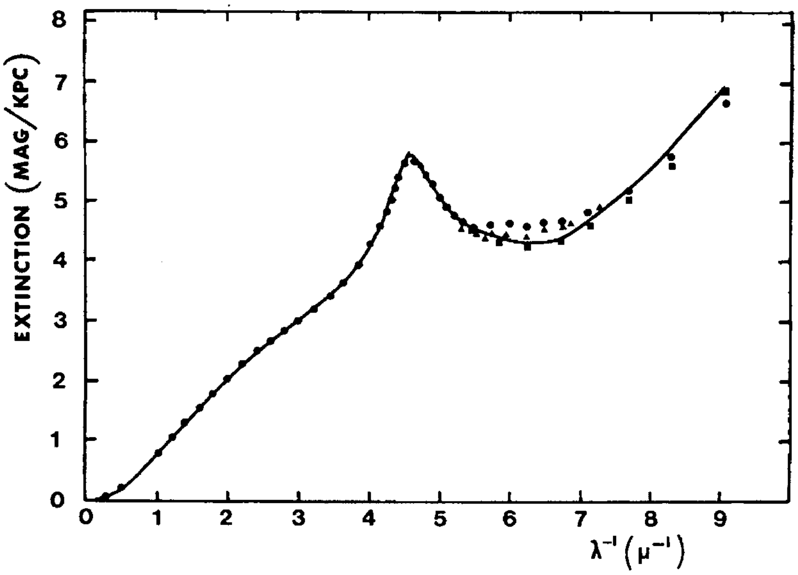

Figure 1. Wavelength dependence of interstellar extinction normalised to 1.8 mag kpc^{-1} at $\lambda^{-1} = 1.8\ \mu\mathrm{m}^{-1}$. Points are astronomical observations; solid curve is for the grain model proposed here. (● average extinction data compiled from many sources by Sapar and Kuusik (1979), ▲ ESA data from Jamar *et al.* (1976), ■ OAO 11 data from Bless and Savage (1972).

based on the amount of material available for grain formation and on a quantum mechanical lower limit calculated by Purcell (1969) will next be discussed.

2. An Upper Limit to the Spatial Density of Grains

Pure hydrogen has considerable attractions as a material for grain formation, but laboratory measurements of the vapour pressure of solid hydrogen at very low temperatures unfortunately made it necessary to rule out this possibility (Wickramasinghe and Nandy, 1968). Neither is helium a possible grain-forming material. We are required therefore to form grains from the higher elements, C, N, O, Mg, Al, Si, Fe, to name the more important ones. Although hydrogen may be in combination with some of these elements, hydrogen cannot thereby add much to the mass of the available grain-forming material.

According to the well-known relative abundance table compiled by Cameron (1970) which we take to apply to interstellar material, the amounts of the important higher elements expressed as percentages of the amount of hydrogen are:

$$\mathrm{C} = 0.45, \quad \mathrm{N} = 0.16, \quad \mathrm{O} = 1.08,$$

$$\mathrm{Mg} = 0.080, \quad \mathrm{Al} = 0.072, \quad \mathrm{Si} = 0.088, \quad \mathrm{Fe} = 0.146.$$

Although nearly all the C and N, and essentially all the Mg, Al, Fe, are known to be depleted from the atomic interstellar gas, and must therefore be in molecular form or in grains, about two-thirds of the O is atomic (Field, 1974; de Boer, 1980). The latter estimate may be subject to a selection effect, however, since directions towards very hot stars are chosen for the observations on which these analyses are based. Estimates for these directions refer therefore to grains which have been exposed to exceptionally heavy doses of destructive radiation, the effect of which is to produce a trend towards 'graphitization' of organic material, a process requiring the removal of O from the material, so increasing selectively the amount of gaseous atomic O. Ignoring this slight complication, the maximum mass density available for grain formation expressed as a percentage of the hydrogen mass density is $\sim (0.45 + 0.16 + 0.36 + 0.08 + 0.07 + 0.09 + 0.15) = 1.36$.

The average hydrogen mass density in the general locality of the Sun is usually taken to be 2.0×10^{-24} g cm^{-3}, corresponding to a number density of 1.2 atoms cm^{-3}. Hence the maximum spatial density in our neighbourhood of available grain-forming material is $\sim 2.7 \times 10^{-26}$ g cm^{-3}. To change this upper limit for the grain density, it would be necessary to alter either the average hydrogen number density or the relative abundances of Cameron.

3. A Lower Limit to the Spatial Density of Grains

Using the observed interstellar extinction, together with the Kramers-Krönig dispersion relations, Purcell (1969) calculated a lower limit for the spatial density of grains in the solar neighbourhood. The method assumes maximum quantum mechanical efficiency at all wavelengths and so yields the smallest grain density consistent with the physical laws. No explicit grain model is required to establish the Purcell lower limit, except that spherical grains of uniform specific gravity, σ say, were used.* In a more recent review article, Purcell and Aannestad (1973) obtained $8.6 \times 10^{-27}\sigma$ gram cm^{-3} for a visual extinction normalized to 2 magnitudes per kiloparsec, which is close to the normalisation value of 1.8 magnitudes per kiloparsec used in Figure 1. A slight adjustment for this small difference changes the above formula to $7.7 \times 10^{-27}\sigma$ gram cm^{-3}.

Since the elements C, N,..., form an assortment of grains with differing specific gravities, it is necessary to interpret σ as an average, weighted with respect to the abundances of the various kinds of grain. We shall see below that a third to a quarter of the carbon must be in the form of graphite, which has a specific gravity of 2.25. If Mg, Al, Si are in the form of magnesium aluminium silicates, as is usually supposed, the silicate grains would have specific gravity ~ 3.3. If Fe is metallic, as is also usually supposed, the iron would contribute particles of specific gravity 7.86.

* Strictly, a few assumptions that have gone into this calculation, are only very weakly dependent on certain model parameters (Purcell, 1969).

These high values of the specific gravity imply poor efficiency in producing extinction. At first sight one might think to improve the efficiency by supposing O to be combined with H_2 to form water-ice ($\sigma \cong 1$), leaving the remaining two-thirds of the C also to combine with hydrogen into a low specific gravity hydrocarbon. This tactic is strictly forbidden by observation, however, because interstellar water-ice would readily be detected in the spectra of all stars where extinction is appreciable, on account of its exceedingly strong absorption band at $\sim 3.1\ \mu$m. Since there has been no such detection, except perhaps marginally in one or two stars for which the extinction is unusually large, not more than a very small fraction of the O can be combined with H_2 into H_2O (Allen and Wickramasinghe, 1981).

The natural association of the oxygen is with the $\sim$ 70% of the carbon that is not graphite. In competition for oxygen, carbon takes precedence over the other common elements, because of the very strong binding energy of the CO molecule. The first step towards forming solid material from CO is a combination with H_2, H_2CO, and then a number of units of H_2CO form either into polyformaldehyde or into sugars and polysaccharides (Wickramasinghe, 1974; Hoyle and Wickramasinghe, 1977). These substances have specific gravities which average about 1.5, and if we take them together with the particles discussed in the previous paragraph the average specific gravity rises to about 2. Inserting $\sigma = 2$ in the result of Purcell and Aannestad, one obtains a quantum mechanical lower limit of $\sim 1.6 \times 10^{-26}$ g cm^{-3}. This is the least grain density that can explain the observed interstellar extinction of Figure 1.

Combining this lower limit derived from quantum mechanics with the upper limit obtained previously, we have the following inequalities that must be satisfied by any proposed model for the interstellar grains,

$$\sim 1.6 \times 10^{-27} \text{ g cm}^{-3} < \text{model density} < \sim 2.7 \times 10^{-27} \text{ g cm}^{-3}.$$

We shall see below that our model requires a grain density of $\sim 1.8 \times 10^{-27}$ g cm^{-3}, not much above the quantum mechanical lower limit and comfortably within the amount of material that is available. The solution leading to Figure 1 is therefore highly efficient in the extinction which it produces. We consider it unlikely that other radically different solutions, based on solids built from C, N, O, Mg, Al, Si, Fe in the correct relative abundances, can be found. Any such alternative solution would have to satisfy the above inequalities as well as give excellent agreement with the extinction data.

4. Graphite Spheres

Figure 2, calculated for graphite spheres with radii 0.02 μm, shows the factor Q_{ext} by which the extinction cross-section exceeds the geometrical cross-section. The contribution of scattering, Q_{sca}, to the extinction is seen to be about 20%, with $\sim$ 80% of the extinction coming from absorption. The measured scattering of the

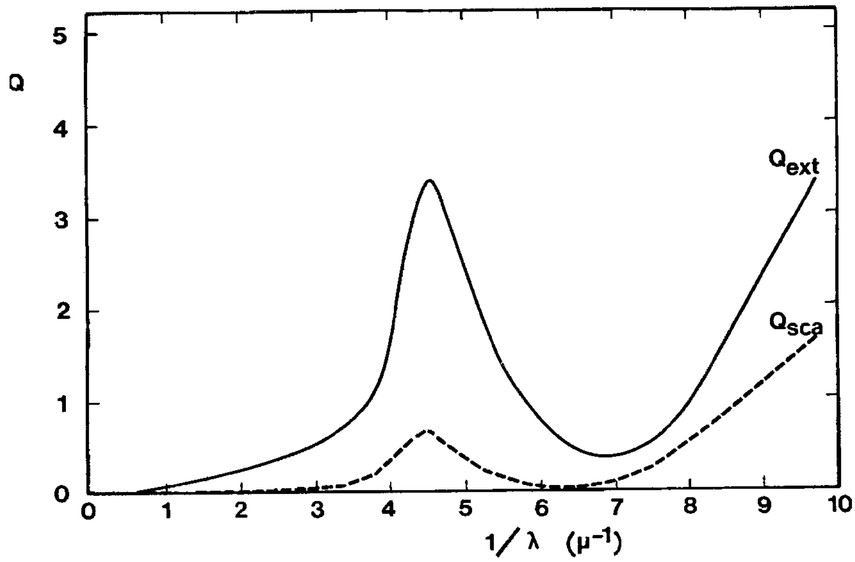

Figure 2. Total extinction and scattering efficiency factors for graphite spheres of radius 0.02 μm calculated using Mie formulae and the measured values of the optical constants for graphite.

interstellar grains at $\lambda^{-l} = 4.6\ \mu\text{m}^{-1}$ is actually about 35% (Lillie and Witt, 1976), but since the other two forms of grain discussed below also contribute significantly to the scattering at this wavelength, the graphite cannot give an appreciably larger Q_{sca} than is shown in Figure 2. This precludes graphite spheres with radii appreciably larger than 0.02 μm, while smaller spheres are excluded by the circumstance that the wavelength of maximum extinction moves shortward for smaller grains, to about 2130 Å, and the precise agreement of the graphite maximum with the observational maximum at $\sim$ 2180 Å is then lost. Nor can the graphite grains be other than spheres, otherwise there would again be a displacement of the wavelength of maximum extinction from $\lambda = 2180$ Å. The grains must be spheres and they must have radii rather precisely determined at 0.02 μm.

In arriving at the calculated curve of Figure 1, the density of graphite spheres was taken to be 1.79×10^{-27} g cm^{-3}.

5. Small Dielectric Spheres

Graphite alone gives too deep a minimum at $\lambda^{-1} \approx 6.5\ \mu^{-1}$ and too little extinction at $\lambda^{-1} \approx 8.5\ \mu\text{m}^{-1}$ for there to be any possibility of graphite spheres being the sole cause of the extinction at these shorter ultraviolet wavelengths. A further component to the grains is needed in the ultraviolet, a need which no model can avoid. Since, moreover, there is a marked increase of the observed scattering of starlight shortward of the graphite peak, the further component must be essentially dielectric, which is to say the complex refractive index of the grains, $n - ik$, cannot have more than a moderate imaginary part (k not larger than about 0.05).

If we take the grains to be spheres, the most efficient radii for producing extinction at the shorter ultraviolet wavelengths lie in the range 0.03 to 0.04 μm. In our calculation we took radii all equal to 0.04 μm, $n - ik = 1.5 - 0.0i$, grain specific gravity 1.6, and an interstellar density of 4.29×10^{-27} cm^{-3}.

In a more refined second-order calculation it would be possible to investigate the interesting region of the spectrum around $\lambda^{-1} = 6\ \mu\text{m}^{-1}$ in more detail, by choosing an appropriate value of k. Using $k = 0$, as we did in our calculation, is almost surely an oversimplification, particularly as organic materials – which we suspect the grains to be – tend to have absorptions at just these wavelengths.

If organic materials based on C, O, H are indeed involved, then a degradation of a fraction of the dielectric spheres contingent on the removal of O and H (such as occurs in the production of coal) would lead to graphitic spheres with radii $\sim 0.02\ \mu$m. Thus instead of the graphite grains being an independent component of the model, there would then be a straightforward connection between them and the dielectric spheres.

6. Hollow Cylinders

There is no possibility of explaining the visual extinction ($\lambda^{-1} <\sim 3.5\ \mu\text{m}^{-1}$) with either of the two kinds of grains discussed so far – both give far too little visual extinction. Whether we like it or not, the facts show that a third type of grain must be present in interstellar space. For maximum efficiency in the visual, this third type must have a characteristic dimension of about 2/3 μm, very much larger than the first two kinds. If the third kind are spheres, then 2/3 μm is the sphere diameter, and if rods or cylinders then 2/3 μm is the cylinder diameter – there is no efficiency condition on the cylinder length.

An apparently small detail at $\lambda^{-1} \cong 2.3\ \mu\text{m}^{-1}$ in Figure 1 has set a hitherto intractable problem. A small reduction in the upward slope of the observational points can be seen to occur at this wavelength, a reduction that Mie calculations for earlier models have persistently failed to explain. The effect is undoubtedly real and is found for stars scattered widely in the galaxy. We realised long ago that this problem might be solved if the real part n of the refractive index of the particles responsible for the visual extinction was less than 1.2, but no sensible solid material based on C, N, O,... satisfies this condition. Recently, however, we came to believe (for reasons unconnected with this article) that the visual grains might be hollow cylinders. The free space within the particles then has the effect of reducing the value of n averaged for the volume of the whole particle to less than 1.2. Using this idea we were able at last to solve the slope problem (Hoyle and Wickramasinghe, 1979).

The present calculation for the third type of particle is the same as that described in Hoyle and Wickramasinghe (1979), except that we have added a small refinement, by taking the averaged dielectric constant to be $1.16 - 0.015i$ instead of $1.16 - 0.0i$. In attacking the Purcell limit discussed above, we wished to take advantage of the available iron, and the simplest way to do so was to distribute the iron inside the hollow grains, when the Mie formulae automatically took it into account.

The particle properties were otherwise the same as we used formerly, particularly the size distribution centred around $2/3\ \mu$m that was specified in Hoyle and Wickramasinghe (1979) by a histogram. The average specific gravity of the hollow cylinders was 0.52, and their interstellar mass density was 7.76×10^{-27} g cm^{-3}. These numerical values refer to the dielectric material of the particles.

Adding the latter density value to those of the graphite and small dielectric spheres gives a combined mass density of 1.38×10^{-26} g cm^{-3}, and adding the further contribution of the iron and the other metals increases the density to a total of $\sim 1.8 \times 10^{-26}$ g cm^{-3}, the value stated previously.

The available density of grain-forming material was calculated above to be $\sim 2.6 \times 10^{-26}$ g cm^{-3}. If the Cameron abundances and the interstellar hydrogen density on which this estimate was based are firmly accepted, there is an unused excess of available material amounting to $\sim 8 \times 10^{-27}$ g cm^{-3}. A fraction of this excess is still required, however, to provide for the CO gas and for other gaseous interstellar molecules. We regard the remaining residue as being present in the form of grains with sizes too large for them to have been relevant in the calculations leading to the curve of Figure 1, as for instance grains with sizes of about 10 μm or more.

7. Second-order Effects

We have omitted some second-order effects but have included others. One omission has been noted already, absorption in the ultraviolet by organic molecules. One inclusion was the change of dielectric constant for the hollow cylinders, from $n - ik = 1.16-0.0i$ to $n-ik = 1.16-0.015i$. This latter refinement changes the visual extinction from being wholly a scattering effect to $\sim$ 75% scattering and $\sim$ 25% absorption, a change in agreement with observation (Lillie and Witt, 1976).

Another second-order effect, the polarization of visual starlight, has also been considered. Polarization is caused by a systematic alignment of a fraction of the cylindrical particles, the alignment being with respect to the configuration of the galactic magnetic field along the line of sight from the Earth to the star in question. The alignment is believed to be caused by an hysteresis effect of domains of iron within the particles. For reasons unconnected with this article, it appears to us improbable that all the iron is distributed uniformly among the hollow particles. We therefore assigned only 50% uniformly and homogeneously among the main set of hollow cylinder particles, the ones with $n - ik = 1.16 - 0.015i$, and we reserved the remaining 50% of the Fe for a special subset comprising only a few percent of the particles. If the excess of iron atoms are gathered into clumps of sizes $\sim$ 200 A these grains could become effectively aligned (Jones and Spitzer, 1967). This procedure gives an explanation of why the polarization of visual starlight usually amounts to only a percent or two, arising from a modest fraction of particles that are well-aligned, the subset with the excess iron in the form of tiny clumps.

The excess iron contained in the aligned subset necessarily raises n above the value 1.16 appropriate to the main set of particles. This detail shows itself in a subtle way, in the behaviour of the polarization with respect to wavelength, which is correct for $n \cong 1.4$, but not quite so for $n = 1.16$.

8. Absorption near 3.4 μm

There is no possibility at all (solid hydrogen being excluded) of explaining the extinction of Figure 1 unless a considerable fraction of the interstellar C, N, O is condensed into solid grains. This almost forces the further conclusion that most of the grain material must be organic, particularly as H_2O-ice grains are excluded for the reasons stated earlier. Organic material inevitably contains C–H linkages, which have an infrared absorption band at 3.4 ± 0.1 μm, the precise wavelength of the band centre and the detailed band profile being variable from one organic substance to another.

The concept of organic solids widespread in space has not lacked for critics, who have maintained the concept to be wrong because otherwise the $\sim$ 3.4 μm C–H band would have been widely observed in reddened stars and in other non-stellar infrared sources. However, the mass absorption coefficient at the centre of the C–H band, taken with respect to the residual absorption in the distant wings of the band, is merely $\sim$ 300 cm^2 g^{-1}, a tiny value compared to $\sim$ 33 000 cm^2 g^{-1} for the nearby water-ice band at 3.1 μ (Bertie *et al.*, 1969). It needs only a few percent of water-ice to be present in organic material for the C–H band to become relegated to a minor shoulder in the absorption spectrum of the material, and such shoulders are in fact observed in many astronomical infrared sources (Merrill *et al.*, 1976).

For the 3.4 μm C-H band to be observable as a clear-cut absorption dip, it is essential both for water-ice to be absent and for the amount of the visual extinction to be very large, much larger even than for highly reddened stars like VI Cyg No. 12, These conditions happen to be satisfied for grains along essentially the whole of the $\sim$ 10 kiloparsec line of sight to the source IRS 7 at the galactic centre, and in this case an absorption band at 3.4 μm due to organic matter has recently been observed (Wickramasinghe and Allen, 1980; Allen and Wickramasinghe, 1981).

We conclude that organic material which forms the principal component of the grains is distributed as hollow dielectric cylinders, including metallic iron impurities, of average diameter $\sim 2/3$ μm, and spherical particles of radii $\sim$ 0.04 μm.

The larger cylindrical particles dominate the extinction and polarisation of starlight at optical wavelengths, whilst the smaller dielectric spheres dominate the extinction at far ultraviolet wavelengths, together accounting for about 70% of the grain mass. An approximately ten percent mass contribution comes from graphite spheres of radii $\sim 0.02\ \mu$m, which produces the observed interstellar absorption band at 2 200 Å. The remainder is attributed to metals and metal oxides more or less uniformly distributed throughout the grains.

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