Chapter 4

Interstellar grains

4.1 Evidence for grains

4.1.1 Depletion of elements

Because the Sun is relatively close to the Earth, readily observed, and apparently fairly typical of stars within our Galaxy, astronomers tend to use it as a standard object. In particular, the relative abundances of elements in the Sun may be measured and are frequently assumed to be typical of the Galaxy. Whether or not this is really true is still unclear. However, it *is* true that the relative abundances found in the Sun are not typical of interstellar clouds. By the means we discussed in Chapter 2, abundances of some elements are determined and turn out to be very greatly reduced, in comparison to the Sun. We show in figure 4.1 results of observations in the direction of the star ζ Ophiuchi. For example, titanium is seen to be depleted, that is, underabundant relative to the Sun by more than a factor 1000 in the direction towards this star; and oxygen is depleted by a factor of about 3. The depletion data are displayed as a function of condensation temperature, i.e. the temperature below which we expect solids of that material to be stable.

If, indeed, the Sun is a standard, where have all these atoms gone? Certainly it is suggestive that elements which are capable of forming refractory (that is heat-stable and resistant) solids are among those which have high depletions. For example, silicon and oxygen form silicates with magnesium and iron. Iron may also form solid iron particles; silicon carbide is very stable, so is graphite, and so are metal oxides. These data suggest that in gas that is cooling as it moves away from a star, some elements that can form refractory solids are removed from the gas as solid particles.

4.1.2 Extinction

In Chapter 2 we described observations which suggest that there is an agent in the Galaxy tending to obscure the stars and other sources of radiation: we called

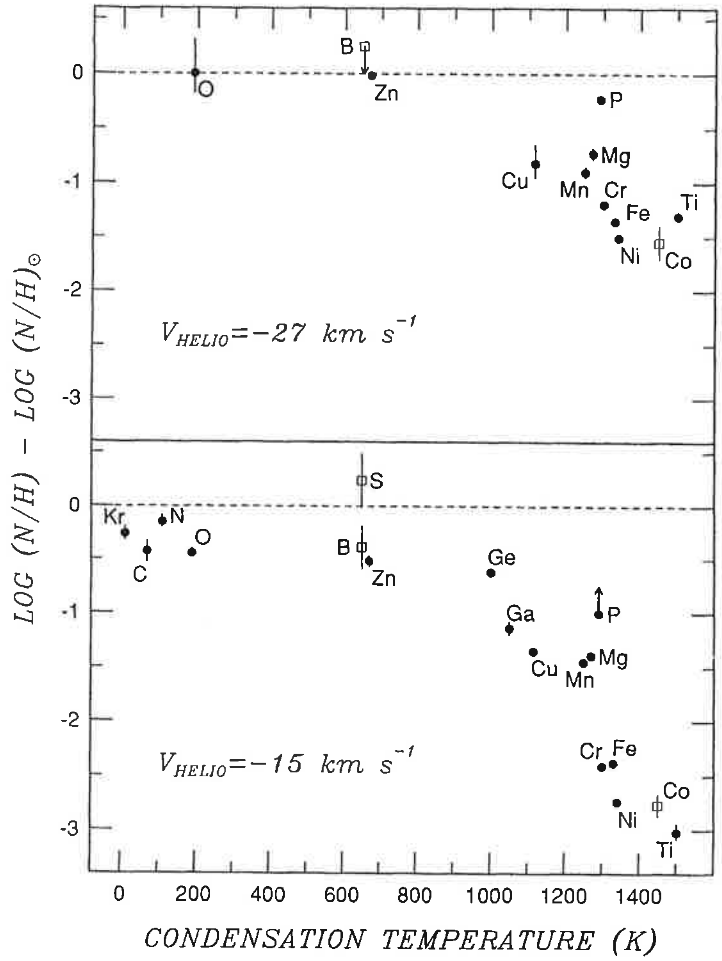

Figure 4.1. Interstellar elemental abundances relative to hydrogen compared with those in the Sun, for two clouds on the line of sight towards ζ Oph. The two clouds are distinguished by their velocity shifts relative to the Sun. The data are displayed as a function of the condensation temperature of the appropriate material. The underabundance of elements relative to the Sun, i.e. the depletion, can be large. In the cloud at -15 km s^{-1} titanium is depleted by three orders of magnitude. (From Federman S R *et al* 1993 *Astrophysical Journal* **413** L51.)

this property *extinction.*

We can define an extinction coefficient α such that the intensity I_0 of a star is reduced to

$$I = I_0 \exp\left(-\int_0^l \alpha \, \mathrm{d}l\right) \tag{4.1}$$

after passage through a distance l of the interstellar medium. The coefficient α is not constant, but seems to be proportional to the density of gas in the interstellar medium, and the density itself may vary with position.

We can measure extinction most easily by comparing two similar stars (i.e. having similar masses, temperatures and compositions, as revealed by their spectra), one of which has little material between it and us and the other being behind a gas cloud. Differences in the intensities received from these two stars may derive in part from differences in distance: this can be allowed for; but there will also be a difference because of extinction. Astronomers measure intensity changes on a logarithmic scale in units of magnitudes. These units are such that a change in intensity by a factor of 100 corresponds to a magnitude difference of 5; we can therefore relate two intensities I_1 and I_2 to a magnitude difference Δm by

$$\Delta m = 2.5 \log_{10}(I_1/I_2). \tag{4.2}$$

Objects with smallest magnitudes are brightest. In these units the typical extinction in the visible regions of the spectrum found in the thin gas filling most of the Galaxy is about 1 magnitude for a path length of 1 kpc. But in denser clouds, of course, the extinction is very much greater, and such clouds appear dark against the background of stars. Indeed, number counts per unit area on the sky of stars exceeding a certain brightness give us another general method of estimating interstellar extinction.

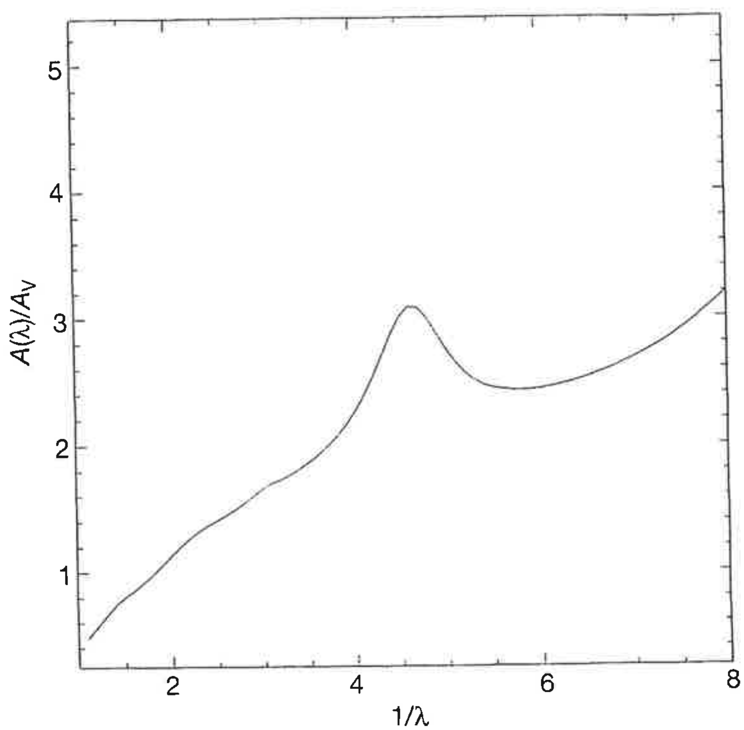

Figure 4.2. The average interstellar extinction curve; the average extinction at wavelength λ is measured in terms of the extinction at wavelength V = 550 nm, and is shown as a function of $1/\lambda$ where λ is measured in μm. Thus, IR is to the left and UV to the right, in this diagram.

Extinction can, in principle, be measured at any frequency or wavelength, and observations have been made at wavelengths from the far UV ($\lambda \approx 100$ nm) through the visible to the IR ($\lambda \approx 10$ μm). It is found to vary with wavelength in the way indicated in figure 4.2. Some differences are found in different regions of the Galaxy; however, the general shape of the extinction curve is usually as indicated. The most pronounced features are the peak at $\lambda \approx 220$ nm or $1/\lambda \approx 4.6\ \mu\mathrm{m}^{-1}$, and the strongly rising portion in the far UV. It is also particularly important to notice that in the visible region of the spectrum the extinction is approximately proportional to $1/\lambda$; this portion of the curve first gave a clue as to the origin of extinction. As we discussed in Chapter 3, extinction is thought to be caused by small solid particles called dust grains which have a diameter comparable to the wavelength of visible light. We shall show in section 4.2.1 that such particles may be expected to produce the $1/\lambda$ behaviour, but that other components in the grains may be necessary to explain other features in the curve. Before we do that, we shall review some other evidence for the existence of grains in the interstellar medium.

4.1.3 Polarization

Although extinction points strongly to the existence of interstellar grains, one might feel that with sufficient ingenuity an alternative source of extinction could be found. However, the observation that starlight is—in general—partially linearly polarized made such a position more or less untenable. Observations of starlight show that visible light is often linearly polarized by a few per cent. The amount of polarization observed seems to be proportional to the amount of extinction.

To create in the laboratory a beam of partially polarized light travelling, say, in the z-direction, we use a polarizing agent such as a piece of polaroid plastic. This is a material which is stressed so as to produce an alignment of the molecules in the plastic material. The result is that the electric vector in one direction (say the x-direction) is preferentially absorbed with respect to the electric vector in the y-direction. This mechanism of polarization is therefore one of preferential extinction (but others also exist).

If this is the mechanism at work in the interstellar medium then we require two things: first, interstellar grains of isotropic behaviour cannot be spherical, but must be elongated; and second, there must be some degree of alignment of these elongated grains. If these two criteria are satisfied, then radiation with electric vectors parallel to the longer axes of the grains will be more heavily extinguished than vectors parallel to shorter ones and polarization occurs. Aligned grains of anisotropic material (such as graphite) may also cause polarization. All grains will normally be rotating; if there is equipartition of energy between gas and grains then

$$\tfrac{1}{2} I \omega^2 = \tfrac{3}{2} kT \tag{4.3}$$

for a grain of moment of inertia I rotating with angular frequency ω in a gas at temperature T. For grains of radius $a \approx 10^{-7}$ m and density 10^3 kg m^{-3}, we expect frequencies of rotation of the order of 10^5 Hz. What we require is a partial alignment of the axes of rotation; we require them to point preferentially in the same direction. We now describe one possible alignment mechanism.

Suppose that a magnetic field exists in the interstellar gas and that the grains are paramagnetic. Then the field induces a magnetic moment within the grain, which is continually changing its orientation within the grain, due to the grain's rotation. The continual change of the magnetic moment inside the grain requires the expenditure of energy which must come from the kinetic energy of rotation of the grain. The energy appears as heat, and the efficiency of the process depends on the imaginary part of the magnetic susceptibility. The drag on the motion is greatest when the grain is rotating about an axis perpendicular to the direction of the external field, and least when the axis is parallel to the external field. Thus the former motion tends to be damped out and some measure of alignment is achieved. This effect, of course, is opposed by the effects of collisions which tend to randomize the spin axes of grain, so the degree of alignment is a subtle balance of the magnetic field and the magnitude of the imaginary part of the susceptibility against the effects of density and temperature. Collisions will succeed in randomizing the orientation unless the gas and grain temperatures are different.

4.1.4 Scattered light

There is another way in which the grains betray their presence, one which would be difficult to explain in any other way. The Galaxy is filled with a *diffuse light*, not directed from any particular source. The most natural origin for this is in the scattering of starlight by some agency. The diffuse light does not appear to have its origin in any other physical process. Scattering by atoms and molecules would be quite inadequate to account for it. The cross-section for Rayleigh scattering of light (i.e. without change in wavelength) by atoms is approximately 10^{-28} m^2, so the scattering effect of H atoms along the path is roughly measured by $10^{-28}n(\mathrm{H})$. For spherical grains of radius a and number density n_g, as we shall see below, the equivalent measure is approximately $\pi a^2 n_g$ in the visible, and this quantity is several orders of magnitude larger (see section 4.2.2). We infer that the diffuse light arises because of scattering of starlight by grains. It should, therefore, contain information about the grain properties: in particular, the 'albedo' (or reflectivity) and the 'phase factor', which describes whether grains scatter light preferentially forwards or backwards. We shall see in section 4.2 that this information is complementary to that contained in the extinction observation.

Besides the general diffuse light, there are some places in which scattered light is directly observed as a reflection nebula. The cluster of stars known as the Pleiades in the constellation Taurus contains stars possessing 'halos'. These stars are situated sufficiently near to a gas and dust cloud that the scattered light is intense enough to be seen even by naked-eye observation.

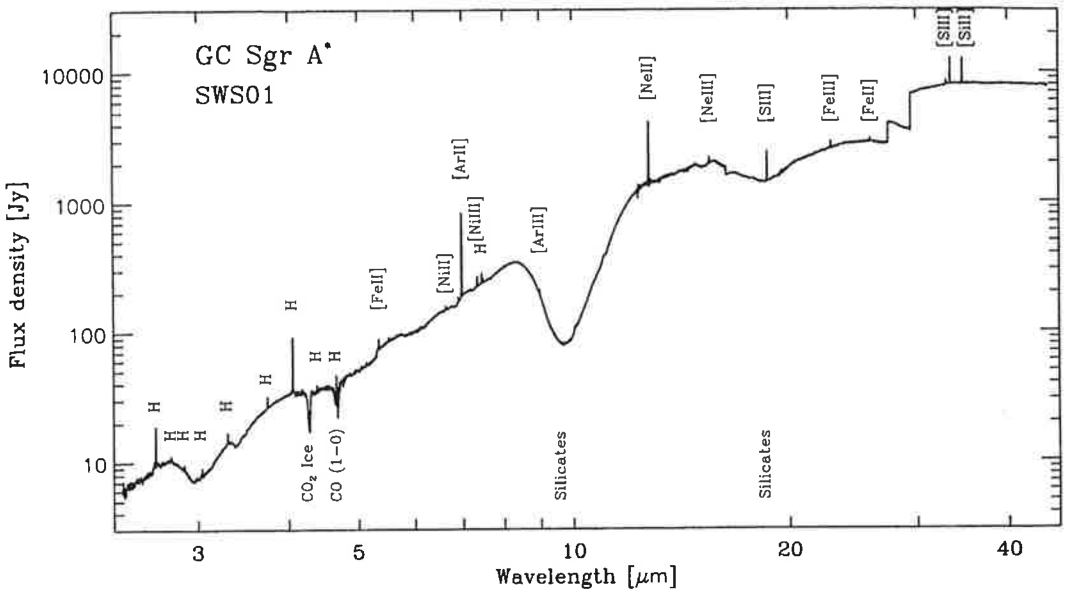

Figure 4.3. The infrared spectrum of the Galactic centre, taken over a wavelength range 2.4–45 μm by the Short Wavelength Spectrometer on the Infrared Space Observatory (ISO). In addition to various emission lines from the hotter regions along this line of sight, there are strong absorptions due to material in the dust grains near 3 μm (H_2O ice), 9.7 μm and 18 μm (silicates). Some weaker features are formed, including those at 3.4 μm (hydrocarbons) and 4.3 μm (solid carbon dioxide). (Courtesy D Lutz *et al* 1996.)

4.1.5 Solid state spectral lines

There are several infrared absorption lines that are attributed to absorption of radiation from background stars by foreground solid particles (see figure 4.3). There is a broad absorption feature with central wavelength at about 9.7 μm, which is about 1 μm wide at half intensity. This is attributed to the Si–O bond in amorphous (i.e. non-crystalline) silicates such as magnesium silicate, Mg_2SiO_4, or iron silicate, $FeSiO_4$, or some mixture of these and other silicates. The feature is caused by stimulating the stretching mode in this bond, and is broadened by interactions of the Si–O structure with its environment. The Si–O is not able to rotate, as a free SiO molecule would be, so lines associated with SiO rotation (see Chapter 3) are absent. However, the SiO structure can also bend to and fro, relative to the rest of the molecule, and setting up this oscillation—which requires less energy than exciting the SiO stretching modes—causes absorption at wavelengths of about 18 μm. This absorption is also detected in the interstellar medium.

In dark regions, where the dust causes extinction of several magnitudes at visual wavelengths, a very strong absorption of the light of background stars is usually detected at a wavelength of about 3.0 μm. This is attributed to excitation of the O–H stretch mode in amorphous H_2O ice. In some sources, much of the oxygen is tied up in this form. In addition, particularly dark regions often show absorption from CO ice, at wavelengths near 4.7 μm. This corresponds to the excitation of the CO vibration $v'' = 0 \rightarrow v'' = 1$. We can be sure that this is not arising in the gas phase CO because the associated rotational structure from free molecules of CO (see Chapter 3) is absent. This solid CO feature is rather sensitive in its central wavelength and width to the environment of the CO; pure solid CO has a narrower feature slightly shifted from that due to a solid solution of CO in H_2O. Therefore, infrared spectroscopy of solids is a useful tool, if not quite as specific as atomic spectroscopy. The absorption features arise in particular bonds of a molecule, and may not define that molecule completely. However, details of the spectrum usually show the influence of the atomic-scale environment in which the bond is found.

If dust grains are hot they will emit radiation not only in a continuum but also in spectral lines. Obviously, H_2O ice would evaporate before it could radiate at 3 μm (emission at this wavelength requires a temperature of about 1000 K—see equation (4.18), below), but silicates are much more robust at high temperatures, and the 9.7 μm feature can be detected in emission from dust that is heated to temperatures above several hundred kelvin by a nearby star.

Other emission features between 3.3 μm and 11.3 μm are detected in some hot sources, and are attributed to hydrocarbon material that may be either in grains small enough to be made hot by a single UV photon, or to free-flying hydrocarbon molecules. The 3.3 μm feature is associated with a C–H stretch mode, and the 11.3 μm feature with a C–H bend mode. Neither is specific to a particular species, and so we can use this information only to confirm the existence of hydrocarbons.

4.1.6 Luminescence from grains

A broad band emission centred on the red or near infrared and several hundred nm broad is observed from certain interstellar regions of high excitation. This emission is interpreted as bandgap luminescence emission from a material that has a bandgap energy $E_g \sim 2$ eV (see figure 4.4). Possible materials with E_g in this range are H-rich amorphous hydrocarbons. Absorption in the UV and visible leads to population of states from which leakage into other modes occurs, until emission across the bandgap occurs.

4.2 Optics of grains

4.2.1 Introduction

The major problem concerned with the grains is to identify the materials of which they are made and the distributions of their shape and size, so that we may then explain the observations described above and go on to predict effects the grains may have on the gas surrounding them. To help us in this study, we have the pieces of evidence described in section 4.1. We must, in particular, be able

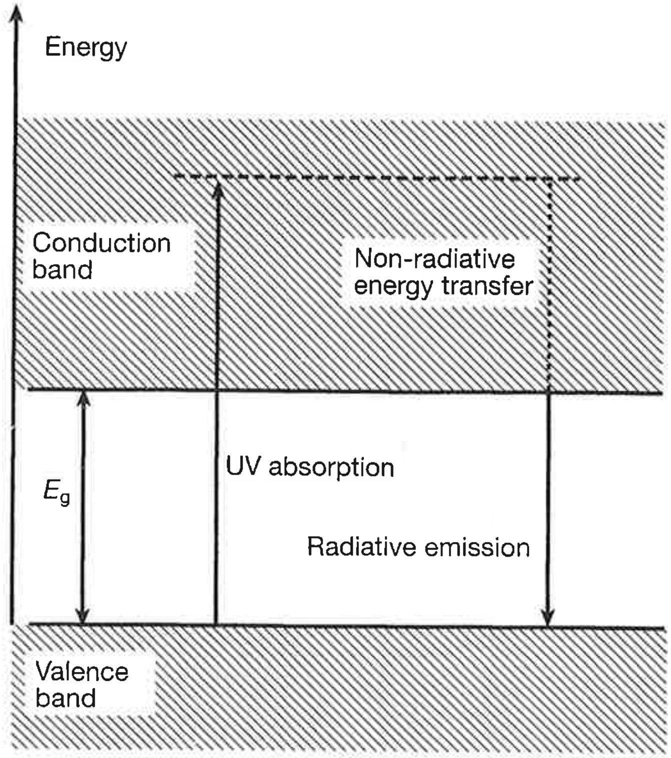

Figure 4.4. UV absorption by a solid may lead to emission of radiation with photons of energy around the bandgap energy, E_g.

to describe the optics of grains: how grains of given size, shape and refractive index modify the electromagnetic radiation which falls on them. The problem is, in a sense, a standard one: it involves the application of Maxwell's equations of electromagnetism to the grains, with proper attention to the boundary conditions at their surfaces. In fact, it is a complicated computational problem which has only been fully worked out in the cases of spheres, spheroids and infinite cylinders. We shall describe some results for spherical grains.

Let us assume that there is a cloud of grains, each of the grains having radius a, with uniform number density n_g (m^{-3}). Then in the case of single scattering, equation (4.1) is replaced by

$$I = I_0 \exp(-n_g \pi a^2 Q_{\text{ext}} l). \tag{4.4}$$

Q_{ext} is called the efficiency factor for extinction, and is made up of two parts

$$Q_{\text{ext}} = Q_{\text{abs}} + Q_{\text{sca}} \tag{4.5}$$

due to absorption and scattering. When calculating extinction we must allow for all photons lost from the beam, so both absorption and scattering must be included. Since we are assuming only single scattering, the scattered photons are never put back into the beam. There are, of course, situations where multiple scattering is important, but we are not concerned with them here. How much scattering and how much absorption occurs depends, ultimately, on the refractive index, m, of the grain material. The refractive index is, in general, complex, and it is the imaginary part that gives rise to absorption, as we can see from the following argument. Suppose an electromagnetic wave with an electric field, E, of the form $E \propto e^{i(kx-\omega t)}$ passes along the x-axis through a medium in which m is complex. The wave has velocity c/m, or in our notation ω/k; thus, since m is complex, k must be complex, say $k = k' + ik''$ where k' and k'' are real. In other words, the wave has a form $E \propto e^{i(k'x-\omega t)}e^{-k''x}$, which shows clearly that the amplitude of the wave decays exponentially with distance penetrated into the medium.

A description of the full theory is beyond the scope of this book. We show in figure 4.5 some curves exhibiting the behaviour of Q_{ext} as a function of the dimensionless parameter $x = 2\pi a/\lambda$ for some different values of the dielectric constant. It is the initial near-linear portion of these curves showing similarity to the interstellar extinction curve (figure 4.2) that provided support for the hypothesis of interstellar grains. In actual materials, of course, the refractive index is a function of the frequency of the radiation, and curves such as that in figure 4.5 are not strictly valid. It is interesting to note that for large x, Q_{ext} approaches 2; i.e. a large particle removes from the incident light exactly twice the amount of light it can intercept! This surprising result arises because we have assumed that *any* light scattered, no matter at how small an angle, is lost from the beam, and that the grain is very far away from us so that it does not cast a direct shadow. The oscillatory nature of the curve arises because of interference effects, similar to those described in terms of 'Cornu's spiral' in the elementary treatment of diffraction by a slit.

4.2.2 Application to the interstellar medium

The major problem is to be able to construct a curve such as that in figure 4.2 out of curves like those in figure 4.5, by choosing 'correctly' a size distribution for the grains and the refractive index of the material of which they are composed, consistent with the information on elemental abundances contained in figure 4.1. In fact, the problem is overdetermined, and by suitably juggling with the parameters one may hope to produce a 'correct' fit to any portion of the extinction curve. Unfortunately, this is not a guarantee of uniqueness!

This is why the other observational evidence (section 4.1) is so important. The constraints placed by the total observational evidence are tight and we are forced to conclude that there must be several components in the grains, each responsible for different aspects of behaviour. Thus, for example, small graphite grains may be responsible for the extinction 'bump' near 220 nm in the UV by virtue of the excitation of a collective mode of oscillation of the electrons—a so-called 'surface plasmon'. However, these graphite grains account satisfactorily for neither the visible nor the far-UV extinction. Very small grains have been suggested as the explanation for the far-UV extinction,

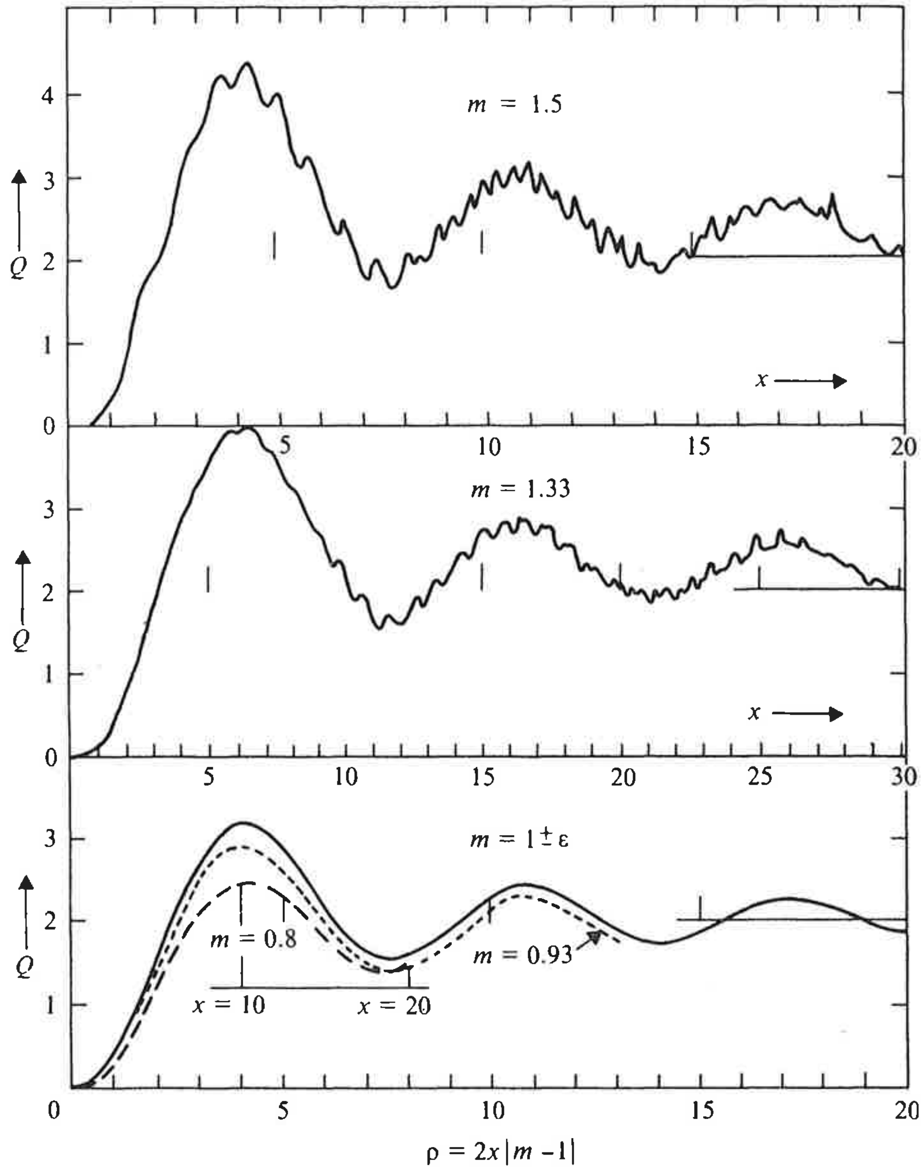

Figure 4.5. Extinction curves for spheres computed from Mie's formula for $m = 1.5$, 1.33, 0.93 and 0.8. The scales of x have been chosen in such a manner that the scale of $\rho = 2x|m-1|$ is common to these four curves and to the extinction curve for $m = 1+\varepsilon$. (From van de Hulst 1957.)

and somewhat larger grains cause much of the visible extinction. A conventional assumption about grains—and one that is probably only partially correct—is that they have radii $a = 3 \times 10^{-7}$ m, their number density n_g is about $10^{-12}\, n_{\mathrm{H}}$ and their refractive index is 1.3 with a small imaginary part. These numbers reproduce the *visual* extinction satisfactorily, and we shall sometimes use them for illustrative purposes. But a distribution of grain sizes is certainly necessary and a common assumption is that the number in the size range $a \to a + \mathrm{d}a$ is proportional to $a^{-3.5}\,\mathrm{d}a$.

4.3 Formation and destruction of grains

4.3.1 Formation

Where can the grains be formed? We might first think that they grow slowly in typical interstellar clouds. However, this takes a very long time, as we shall see by the following simple argument. Suppose at time $t = 0$ the grain radius is $r(0)$, and that the grain grows by the addition of species i (an atom or molecule) which has mass m_i, mean thermal velocity $\bar{v}_i$. Let s be the bulk density of the material. Then at time t we easily find that

$$r(t) = r(0) + \frac{\epsilon n_i m_i \bar{v}_i}{4s} t \tag{4.6}$$

where ϵ is a sticking coefficient. If small condensation centres exist, then the minimum time required to grow a solid of density $s = 10^3$ kg m^{-3} to radii $\approx 10^{-7}$ m is about $10^{20}/\epsilon n_i$ seconds, which for $n = 10^7$ m^{-3} and $n_i < 10^3$ m^{-3} exceeds $3 \times 10^9/\epsilon$ yr. Since $\epsilon \lesssim 1$, this is a long time compared with other relevant timescales.

We must look instead for denser regions where timescales are shorter. One such place is in the outflowing gas from cool stars. The material originally was so hot that it did not contain solids. The material cools as it moves away from the star, but the densities (approximately 10^{19} m^{-3}) and temperatures ($\sim 10^3$ K) are so high compared with interstellar clouds that atoms can arrange themselves into the most stable molecules at that temperature. It is quite likely that in this process the partial pressure of molecule X may exceed the vapour pressure of solid X. For example, at a pressure of 10^{-1} N m^{-2} and a temperature of 1500 K, the vapour pressure of solid Al_2O_3 (corundum) is exceeded in a gas of cosmic abundances. As the temperature drops further, the gas becomes supersaturated in Al_2O_3 molecules, and corundum particles may nucleate and settle out. Such a picture is consistent with the picture presented in section 4.1.1 from depletions. As solid absorbing particles, they experience a radiation pressure due to the stellar radiation flux, and may be blown clear into the interstellar medium.

One must consider how quickly nucleation processes can act, and classical homogeneous nucleation theory can give us some idea about the rapidity of such processes. The theory states that, in equilibrium, the number density of a cluster of j atoms is

$$n_j = n_1 \exp(-\Delta G_j/kT)$$

where ΔG_j is the thermodynamic free energy of formation for the cluster, and n_1 is the number density of single atoms. ΔG_j depends on bulk properties of the solid: the surface energy and the molecular volume. Initially ΔG_j increases for increasing j, so n_j decreases. For j larger than some critical value, j_c, however, clusters become more stable as more atoms are added, and n_j increases with j. If this equilibrium situation can be established in the time available then the clusters with $j > j_c$ tend to grow. Nucleation also tends to occur rapidly on ions which are present in the stellar atmosphere. Assuming that classical nucleation theory holds, then clusters should appear in the gas, and should grow to the required size in the time available if the density is high enough. One uncertainty in this picture is whether the assumption of equilibrium is justified, or whether a time-lag occurs which is comparable to the timescale over which conditions in the stellar atmosphere are suitable for grains to grow. Of course, the gas is far from chemically homogeneous and the description given above may be inappropriate. It has been suggested that the minimum cluster that is stable, which forms a substrate on which larger grains may grow, is in fact formed through chemical processes that produce molecules. The types of chemical reaction involved have been described in Chapter 3. A molecule that is stable against disruption in the conditions in stellar envelopes may need to have 10–20 atoms. Once such species have formed, they may grow by simple kinetic effects.

The nature of the particles that form is sensitive to the cosmic abundance of the elements. At temperatures of 1000–2000 K the molecule CO is stable, and most of the C and O atoms are tied up in this form. If O atoms are in excess, then we expect such oxides as Al_2O_3 to form. Some stars are observed to have an excess of carbon, and these are expected to form solid grains of carbon.

A large velocity may be attained by grains as they are blown out of the atmosphere by radiation pressure. The radiation acceleration is usually much greater than gravity, and acceleration outwards is impeded only by collisions with the gas. Balancing these two forces for grains of radius a at distance R from the star of radius R_0 gives for the velocity v_g of the grains, of number density $n(R)$,

$$\mathcal{F}(R_0)\left(\frac{R_0}{R}\right)^2 Q_{pr}\pi a^2 \frac{h}{\lambda}\Delta\lambda \approx n(R)\pi a^2 m_H v_g^2 \tag{4.7}$$

for a flux $\mathcal{F}(R_0)$ photons $\mathrm{m^{-2}\,s^{-1}\,nm^{-1}}$ over a bandwidth $\Delta\lambda$ at wavelength λ, and Q_{pr} is the radiation pressure efficiency of the grain, and is approximately 1.

Once grains have moved away from their formation sources they may grow further by the accretion of atoms and molecules from the gas. But, as we have seen, the timescale for this will be unacceptably long unless the gas density $n \gtrsim 10^9\ \mathrm{m^{-3}}$.

4.3.2 Destruction

If grains do accrete icy mantles then these are fairly readily destroyed by evaporation, should the grain temperature rise when the grains pass near to a star (see section 4.4). But refractory materials such as hydrocarbons, graphite, or silicates, or silicon carbide are very durable, although they are vulnerable to sputtering by high-speed atoms. Sputtering is a process in which an incident atom travelling with sufficient speed knocks one of the lattice atoms completely out of the lattice. Velocities greater than about 50 km s^{-1} are required, and these are probably attained in shocks that occur in a variety of interstellar situations (see Chapter 7). A supernova of energy 5×10^{43} J may set up shocks that destroy all grains in a mass of gas $\approx 300 M_{\odot}$. There is some evidence that such a process has occurred in material which we can observe and which has recently been shocked by a supernova blast-wave.

4.4 Physical properties of grains

4.4.1 Temperature

In section 4.2.1 we defined the efficiency for absorption of radiation by a grain as Q_{abs}. In clouds of low density the most important way energy is transferred to the grain is by absorption of photons. Collisions are not so important. A UV flux of 10^{10} photons $\text{m}^{-2}\,\text{s}^{-1}\,\text{nm}^{-1}$ in the low-density interstellar medium, with $Q_{\text{abs}} = 1$, deposits 10^{-20} J s^{-1} into each unshielded grain, whereas collisions deposit $\lesssim 10^{-26} n_{\text{H}}$ J s^{-1} per grain.

The grains, therefore, readjust their temperatures by re-radiating, but at a lower temperature, T_g, than the stellar radiation temperature. T_g is found from the equation

$$\int F(\lambda) Q_{\text{abs}}(a, \lambda)\, \text{d}\lambda = \int Q_{\text{abs}}(a, \lambda) B(\lambda, T_g)\, \text{d}\lambda \tag{4.8}$$

in which $F(\lambda)$ is the energy flux of stellar radiation, and B is the Planck function

$$B(\lambda, T_g) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/k\lambda T_g} - 1}. \tag{4.9}$$

The two integrals contribute over different wavelength ranges. The left-hand side calculates energy input into the grain from the radiation field in the visible and UV. The right-hand side calculates the energy emitted, and this range of wavelengths is generally in the infrared. Were the grain a perfect radiator, its temperature would reflect the energy content of space and be equal to the black-body temperature $T_{\text{BB}} \approx 3$ K. At this temperature, however, the peak of the Planck function occurs in the millimetre range, and grains of approximately 10^{-7} m radius cannot readily radiate at these wavelengths. Consequently T_g is higher than T_{BB}. Illustrative grain temperatures are shown in table 4.1 for some grain materials in a mean interstellar radiation field. Temperatures inside clouds are, of course, lower. Nevertheless, because interior grains absorb infrared photons emitted by hotter grains at the edges of a cloud, interior grain mean temperatures are unlikely to fall to T_{BB}. For very small grains, the random arrival of photons may cause considerable variation in grain energy content. The grain temperature may therefore show severe 'spiking', in which the temperature may sometimes be far from its mean value. We shall see that grain temperature can be an important parameter in determining mechanisms by which grains may act as catalysts (section 4.6). The calculations leading to the results in table 4.1 depend on $Q_{\rm abs}$ in the IR, which in turn depends on the refractive index in that region. This quantity may be uncertain for small grains in the interstellar medium, so the results may not be very accurate.

Table 4.1.

Grain material	Radius (μm)	Temperature (K)
Graphite	0.05	45
Silicates	0.10	42
Olivine	0.05	22
	0.10	20
Fused quartz	0.05	19
	0.10	17
Silicate (0.05 μm) + ice mantles	0.10	14

4.4.2 Grain electric charge

This is another parameter which is important in connection with the rate at which ions may collide with and stick to grains. Ions in the gas, such as C^+ or H^+, will have either enhanced or inhibited collision rates with grains depending on whether the grain is charged negatively or positively. In this section we briefly discuss the physical effects which control the charge on a solid particle. Obviously, collisions of positive ions and electrons with grains will affect the charge, and therefore alter the rate of such collisions on grains. Let us assume that each such particle that hits a grain actually sticks to it.

Consider a positive ion of mass m_i and positive charge e approaching a spherical grain of radius a carrying a charge of Z electrons. It follows the path shown in figure 4.6, on which it is *just* captured by the grain due to electrostatic attraction. We say that it has an impact parameter p_0. For all impact parameters $p < p_0$ then capture occurs, so the capture cross-section is πp_0^2. If the velocity of the ion relative to the grain is u_i when they are well separated and v when at the point of capture, then by conservation of angular momentum

$$u_i p_0 = av \tag{4.10}$$

and by conservation of energy

$$\begin{aligned} \frac{1}{2}m_i u_i^2 &= \frac{1}{2}m_i v^2 - \frac{Ze^2}{4\pi\varepsilon_0 a} \\ &= \frac{1}{2}m_i\frac{u_i^2 p_0^2}{a^2} - \frac{Ze^2}{4\pi\varepsilon_0 a} \end{aligned} \tag{4.11}$$

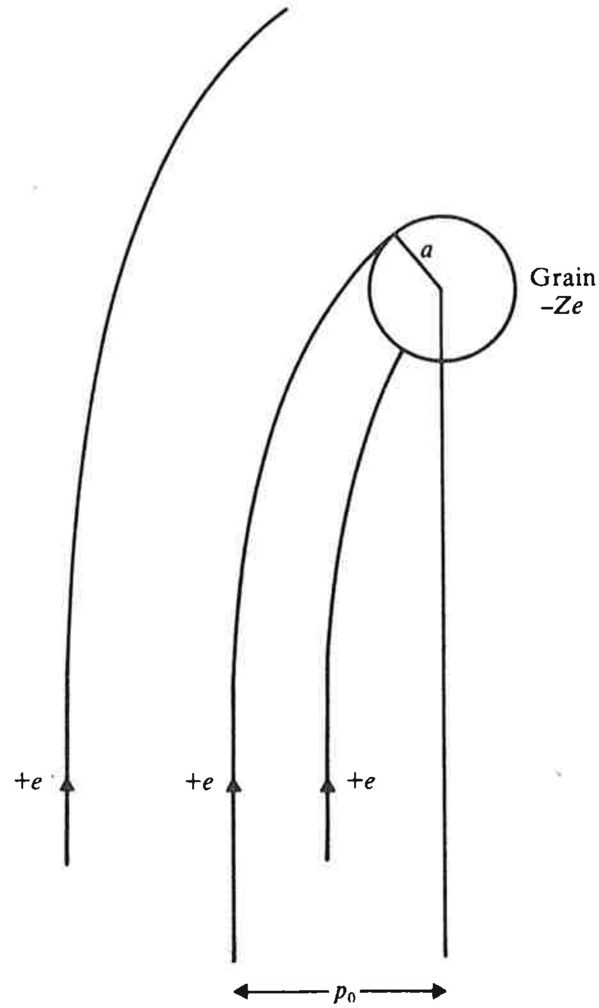

Figure 4.6. The capture of a positive ion charge $+e$ by a grain carrying negative charge $-Ze$. The impact parameter at which a grazing collision occurs is p_0.

from which we find the capture cross-section

$$\sigma_i = \pi p_0^2 = \pi a^2 \left(1 + \frac{2Ze^2}{4\pi\varepsilon_0 a m_i u_i^2}\right) \tag{4.12}$$

for ions being captured. Similarly, for electrons the capture cross-section is

$$\sigma_e = \pi a^2 \left(1 - \frac{2Ze^2}{4\pi\varepsilon_0 a m_e u_e^2}\right) \tag{4.13}$$

where m_e is the electron mass and u_e is the electron's velocity far away from the grain. In equilibrium the rate of collisions of electrons and ions must be equal if no other process plays a part; we should calculate these rates by integrating over Maxwellian distributions in velocity for ions and electrons in equations (4.12) and (4.13). However, we can obtain an approximate measure of the charge by using the most probable velocities $\bar{u}_i$ and $\bar{u}_e$. Equilibrium means that

$$n_e \sigma_e \bar{u}_e = n_i \sigma_i \bar{u}_i. \tag{4.14}$$

If the cloud is overall neutral, then $n_e = n_i$, and from (4.12), (4.13) and (4.14) we find

$$Z = \frac{3kT/2}{e^2/4\pi\varepsilon_0 a} \frac{\bar{u}_e - \bar{u}_i}{\bar{u}_e + \bar{u}_i} \approx \frac{3kT/2}{e^2/4\pi\varepsilon_0 a}. \tag{4.15}$$

At $T = 100$ K, Z is therefore of the order of 1 for $a = 10^{-7}$ m, while at $T = 10\,000$ K, Z is approximately 100.

There is another effect which may be important in determining the grain charge: photoelectric emission from grains (see section 3.3.4). At visible wavelengths, the efficiency of photoelectric emission, y, is rather small, near 10^{-4}; that is, about 10^4 photons may be needed for the emission of one electron. For photons in the far UV ($\lambda \approx 100$ nm) efficiencies are probably higher, especially in the case of very small particles ($a \approx 10$ nm) from which the electrons released escape easily. A typical interstellar photon flux near $\lambda = 100$ nm is 10^{10} photons $\mathrm{m^{-2}\,s^{-1}\,nm^{-1}}$. We might expect about $10^{11} y$ electrons to be released per $\mathrm{m^2}$ of grain surface per second in an unshielded region. This may be compared with a collision rate for electrons of $n_e v_e$ $\mathrm{m^{-2}\,s^{-1}}$ (if the accumulated charge is not large). We see that if y can be as large as 0.1 then typical low-density clouds in which $n_e \approx 10^5$ $\mathrm{m^{-3}}$ have grains whose charge is dominated by the photoelectric effect and are therefore positively charged. If this is so, then collisions of C^+ and H^+ will be partially suppressed, with consequences for catalysis involving these ions.

4.5 Grains as heating or cooling agents in interstellar gases

It is possible that the grains may contribute to the heating and cooling processes which we discussed in Chapter 3. Certainly, the photoelectric effect which we mentioned in the previous section would add to the heating of the gas, for each electron released would carry with it several eV of energy. The energy, E, of the emitted electron is given by

$$E = h\nu - W \tag{4.16}$$

where W is the work function of the material (typically about 5 eV) and $h\nu$ is the energy of the UV photon, approximately 11 eV. With the parameters used in section 4.4.1 we find a heating rate of about $10^{-26} ny$ $\mathrm{J\,m^{-3}\,s^{-1}}$, which by comparison with the values in section 3.3.2 may be important, if y is not too small (cf section 4.4.2).

In another way, grains may act as a sink for energy. If an H atom of a 100 K gas hits and sticks to grain at temperature 20 K, then an energy equivalent to 80 K has been lost from the gas, and will be present in the grain and ultimately radiated away. A simple calculation shows that a cooling rate for this process is

$$\Lambda_g \approx 3 \times 10^{-32} n^2 (T/100\ \mathrm{K}) \quad \mathrm{J\,m^{-3}\,s^{-1}} \tag{4.17}$$

which is clearly unimportant in low-density clouds.

An interesting situation can arise, however, when a dense cloud is heated and becomes optically thick in IR radiation. Then the grains radiate like a black-body. The peak wavelength λ_m (m) of a black-body at temperature T_{BB} (K) is given by

$$\lambda_m T_{\mathrm{BB}} \approx 3 \times 10^{-3}\ \mathrm{m\ K} \tag{4.18}$$

so that if the grains are at, say, 300 K, the emitted radiation is predominantly around 10 μm. Such sources are observed, and are very bright in the IR. They occur when all the UV radiation from a powerful star is trapped inside a dense cloud of gas and dust. Such a phenomenon—sometimes called a cocoon star—may arise in the process of star formation when a star begins to shine brightly although still inside the cloud which gave birth to it.

4.6 Grains as sites of molecule formation

4.6.1 The rate of H_2 formation on grain surfaces

We suggested in section 3.5 that the question of how hydrogen molecules form in the interstellar gas may be answered by the contribution that grains might make. It need not be surprising that they have some effect, for we know that in the laboratory the recombination of atoms into molecules occurs readily on the surfaces of vessels containing the atomic gas as well as in three-body collisions in the gas. The surfaces act as a third body, allowing stabilization of the molecule to occur. The major question really is: can grains be efficient enough in producing molecules so as to compete with the loss mechanisms we described in Chapter 3?

Let us try to answer this question by assuming that a catalytic process for

$$\mathrm{H} + \mathrm{H} \rightarrow \mathrm{H_2} \tag{4.19}$$

is completely efficient for all H atoms arriving at a grain surface. Then the rate of formation of H_2 is simply determined by the rate of arrival of H atoms at the surfaces of dust grains:

$$\frac{\mathrm{d}}{\mathrm{d}t} n(\mathrm{H_2}) = \frac{1}{2} n(\mathrm{H}) \pi a^2 n_g v_{\mathrm{H}} \tag{4.20}$$

for grains of radius a, number density n_g, and where v_{H} is the most probable velocity of H atoms. Now the quantity $\pi a^2 Q_{\mathrm{ext}} n_g$ is related to extinction, and if we assume $Q_{\mathrm{ext}} \approx 1$, then the grains causing visual extinction give a value for $\pi a^2 n_g$ of $3 \times 10^{-26} n\ \mathrm{m^{-1}}$, so that H_2 forms in a gas at $\sim$100 K at a rate

$$\frac{\mathrm{d}}{\mathrm{d}t} n(\mathrm{H_2}) \approx 3 \times 10^{-23} n\, n(\mathrm{H}) \quad \mathrm{m^{-3}\,s^{-1}} \tag{4.21}$$

(see section 3.4.3), where $n = n(\mathrm{H}) + 2n(\mathrm{H_2})$. The formation rate may be larger than this if other smaller grains are present, not contributing significantly to visual extinction, but providing more grain surface area per unit volume.

The mechanism by which H_2 molecules are destroyed has been described in section 3.3.2. Since this is a process which depends on the absorption of radiation in spectral *lines*, the molecules at the edge of a cloud may shield molecules of the interior by using up photons in the lines which do not penetrate further. The photodissociation rate for H_2 varies strongly with column density, $N(\mathrm{H_2})$ $\mathrm{m^{-2}}$, being approximately 10^{-10} $\mathrm{s^{-1}}$ for small $N(\mathrm{H_2})$ ($< 10^{18}$ $\mathrm{m^{-2}}$) but being 10^{-14} $\mathrm{s^{-1}}$ for large $N(\mathrm{H_2})$ ($\approx 10^{24}$ $\mathrm{m^{-2}}$). In the centre of a cloud of moderate density—say $n = 10^8$ $\mathrm{m^{-3}}$—the formation rate is therefore adequate to convert the bulk of hydrogen to molecular form, in which it is protected against photodissociation by self-shielding. Detailed studies show reasonable harmony between theory and observation. We conclude that grains do contribute H_2. In the next section we examine a simple picture of how this might occur.

4.6.2 H_2 formation on grains

To form a hydrogen molecule on a grain surface the minimum requirement is that one H atom is retained at the surface long enough for a second H atom to arrive and locate the first.

An H atom in the vicinity of a grain experiences long-range van der Waals forces arising from its interaction with all the atoms of the grain. If the atom is not chemically bound as it aproaches close to the surface, these weak forces create a potential well of depth q, where $q/k \approx 300$ K, for the infalling atom. On collision, the atom will generally transfer some energy to the lattice by exciting lattice photons, and so will remain bound to the surface. It may then move laterally across the surface, or it may become bound to a particular site in the lattice, and lateral motion will be impeded by another energy barrier, typically of energy equivalent to 50 K for physical adsorption on a perfect crystal. It is most unlikely, however, that grains are perfect crystals because of the violent events to which they are subject. There will be sites of dislocation, imperfections and vacancies which cause binding sites of energies ranging from weak physical adsorption to strong chemisorption.

To ensure that the second H atom arrives on the grain before the first has left we must require, at least, that the rate of arrival of H atoms exceeds the evaporation rate, i.e.

$$n(\mathrm{H})\pi a^2 \bar{v}_{\mathrm{H}} > \nu\, \mathrm{e}^{-q/kT_g}. \qquad (4.22)$$

Here πa^2 represents the cross-sectional area of the grain and $\bar{v}_{\mathrm{H}}$ is a most probable H-atom velocity. The frequency of oscillation of the bound H atom perpendicular to the surface is ν inside the well of depth q, and the grain temperature is T_g. We are here assuming that a classical description is adequate, and the exponential gives the fraction of a Maxwellian distribution with energy sufficient to overcome the energy barrier to evaporation, q.

Hence

$$T_g < \frac{q}{k}\left(\ln\frac{\nu}{n(\mathrm{H})\pi a^2 \bar{v}_{\mathrm{H}}}\right)^{-1}. \tag{4.23}$$

For a physically adsorbed atom (i.e. adsorbed by weak forces, not chemisorbed) this gives $T_g \lesssim 12$ K for numbers given above. If $T_g > 12$ K, in this case, then the second H atom arrives too late! From our discussion of temperatures (section 4.4.1), we see that T_g is unlikely to satisfy this condition, and so we infer that H atoms must be more strongly bound to the surface for H_2 formation to occur.

Motion across the grain surface affects the rate at which the adsorbed atoms find each other. If they have relaxed to the grain temperature and are bound to lattice sites then they can travel only by quantum-mechanical penetration of the barrier between the sites. We can describe the motion in a weak binding case in the following way: the atom vibrates laterally with a frequency ν' and has a probability P of penetrating the barrier to the neighbouring site a distance a' away. The atom therefore migrates over the surface with a velocity $u = Pa'\nu'$. Clearly P and ν' are dependent on T_g, but a simple calculation in quantum mechanics gives typical values $P \approx 10^{-3}$, for $a' \approx 3 \times 10^{-10}$ m and $\nu' \approx 3 \times 10^{11}$ s, so that $u \approx 0.1$ m s^{-1}. If the atom is likely to interact with another atom within a distance $l \approx 3 \times 10^{-10}$ m it will search the whole surface area, $4\pi a^2$, of the grain in a time $4\pi a^2/lu$, which is $\sim 10^{-3}$ s for the above numbers. This time must be short compared with the residence time, $(1/\nu)\,\mathrm{e}^{q/kT_g}$.

A preferable description of the atom–surface interaction when the surface is presumed to be a regular crystal would be a quantum-mechanical description of the surface state with non-localized atoms. If chemisorption occurs on a perfect crystal, this is the proper description.

However, these simple calculations indicate that an H atom arriving at a surface and being bound at a moderate-energy site so that it is retained long enough for a second atom to arrive will usually meet the second atom. We assume that they then form a molecule. It is worth noting that binding energies for other atoms and radicals on to grain surfaces are larger than for hydrogen. If catalysis works for hydrogen, it is likely to work for other molecules, too. We therefore expect that H_2O, CH_4 and NH_3 will also be formed on surfaces.

4.6.3 Grains as sites for ice deposition

We have already remarked that dust in denser regions exhibits absorption characteristics of amorphous ice and of solid CO. The existence of these two solids illustrates the two processes by which ices are formed on interstellar dust. Water ice is found in regions where H_2O is not sufficiently abundant to form ice by simple accretion, according to the process described in equation (4.6). It seems more likely that free oxygen atoms arriving at the surfaces of dust grains are converted to H_2O molecules, and—mostly—retained to form ices:

$$\mathrm{O_{gas}} \rightarrow \mathrm{O_{surface}} \rightarrow \mathrm{H_2O_{surface}}. \tag{4.24}$$

By contrast, in regions where solid CO is found, nearly all the carbon is in CO and the solid is formed from simple freeze-out on the cold dust, according to equation (4.6).

Problems

1. Suppose that the interstellar medium contains dust grains with uniform number density 10^{-6} m^{-3}, all with the same radius, 10^{-7} m, and extinction efficiency $Q_{\rm ext} = 0.5$ at wavelength λ_0. Find the extinction in magnitudes at wavelength λ_0 for a star at a distance 1 kpc from the Earth.
2. Derive equation (4.6). What assumption is made concerning n_i? Consider an interstellar cloud in which the number density of CO molecules is 10^6 m^{-3}, and in which the temperature is 10 K. How long would it take for a grain of radius 10^{-7} m to grow to a radius of 2×10^{-7} m by adding a mantle of CO? Assume that the sticking coefficient of CO is unity and that the density of solid CO is 10^3 kg m^{-3}.
3. Estimate a lifetime for interstellar grains in a uniform interstellar gas, H-atom density 10^6 m^{-3}, by sputtering in supernova blast waves, using the information in section 4.3.2 and assuming a supernova rate for the Galaxy of one every thirty years.
4. Suppose that the heat input into an interstellar grain is entirely by UV absorption. Assume that the UV flux is 10^{10} photons m^{-2} s^{-1} nm^{-1}, that the bandwidth is 100 nm, and that the mean photon energy is 9 eV. If the grain cools by radiating like a black-body with an efficiency of 0.1%, find the grain temperature.
5. At a point P in an interstellar cloud $n(\mathrm{H}) = 10^7$ m^{-3} and $n(\mathrm{H_2}) = 4.5 \times 10^7$ m^{-3}. Use equation (4.21) to find the photodissociation rate, $\beta(\mathrm{H_2})$, at P. In a plane-parallel slab model, an approximation for $\beta(\mathrm{H_2})$ is $4 \times 10^4 N^{-0.8}$ s^{-1}, where N is the column density of H_2 (m^{-2}) towards the cloud edge. Find N at the point P.
6. Using equation (4.7) make an estimate of the velocity at which dust grains are driven by radiation pressure through an envelope of cool gas surrounding a star. Assume that the effective temperature of the star is $10^{3.5}$ K and that the number density of the envelope gas at radius R_0, $n(R_0)$, is 10^{18} m^{-3}.