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Interstellar Dust

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Abstract

In the interstellar medium of the Milky Way, certain elements (e.g., Mg, Si, Al, Ca, Ti, and Fe) reside predominantly in interstellar dust grains. These grains absorb, scatter, and emit electromagnetic radiation, heat the interstellar medium by photoelectric emission, play a role in the ionization balance of the gas, and catalyze the formation of molecules, particularly H_2. I review the state of our knowledge of the composition and sizes of interstellar grains, including what we can learn from spectral features, luminescence, scattering, infrared emission, and observed gas-phase depletions. The total grain volume in dust models that reproduce interstellar extinction is significantly greater than estimated from observed depletions.

Dust grains might reduce the gas-phase D/H ratio, providing an alternative mechanism to explain observed variations in the gas-phase D/H ratio in the local interstellar medium. Transport in dust grains could cause elemental abundances in newly formed stars to differ from interstellar abundances.

1.1 Introduction

Certain elements—Si and Fe being prime examples– are often extremely *depleted* from the interstellar gas (Jenkins 2004). The explanation for this depletion is that the atoms that are "missing" from the gas phase are located in solid particles—interstellar dust grains. The existence of this solid phase complicates efforts to determine elemental abundances, due to the difficult-to-determine abundance in grains.

The concentration of certain elements in dust grains also creates the possibility of selective transport of those elements through the gas, which could, at least in principle, lead to variations in elemental abundances from point to point in the interstellar medium, and possibly even differences between stellar and interstellar abundances. Dust grains might even deplete deuterium from the gas, providing an alternative explanation for observed variations in D/H ratios.

Observations of interstellar dust were recently reviewed by Whittet (2003) and Draine (2003a). The astrophysics of interstellar dust is a broad subject, encompassing dust grain formation and destruction, charging of dust grains, heating of interstellar gas by photoelectrons from dust, electron transfer from dust grains to metal ions, the optics of interstellar dust, optical luminescence and infrared emission from dust, chemistry on dust grains, and the dynamics of dust grains, including radiation-driven drift of grains relative to gas and alignment of dust by the magnetic field. Introductions to the astrophysics of dust can be found in Krügel (2003) and Draine (2003d).

1.2 Presolar Grains in Meteorites are Nonrepresentative

Genuine interstellar grains are found in meteorites (Clayton & Nittler 2004), but, because present search techniques rely on isotopic anomalies, the grains that are found are limited to those formed in stellar winds or ejecta. Theoretical studies of grain destruction by supernova-driven blastwaves lead to estimated grain lifetimes of only $\sim (2-3) \times 10^8$ yr (Draine & Salpeter 1979; Jones et al. 1994); this, together with the large depletions typically seen for elements like Si, implies that the bulk of interstellar grain material must be regrown in the interstellar medium (Draine & Salpeter 1979; Draine 1990).

Because the typical interstellar grains do not bear a distinctive isotopic signature, we do not know how to identify them in meteorites. We are therefore forced to study interstellar grains remotely.

1.3 Interstellar Reddening

Our knowledge of interstellar dust is largely derived from the interaction of dust particles with electromagnetic radiation: attenuation of starlight, scattering of light, and emission of infrared and far-infrared radiation.

The wavelength dependence of interstellar extinction tells us about both the size and composition of the grains. The extinction is best determined using the "pair method"—comparison of the fluxes from two stars with nearly identical spectroscopic features (and therefore photospheric temperature and gravity) but with one of the stars nearly unaffected by dust. With the assumption that the extinction goes to zero as wavelength $\lambda \to \infty$, it is possible to determine the extinction A_λ as a function of wavelength (see, e.g., Fitzpatrick & Massa 1990, and references therein).

The extinction A_λ is obviously proportional to the amount of dust, but A_λ/A_{λ_0}, the extinction normalized to some reference wavelength λ_0, characterizes the *kind* of dust present, and its size distribution. The quantity $R_V \equiv A_V/(A_B - A_V)$ characterizes the slope of the extinction curve between $V = 0.55\,\mu$m and $B = 0.44\,\mu$m; small values of R_V correspond to steep extinction curves.

In principle, the function A_λ/A_{λ_0} is unique to every sightline, but Cardelli, Clayton, & Mathis (1989) found that the observed A_λ/A_{λ_0} can be approximated by a one-parameter family of curves: $A_\lambda/A_{\lambda_0} = f(\lambda, R_V)$, where they chose $R_V \equiv A_V/(A_B - A_V)$ as the parameter because it varies significantly from one curve to another. Cardelli et al. obtained functional forms for $f(\lambda, R_V)$ that provided a good fit to observational data; Fitzpatrick (1999) revisited this question and, explicitly correcting for the finite width of photometric bands, obtained a slightly revised set of fitting functions. Figure 1.1 shows the Fitzpatrick (1999) fitting functions, using $I_C = 0.802\,\mu$m, the central wavelength of the Cousins I band, as the reference wavelength. The parameterization is shown for values of R_V ranging from 2.1 to 5.5, which spans the range of R_V values encountered on sightlines through diffuse clouds in the Milky Way. Also shown is an empirical fit to the extinction measured toward HD 210121, showing how an individual sightline can deviate from the one-parameter fitting function $f(\lambda, R_V)$.

Dust on sightlines with different values of R_V obviously must have either different compositions or different size distributions, or both. Also of interest is the total amount of dust per unit H. This requires measurement of the total H column density $N_{\rm H} \equiv N({\rm H}) + 2N({\rm H_2}) +$

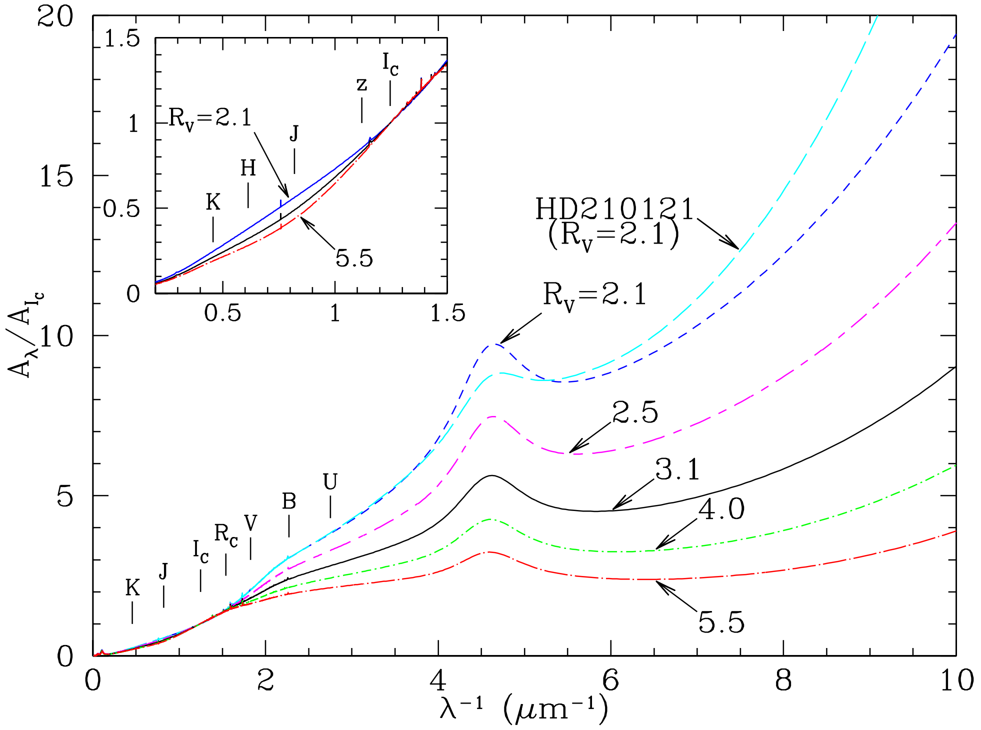

Fig. 1.1. Extinction normalized to Cousins I-band extinction for R_V values ranging from 2.1 to 5.5, using the Fitzpatrick (1999) parameterization, plus diffuse interstellar bands following Jenniskens & Desert (1994). Also shown is an improved fit to the extinction curve toward HD 210121, providing one example of how a sightline can deviate from the average behavior for the same value of R_V.

$N(H^+)$. On most sightlines the ionized hydrogen is a small correction; $N(H)$ and $N(H_2)$ can be measured using ultraviolet absorption lines.

Rachford et al. (2002) determined N_H to an estimated accuracy of better than a factor 1.5 on 14 sightlines. It appears that A_I/N_H is positively correlated with R_V, with

$$A_I/N_H \approx \left[2.96 - 3.55\left(\frac{3.1}{R_V} - 1\right)\right] \times 10^{-22}\mathrm{cm}^2, \tag{1.1}$$

providing an empirical fit (Draine 2003a). We can use the Fitzpatrick (1999) parameterization and Equation (1.1) to estimate A_λ/N_H for sightlines with different R_V. The results are shown in Figure 1.2—sightlines with larger R_V values appear to have larger values of A_λ/N_H for $\lambda^{-1} \lesssim 3\,\mu\mathrm{m}^{-1}$, and decreased values for $\lambda^{-1} \gtrsim 4\,\mu\mathrm{m}^{-1}$. This is interpreted as resulting from coagulation of a fraction of the smallest grains onto the larger grains; loss of small grains decreases the ultraviolet extinction, while adding mass to the larger grains increases the scattering at $\lambda \gtrsim 0.3\,\mu$m.

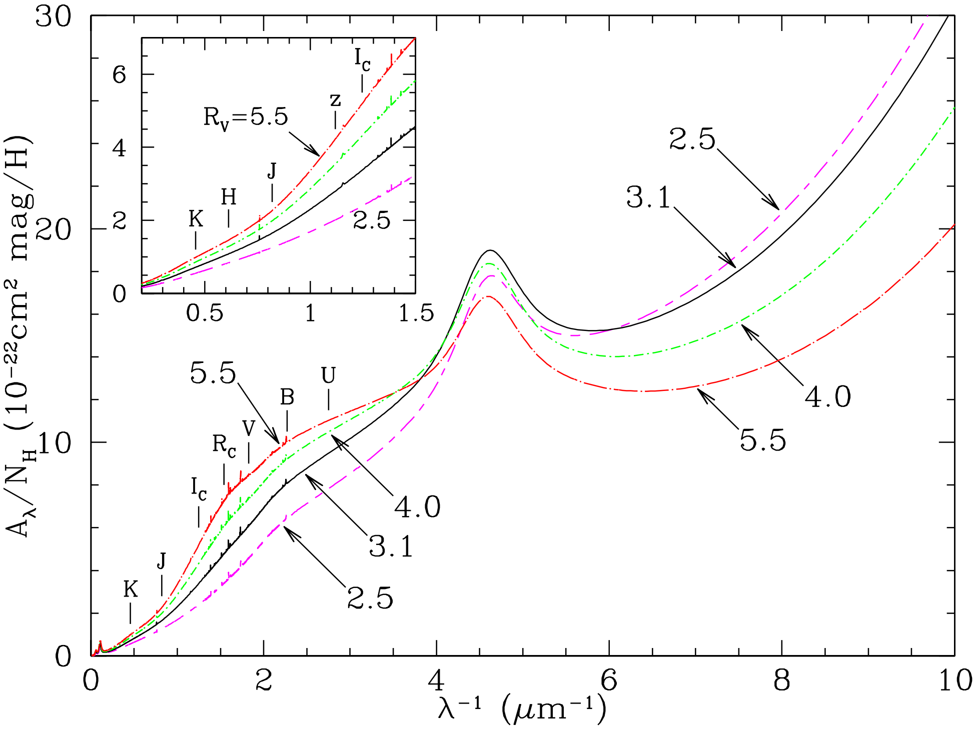

Fig. 1.2. Extinction per unit H column density, for different R_V. (Adapted from Draine 2003a.)

1.4 Spectroscopy of Dust in Extinction and Emission

1.4.1 PAH Emission Features

Interstellar dust glows in the infrared, with a significant fraction of the power radiated at $\lambda \lesssim 25\,\mu$m. In reflection nebulae the surface brightness is often high enough to permit spectroscopy of the emission; the 5–15 μm spectrum of NGC 7023 is shown in Figure 1.3. The spectrum has five very conspicuous emission peaks, at $\lambda = 12.7, 11.3, 8.6, 7.6$, and 6.25 μm; there is an additional emission peak at 3.3 μm (not shown here), as well as weaker peaks at 12.0 and 13.6 μm.

These emission features are in striking agreement with the wavelengths of the major optically active vibrational modes for polycyclic aromatic hydrocarbon (PAH) molecules: the 5–15 μm features are labelled in Figure 1.3; the 3.3 μm feature (not shown) is the C-H stretching mode. The vibrational excitation results from single-photon heating (see §1.5). The strength of the observed emission requires that PAH molecules be a major component of interstellar dust. Modeling the observed emission in reflection nebulae indicates that the PAH species containing $\lesssim 10^3$ C atoms contain ~40 ppm C/H—approximately 15% of $(C/H)_\odot = 246 \pm 23$ ppm (Allende Prieto, Lambert, & Asplund 2002).

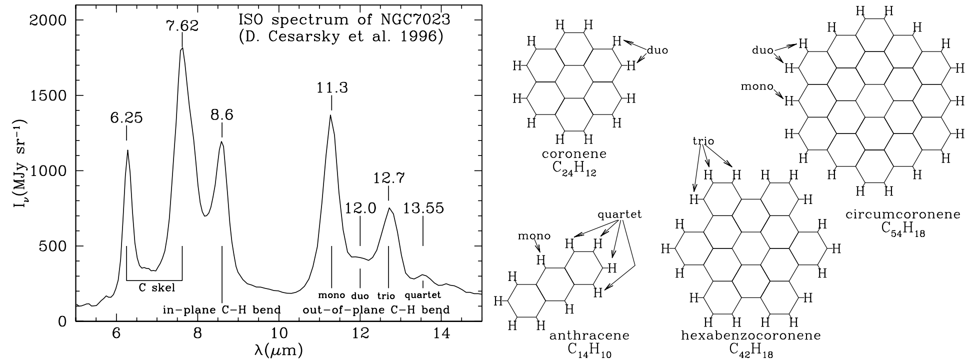

Fig. 1.3. PAH emission features in the 5–15 μm emission spectrum of the reflection nebula NGC 7023 (Cesarsky et al. 1996), and four PAH molecules, with examples of mono, duo, trio, and quartet H sites indicated.

1.4.2 2175 Å Feature: Graphitic C

By far the strongest feature in the extinction curve is the 2175 Å "bump" (see Figs. 1.1 and 1.2). Stecher & Donn (1965) pointed out that the observed feature coincided closely with the position and width of absorption expected from small spheres of graphite. Graphite consists of parallel sheets of graphene—two-dimensional hexagonal carbon lattices; adjacent graphene layers interact only through a weak van der Waals interaction.

The 2175 Å feature arises from a $\sigma \rightarrow \sigma^*$ excitation of a σ orbital in graphene; in small graphite spheres the feature strength corresponds to an oscillator strength per C of 0.16 (Draine 1989), so that the observed 2175 Å feature requires C/H $\approx$ 60 ppm $\approx 0.25(\mathrm{C/H})_\odot$ to account for the observed strength of the 2175 Å feature.

In a large PAH molecule, the interior C atoms have electronic orbitals closely resembling those in graphene, and one therefore expects that large PAH molecules will have a strong absorption feature peaking near 2175 Å, with an oscillator strength per C expected to be close to the value for graphite. It is of course interesting to note that the C/H in PAHs required to account for the 3–15 μm infrared emission is $\sim 2/3$ of that required to account for the 2175 Å bump. Since it would be entirely natural to have additional PAHs containing $> 10^3$ C atoms, it is plausible that the 2175 Å feature could be entirely due to PAHs, in which case the PAHs contain C/H $\approx$ 60 ppm.

The 2175 Å feature is suppressed in graphite grains with $a \gtrsim 0.02\,\mu$m because the grain becomes opaque throughout the 1800–2600 Å range. There can therefore be additional "aromatic" C within $a \gtrsim 0.02\,\mu$m grains.

1.4.3 10 and 18 μm Silicate Features

Interstellar dust has a strong absorption feature at 9.7 μm. While the precise composition and structure of the carrier remains uncertain, there is little doubt that the 9.7 μm feature is produced by the Si–O stretching mode in silicates. In the laboratory, crystalline silicates have multiple narrow features in their 10 μm spectra, while amorphous silicate material has a broad profile.

The interstellar 9.7 μm feature is seen in absorption on a number of sightlines. The observed profiles are broad and relatively featureless, indicative of amorphous silicate material. The observed strength of the absorption feature requires that much, perhaps most, of interstellar Si atoms reside in silicates. Li & Draine (2001a) estimated that at most 5% of interstellar silicate material was crystalline. Conceivably, a mixture of a large number of different crystalline minerals (Bowey & Adamson 2002) could blend together to produce the observed smooth profiles, although it seems unlikely that nature would have produced a blend of crystalline types with no fine structure evident in either absorption or emission, including emission in the far-infrared (Draine 2003a). The $9.7\,\mu$m extinction profile does not appear to be "universal"—sightlines through the diffuse interstellar medium show a *narrower* feature than sightlines through dense clouds (Roche & Aitken 1984; Bowey, Adamson, & Whittet 1998). Evidently the silicate material is altered in interstellar space.

Identification of the $9.7\,\mu$m feature as the Si–O stretching mode is confirmed by the presence of a broad feature centered at $\sim 18\,\mu$m (McCarthy et al. 1980; Smith et al. 2000) that is interpreted as the O–Si–O bending mode in silicates.

Spectral features of crystalline silicates are seen in some circumstellar disks (Artymowicz 2000; Waelkens, Malfait, & Waters 2000) and some comets (Hanner 1999), but even in these objects only a minority of the silicate material is crystalline (e.g., Bouwman et al. 2001).

1.4.4 3.4 μm C-H Stretch: Aliphatic Hydrocarbons

Sightlines with sufficient obscuration reveal a broad absorption feature at $3.4\,\mu$m that is identified as the C–H stretching mode in aliphatic (i.e., chain-like) hydrocarbons. Unfortunately, it has not proved possible to identify the specific aliphatic hydrocarbon material, and the band strength of this mode varies significantly from one aliphatic material to another. Sandford et al. (1991) suggest that the $3.4\,\mu$m feature is due to short saturated aliphatic chains incorporating C/H $\approx$ 11 ppm, while Duley et al. (1998) attribute the feature to hydrogenated amorphous carbon (HAC) material containing C/H $\approx$ 85 ppm.

1.4.5 Diffuse Interstellar Bands

In addition to narrow absorption features identified as atoms, ions, and small molecules, the observed extinction includes a large number of broader features—known as the "diffuse interstellar bands" (DIBs). The first DIB was recognized over 80 years ago (Heger 1922), and shown to be interstellar 70 years ago (Merrill 1934). A recent survey by Jenniskens & Desert (1994) lists over 154 "certain" DIBs, with another 52 "probable" features. Amazingly, not a single one has yet been positively identified!

High resolution spectroscopy of the 5797 Å and 6614 Å DIBs reveals fine structure that is consistent with rotational bands in a molecule with tens of atoms (Kerr et al. 1996, 1998), and there is tantalizing evidence that DIBs at 9577 Å and 9632 Å may be due to C_{60}^{+} (Foing & Ehrenfreund 1994; Galazutdinov et al. 2000; but see also Jenniskens et al. 1997 and Moutou et al. 1999.)

It appears likely that some or all of the DIBs are due to absorption in large molecules or ultrasmall grains. As noted above, a large population of PAHs is required to account for the observed infrared emission, and it is reasonable to suppose that these PAHs may be responsible for many of the DIBs. What is needed now is laboratory gas-phase absorption spectra for comparison with observed DIBs. Until we have precise wavelengths (and band profiles) from gas-phase measurements, secure identification of DIBs will remain problematic.

1.4.6 Extended Red Emission

Interstellar dust grains luminesce in the far-red, a phenomenon referred to as the "extended red emission" (ERE). The highest signal-to-noise ratio observations are in reflection nebulae, where a broad, featureless emission band is observed to peak at wavelengths 6100 Å $\lesssim \lambda_p \lesssim$ 8200 Å, with a FWHM in the range 600–1000 Å (Witt & Schild 1985; Witt & Boroson 1990). The ERE has also been seen in H II regions (Darbon et al. 2000), planetary nebulae (Furton & Witt 1990), and the diffuse interstellar medium of our Galaxy (Gordon, Witt, & Friedmann 1998; Szomoru & Guhathakurta 1998).

The ERE is photoluminescence: absorption of a starlight photon raises the grain to an excited state from which it decays by spontaneous emission of a lower-energy photon. The reported detection of ERE from the diffuse interstellar medium (Gordon et al. 1998; Szomoru & Guhathakurta 1998) appears to require that the interstellar dust mixture have an overall photoconversion efficiency of order $\sim$10% for photons shortward of $\sim$5000 Å. If the overall efficiency is $\sim$10%, the ERE carrier itself must contribute a significant fraction of the overall absorption by interstellar dust at $\lambda \lesssim$ 5000 Å.

Candidate ERE carriers that have been proposed include PAHs (d'Hendecourt et al. 1986) and silicon nanoparticles (Ledoux et al. 1998; Witt, Gordon, & Furton 1998; Smith & Witt 2002). While some PAHs are known to luminesce, attribution of the ERE to PAHs is difficult because of nondetection of PAH emission from some regions where ERE is seen (Sivan & Perrin 1993; Darbon et al. 2000) and nondetection of ERE in some reflection nebulae with PAH emission (Darbon, Perrin, & Sivan 1999). Oxide-coated silicon nanoparticles appear to be ruled out by nondetection of infrared emission at $\sim 20\,\mu$m (Li & Draine 2002a). The search to identify the ERE carrier continues.

1.4.7 X-ray Absorption Edges

Dust grains become nearly transparent at X-ray energies, so that the measured X-ray absorption is sensitive to *all* of the atoms, not just those in the gas phase. Consider, for example, K shell absorption by an oxygen atom, where photoabsorption excites one of the $1s$ electrons to a higher (initially vacant) energy level. Transitions to a bound state ($2p$, $3p$, $4p$, ...) produce a series of absorption lines, and transitions to unbound "free" (i.e., "photoelectron") states result in a continuum beginning at the "absorption edge." If the atom is in a solid, the absorption spectrum is modified because the available bound states and free electron states are modified by the presence of other nearby atoms. High-resolution X-ray absorption spectroscopy of interstellar matter could thereby identify the chemical form in which elements are bound in dust grains (Forrey, Woo, & Cho 1998, and references therein).

Figure 1.4 shows the structure expected for scattering, absorption, and extinction near the major X-ray absorption edges in a grain model composed of sp^2-bonded carbon grains plus amorphous $MgFeSiO_4$ grains (Draine 2003c). Spectroscopy with $\lesssim$ 1 eV energy resolution near these absorption edges for both interstellar sightlines and laboratory samples can test this model for the composition of interstellar dust. The *Chandra X-ray Observatory* has measured the wavelength-dependent extinction near the absorption edges of O (Paerels et al. 2001; Takei et al. 2002) and O, Mg, Si, and Fe (Schulz et al. 2002), but it has not yet proved possible to identify the chemical form in which the solid-phase Mg, Si, Fe, and O reside.

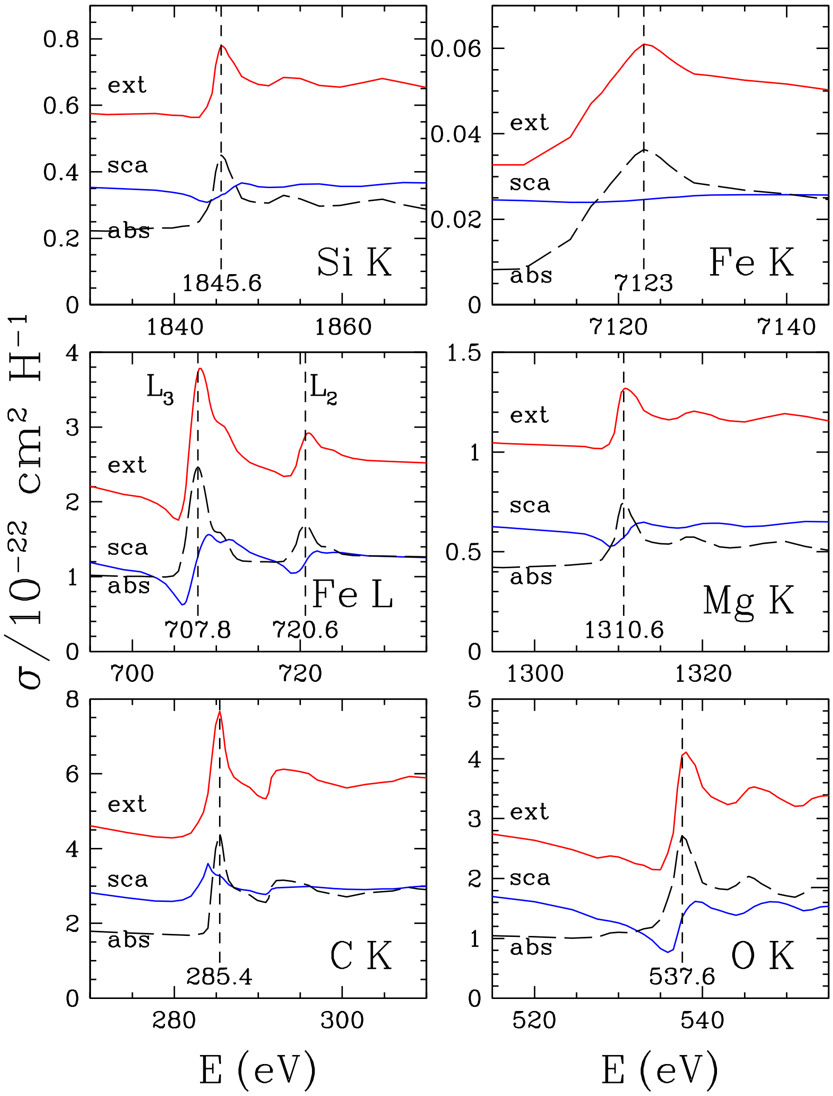

Fig. 1.4. Scattering and absorption cross-sections per H nucleon near principal X-ray absorption edges, for an interstellar dust model consisting of graphite and amorphous silicate grains. (From Draine 2003c.)

1.5 Infrared Emission Spectrum of Interstellar Dust

Interstellar dust grains are heated primarily by absorption of starlight photons. A small fraction of the absorbed starlight energy goes into luminescence or ejection of a photoelectron, but the major part of the absorbed starlight energy goes into heating (i.e., vibrationally exciting) the interstellar grain material. Figure 1.5 shows grain temperature vs. time simulated for four sizes of carbonaceous grains exposed to the average interstellar radiation field. For grain radii $a \gtrsim 100$ Å, individual photon absorptions are relatively frequent, and

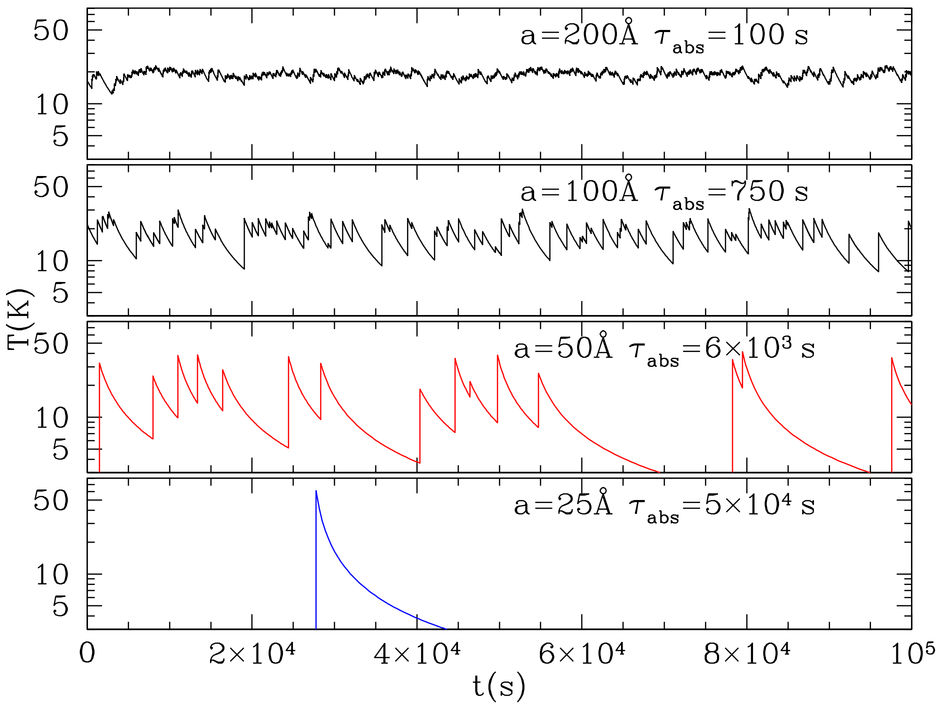

Fig. 1.5. A day in the life of four carbonaceous grains, exposed to the average starlight background. $\tau_{\rm abs}$ is the mean time between photon absorptions.

the grain heat capacity is large enough that the temperature excursions following individual photon absorptions are relatively small; it is reasonable to approximate the grain temperature as approximately constant in time. For $a \lesssim 50$ Å grains, however, the grain is able to cool appreciably in the time between photon absorptions; as a result, individual photon absorption events raise the grain temperature to well above the mean value. To calculate the time-averaged infrared emission spectrum for these grains, one requires the temperature distribution function (see, e.g., Draine & Li 2001).

Figure 1.6 shows the average emission spectrum of interstellar dust, based on observations of the far-infrared emission at high galactic latitudes, plus observations of a section of the Galactic plane where the surface brightness is high enough to permit spectroscopy by the *IRTS* satellite (Onaka et al. 1996; Tanaka et al. 1996).

The similarity of the 5–15 μm spectrum with that of reflection nebulae is evident (see Fig. 1.3). Approximately 21% of the total power is radiated between 3 and 12 μm, with another $\sim$ 14% between 12 and 50 μm. This emission is from dust grains that are so small that single-photon heating (see Fig. 1.5) is important. The remaining $\sim$65% of the power is radiated in the far-infrared, with λI_λ peaking at $\sim 130\,\mu$m. At far-infrared wavelengths, the grain opacity varies as $\sim \lambda^{-2}$, and $\lambda I_\lambda \propto \lambda^{-6}/(e^{hc/\lambda k T_d}-1)$ peaks at $\lambda = hc/5.985kT_d = 134(18\,{\rm K}/T_d)\,\mu$m. The emission spectrum for 18 K dust with opacity $\propto \lambda^{-2}$ shown in Figure 1.6 provides a good fit to the observed spectrum for $\lambda \geq 80\,\mu$m, but falls far below the observed emission at $\lambda \leq 50\,\mu$m. From Figure 1.6 it is apparent that $\sim$ 60% of the radiated

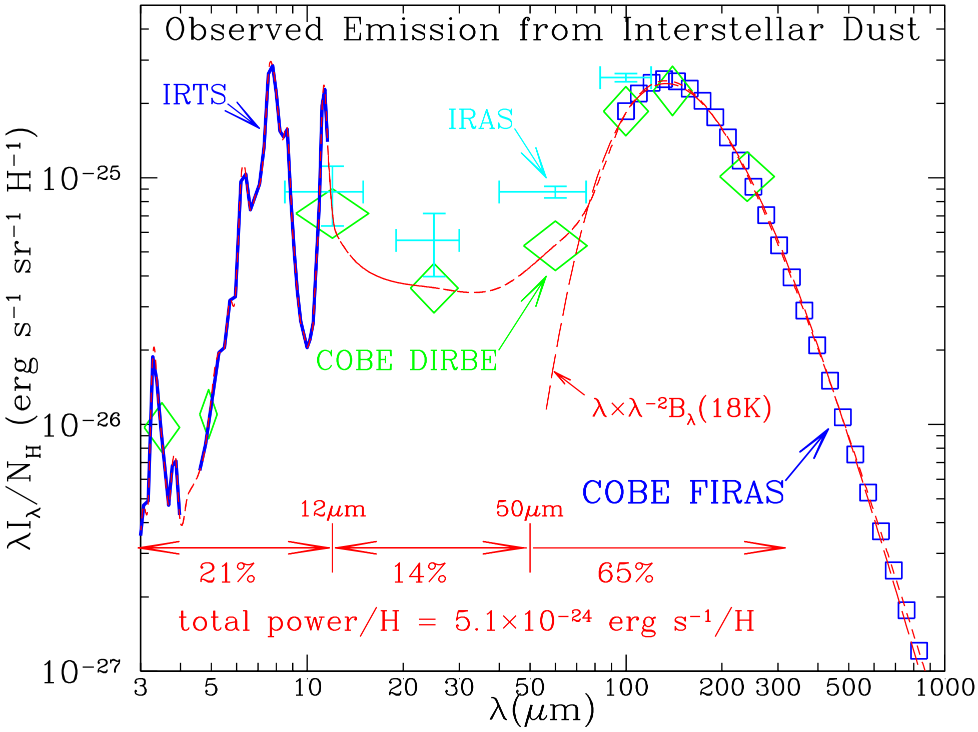

Fig. 1.6. Observed emission spectrum of diffuse interstellar dust in the Milky Way. Crosses: *IRAS* (Boulanger & Perault 1988); squares: *COBE*-FIRAS (Finkbeiner, Davis, & Schlegel 1999); diamonds: *COBE*-DIRBE (Arendt et al. 1998); heavy curve for 3–4.5 μm and $5-11.5\,\mu$m: *IRTS* (Onaka et al. 1996; Tanaka et al. 1996). The total power, $\sim 5.1 \times 10^{-24}\,\mathrm{erg\,s^{-1}/H}$, is estimated from the interpolated broken line.

power appears to originate from grains that are sufficiently large (radii $a \gtrsim 100$ Å) so that individual photon absorption events do not appreciably raise the grain temperature.

1.6 Dust Grain Size Distribution

A physical grain model of PAHs, carbonaceous grains, and amorphous silicate grains has been constructed to reproduce observations of interstellar extinction and infrared emission (Li & Draine 2001a; Weingartner & Draine 2001a). The material dielectric functions and heat capacities, and absorption cross-sections for the PAHs, are consistent with laboratory data and physics; once the size distribution is specified, the properties of the grain model (scattering, extinction, infrared emission) can be calculated.

The grain size distribution for average diffuse clouds ($R_V \approx 3.1$) in our region of the Milky Way is shown in Figure 1.7. The mass distribution must peak near $\sim 0.3\,\mu$m in order to reproduce the observed extinction near visual wavelengths. The peak in the PAH distribution near $0.0005\,\mu$m is required for single-photon heating to reproduce the observed 3–12 μm emission, but the secondary peak near $0.005\,\mu$m in Figure 1.7 may be an artifact of the fitting procedure.

Milky Way extinction curves with different R_V values, or extinction curves for the LMC

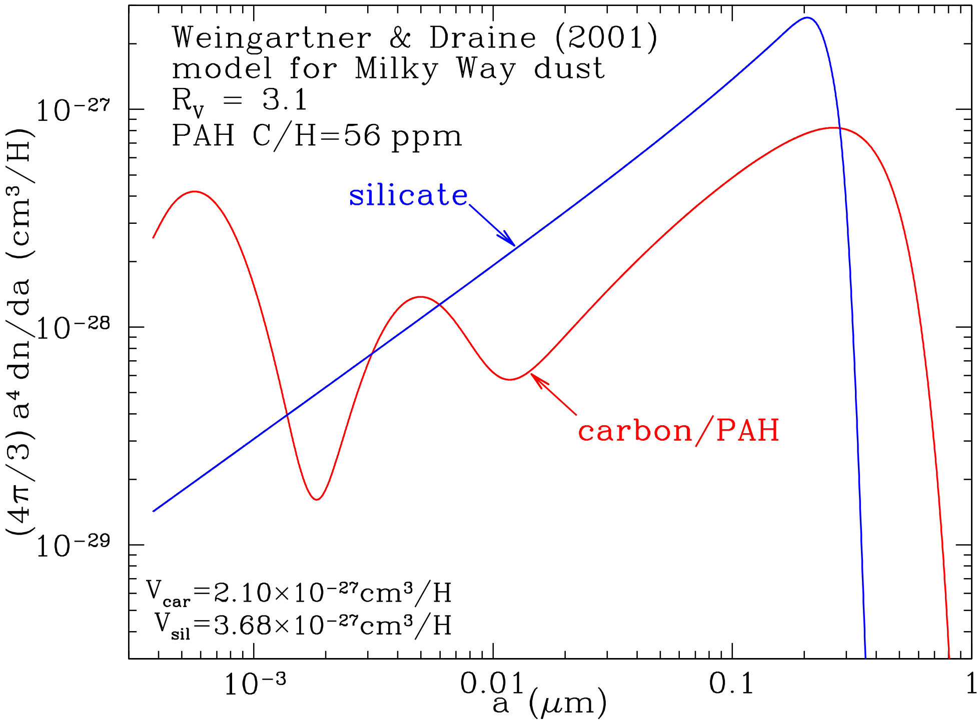

Fig. 1.7. Size distributions for dust model of Weingartner & Draine (2001a).

and SMC, can be reproduced by varying the size distribution. The grain model appears to be consistent with the observed scattering properties of interstellar dust in the optical and ultraviolet (Draine 2003b) and at X-ray energies (Draine 2003c).

The grain model also reproduces the observed infrared emission in the diffuse interstellar medium of the Milky Way (Li & Draine 2001a), reflection nebulae (Li & Draine 2002b), and the SMC Bar (Li & Draine 2002c).

1.7 Dust Abundances vs. Depletion Patterns

Jenkins (2004) finds that observed depletions on many sightlines suggest two types of grain material: a "core" material that is returned to the gas phase only in very high velocity shock waves, and a "mantle" material that is more easily stripped. For low velocity gas, variations in depletion from one sightline to another are interpreted as due to invariant grain cores plus varying amounts of mantle material.

What do Jenkins' abundances of elements in the cores and mantles suggest as regards the volumes of cores and mantles? Table 1.1 shows one possible mix of minerals that could reproduce the overall elemental compositions deduced by Jenkins for sightlines with "depletion multiplier" $F_* = 1$, representative of "cool disk" material. The aims of this exercise are to estimate (1) how much oxygen is likely to be in the grain material and (2) the volumes of core and mantle material that would be consistent with the depletion patterns found by Jenkins, for comparison with the grain volume required by physical dust models. The compositions in Table 1.1 are purely illustrative and should *not* be taken to be realistic.

Table 1.1. *Jenkins (2004) Grain Composition: One Illustrative Possibility*

Material	C [a]	O [a]	Mg [a]	Si [a]	Al [a]	Ca [a]	Fe [a]	Ni [a]	ρ [b]	V [c]
Grain Cores										
C,PAH,HAC,...	71	-	-	-	-	-	-	-	2.2	6.5
$MgFeSiO_4$ olivine	-	52	13	13	-	-	13	-	3.8	9.8
$CaMgSiO_4$ monticellite	-	8	2	2	-	2	-	-	3.2	1.6
Fe_2O_3 hematite	-	18	-	-	-	-	12	-	5.3	3.0
Al_2O_3 corundum	-	4.5	-	-	3	-	-	-	4.02	0.6
Ni_2O_3 dinickel trioxide	-	2.4	-	-	-	-	-	1.6	4.84	0.5
Illustrative Core Total	71	85	15	15	3	2	25	1.6	3.5	22.1
Observed Core Total [d]	71^{+61}_{-71}	53^{+49}_{-53}	15	14	3.0	2.2	25	1.6		
Grain Mantles										
C,PAH,HAC,...	35	-	-	-	-	-	-	-	2.2	3.2
$Mg_{0.9}Fe_{0.1}SiO_3$ pyroxene	-	57	17	19	-	-	2	-	3.3	9.9
Illustrative Mantle Total	35	57	17	19	-	-	2	-	3.5	13.1
Cores + Mantles										
C,PAH,HAC,...	106	-	-	-	-	-	-	-	2.2	9.7 [e]
silicates	-	117	32	34	-	2	15	-	3.5	21.4 [e]
other	-	24	-	-	3	-	12	1.6	5.2	4.0
Illustrative Core + Mantle Total	106	142	32	34	3	2	27	1.6	3.5	35.2 [e]
Observed Core + Mantle Total [d]	106^{+16}_{-20}	134^{+22}_{-23}	32	33	3.0	2.2	28	1.8		

[a] Atomic abundance (ppm) per total H.
[b] Solid density ($g\,cm^{-3}$).
[c] Grain volume per total H ($10^{-28}\,cm^3$).
[d] From Jenkins (2004). Quoted uncertainties do not include uncertainties in assumed total abundances.
[e] Models that reproduce the observed interstellar extinction per H require a greater volume of grain material than provided by the depletions found by Jenkins (2004). A model based on carbonaceous grains plus silicate grains (see Draine 2003a) has $V = 37 \times 10^{-28}\,cm^3/H$ for silicate grains and $V = 21 \times 10^{-28}\,cm^3/H$ for carbonaceous grains (see text).

In Table 1.1 the overall composition of the core material is consistent with Jenkins' results. The amounts of Mg, Fe, and Si in the mantle require $\sim$57 ppm O if combined into pyroxene—consistent with the O/H = 81^{+54}_{-58} ppm that Jenkins assigns to the mantle.

Studies of total depletions infer the amount of grain material based on an assumed value for the total abundance of each element; Jenkins adopted current estimates for solar abundances. It is important to remember that estimates of solar abundances have varied considerably over time; the review by Anders & Grevesse (1989) had C/H= 363 ± 35 ppm and O/H = 851 ± 72 ppm, whereas the most recent redeterminations find C/H=246 ± 23 ppm (Allende Prieto, Lambert, & Asplund 2001) and O/H = 490 ± 47 ppm (Allende Prieto et al. 2002)—C/H has gone down by a factor 1.5, and O/H by a factor 1.7! Tomorrow's "solar abundance" values may differ from today's. Furthermore, interstellar abundances may not be equal to solar, or even to the abundances in young stars, as discussed in §1.10 below.

The total grain volume indicated by Jenkins' abundance estimates is $35 \times 10^{-28}\,cm^3/H$, only $\sim$60% of the total grain volume for the physical dust model of Weingartner & Draine (2001a). The dust modeling has approximated the dust as solid spheres, and it is expected that nonspherical porous grains would allow the extinction to be reproduced with a slightly reduced total solid volume, but it is not clear that this would reduce the required solid volume by 40%.

One is compelled to consider seriously the possibility that interstellar abundances of the depleted elements—especially C—may exceed solar abundances. This will be discussed further in §1.10.

1.8 Time Scale for Depletion

Lifetimes of grains in H I clouds against destruction in supernova blast waves are only $\sim 3 \times 10^8$ yr (e.g, Draine & Salpeter 1979; Jones et al. 1994). How then can we understand the very small gas-phase abundances routinely found for elements like Si? The kinetics of depletion have been studied by Weingartner & Draine (1999), who show that the population of very small grains is capable of accreting metal ions rapidly enough to achieve the required depletions, provided that interstellar material is rapidly cycled between dense clouds and diffuse clouds.

1.9 Local Variations in D/H: Does Dust Play a Role?

The evidence concerning primordial abundances of D, He, and Li appear to be consistent with D/H $\approx 28 \pm 4$ ppm produced by nucleosynthesis in the early Universe (O'Meara et al. 2001; Kirkman et al. 2004). Observations of D/H in the Milky Way have been reviewed by Linsky (2004). The local interstellar medium has a weighted mean D/H = 15.2 ± 0.8 ppm (1-σ uncertainties) within $\sim$180 pc of the Sun (Moos et al. 2002). This value could be consistent with "astration" if $\sim$50% of the H atoms now in the interstellar medium have previously been in stars that burnt D to ^{3}He. Observations appear to find spatial variations in the D/H ratio in the interstellar medium within $\sim$ 500 pc, with values ranging from $7.4^{+1.9}_{-1.3}$ ppm toward δ Orionis (Jenkins et al. 1999) to $21.8^{+3.6}_{-3.1}$ ppm toward γ^2 Vel (Sonneborn et al. 2000). On longer sightlines in the Galactic disk, Hoopes et al. (2003) find D/H = $7.8^{+2.6}_{-1.3}$ ppm toward HD 191877 ($d = 2200 \pm 550$ pc) and $8.5^{+1.7}_{-1.2}$ ppm toward HD 195965 ($d = 800 \pm 200$ pc). These variations in D/H are usually interpreted as indicating variations in "astration," with as much as $\sim$ 75% of the D on the sightline to δ Ori having been "burnt," vs. only $\sim$20% of the D toward γ^2Vel. Such large variations in astration between regions situated just a few hundred pc apart would be surprising, since the interstellar medium appears to be sufficiently well mixed that large local variations in the abundances of elements like N or O are not seen outside of recognizable stellar ejecta such as planetary nebulae or supernova remnants.

Jura (1982) pointed out that interstellar grains could conceivably sequester a significant amount of D. Could the missing deuterium conceivably be in dust grains?

Let us suppose that dust grains contain 200 ppm C relative to total H (as in the dust model of Weingartner & Draine 2001a) with $\sim$60 ppm in PAHs containing $N_C \lesssim 10^4$ atoms.

The solid carbon will be hydrogenated to some degree. The most highly pericondensed PAH molecules (coronene $C_{24}H_{12}$, circumcoronene $C_{54}H_{18}$, dicircumcoronene $C_{96}H_{24}$) have H/C = $\sqrt{6/N_C}$, where N_C is the number of C atoms; other PAHs have higher H/C ratios for a given N_C. Let us suppose that the overall carbon grain material—including small PAHs and larger carbonaceous grains—has H/C = 0.25.

The carbonaceous grain population would then contain $\sim$50 ppm of hydrogen. If $\sim$20% of the hydrogen in the carbonaceous grains was deterium, the deuterium in the grains would then be $(\mathrm{D})_{\mathrm{grain}}/(\mathrm{H})_{\mathrm{total}} \approx 10$ ppm. If the total D/H = 20 ppm, this would reduce the gas-phase D/H to 10 ppm, comparable to the value observed toward δ Ori.

Is it conceivable the D/H ratio in dust grains could be $\sim 10^4$ times higher than the overall D/H ratio? Some interplanetary dust particles have D/H as high as 0.0017 (Messenger & Walker 1997; Keller, Messenger, & Bradley 2000), although this factor $\sim$85 enrichment (relative to D/H = 20 ppm) is still 2 orders of magnitude less than what is required to significantly affect the gas-phase D/H value. Extreme D enrichments are seen in some interstellar molecules—D_2CO/H_2CO ratios in the range of 0.01–0.1 are seen (Ceccarelli et al. 2001; Bacmann et al. 2003), and attributed to chemistry on cold grain surfaces in dense clouds.

Could such extreme enrichments occur in the diffuse interstellar medium? The thermodynamics is favorable. The H or D would be bound to the carbon via a C-H bond. The C-H bond—with a bond strength $\sim 3.5\,\mathrm{eV}$—has a stretching mode at $\lambda_{\mathrm{CH}} = 3.3\,\mu$m, while the C-D bond, with a larger reduced mass, has its stretching mode at $\lambda_{\mathrm{CD}} \approx \sqrt{2}\lambda_{\mathrm{CH}} \approx 4.67\,\mu$m. Because of the difference in zero-point energy, the difference in binding energies is

$$\Delta E_{\mathrm{CD-CH}} = \frac{hc}{2}\sum_{j=1}^{3}(\lambda_{\mathrm{CH},j}^{-1} - \lambda_{\mathrm{CD},j}^{-1}) \approx \frac{hc}{2}\left(1-\frac{1}{\sqrt{2}}\right)\sum_{j=1}^{3}\lambda_{\mathrm{CH},j}^{-1} = 0.092\,\mathrm{eV}\ , \qquad (1.2)$$

where the sum is over the stretching, in-plane bending, and out-of-plane bending modes, with $\lambda_{\mathrm{CH}} = 3.3$, 8.6, and $11.3\,\mu$m. This exceeds the difference $\Delta E_{\mathrm{HD-H_2}} = 0.035\,\mathrm{eV}$ in binding energy between HD and H_2. It is therefore energetically favored for impinging D atoms to displace bound H atoms via reactions of the form (Bauschlicher 1998)

$$\mathrm{C}_l\mathrm{D}_m\mathrm{H}_n^+ + \mathrm{H} \ \rightarrow\ \mathrm{C}_l\mathrm{D}_m\mathrm{H}_{n+1}^+ \qquad (1.3)$$

$$\mathrm{C}_l\mathrm{D}_m\mathrm{H}_{n+1}^+ + \mathrm{D} \ \rightarrow\ \mathrm{C}_l\mathrm{D}_{m+1}\mathrm{H}_{n-1}^+ + \mathrm{H}_2 \quad \text{branching fraction } f_1 \qquad (1.4)$$

$$\text{versus} \qquad \rightarrow\ \mathrm{C}_l\mathrm{D}_m\mathrm{H}_n^+ + \mathrm{HD} \quad \text{branching fraction } f_2\ . \qquad (1.5)$$

The branching ratio $f_1/f_2 \approx \exp[(\Delta E_{\mathrm{CD-CH}} - \Delta E_{\mathrm{HD-H_2}})/kT_{\mathrm{d}}] > 10^4$ if $T_{\mathrm{d}} \lesssim 70\,\mathrm{K}$. If no other reactions affect the grain hydrogenation, then the grains would gradually become D enriched.

However, the interstellar medium is far from LTE—the hydrogen is atomic (rather than molecular) and, indeed, partially ionized because of the presence of ultraviolet photons, X-rays, and cosmic rays. It is not yet clear whether the mixture of non-LTE reactions will allow the grains to become deuterated to a level approaching D/H $\approx$ 1/4, but it seems possible that this may occur. Deuterated PAHs would radiate in the C-D stretching and bending modes at ~ 4.67, 12.2, and $16.0\,\mu$m. The $12.2\,\mu$m emission will be confused with C-H out-of-plane bending emission (see Fig. 1.3), but the other two modes should be searched for.

Even if extreme D-enrichment of carbonaceous grains is possible, it will take time to develop. Meanwhile, the gas in which the grain is found may undergo a high-velocity shock, with grain destruction by a combination of sputtering and ion field emission in the high-temperature postshock gas. D incorporated into dust grains would be released and returned to the gas phase if those dust grains are destroyed. PAHs, in particular, would be expected to be easily sputtered in shock-heated gas; destruction by ion field emission would be expected to be even more rapid. Thus, if D is depleted into dust grains, we would expect to see the gas-phase D/H to be larger in recently shocked regions. This could explain the large D/H value observed by Sonneborn et al. (2000) toward γ^2 Vel.

It should be noted that significant depletion of D from the gas can only occur if there is sufficient carbonaceous grain material to retain the D. This can occur if gas-phase abundances are approximately solar (with $\sim$200 ppm C in dust) but would not be possible for abundances significantly below solar (e.g., the abundances in the LMC and SMC). The factor-of-two variations in D/H seen in the local interstellar medium would *not* be possible in gas with metallicities characteristic of the LMC, SMC, or high-velocity clouds such as "Complex C" (see Jenkins 2004).

1.10 Transport of Elements in Dust Grains

Elements like Mg, Si, Al, Ca, Ti, Fe, and Ni are concentrated in interstellar dust grains. Since dust grains can move through the gas, transport in dust grains could produce local variations in elemental abundances.

1.10.1 Anisotropic Starlight

Starlight is typically anisotropic, as can be confirmed by viewing the night sky on a clear night. The anisotropy is a function of wavelength, with larger anisotropies at shorter wavelengths because ultraviolet is (1) more strongly attenuated by dust grains and (2) originates in a smaller number of short-lived stars that are clustered. At the location of the Sun, Weingartner & Draine (2001b) found starlight anistropies ranging from 3% at 5500 Å to 21% at 1565 Å.

The dust grains are charged, and fairly well coupled to the magnetic field lines. Let θ_B be the angle between the starlight anisotropy direction and the magnetic field. The drift tends to be approximately parallel to the magnetic field direction, with a magnitude $v_d \approx v_{d0} \cos\theta_B$; for a starlight anisotropy of 10%, $v_{d0} \approx 0.5\ \mathrm{km\,s^{-1}}$ in the "warm neutral medium," and $0.03\ \mathrm{km\,s^{-1}}$ in the "cold neutral medium" (Weingartner & Draine 2001b).

If the radiation anisotropy is stable for $\sim 10^7$ yr, a dust grain in the cold neutral medium would be driven $0.3 \cos\theta_B$ pc from the gas element in which it was originally located.

If the magnetic field is nonuniform, spatial variations in the drift velocity can then lead to variations in the dust/gas ratio. Indeed, if there are "valleys" in the magnetic field (with respect to the direction of radiation anisotropy), the dust grains would tend to be concentrated there. Radiation pressure acting on the concentrated dust grains would in fact cause such perturbations in the magnetic field to be unstable.

Dust impact detectors on the *Ulysses* and *Galileo* spacecraft measure the flux and mass distribution of interstellar grains entering the solar system, finding a much higher flux of very large ($a \gtrsim 0.5\,\mu$m) dust grains than would be expected for the average interstellar grain size distribution (Frisch et al. 1999). The inferred local dust size distribution is very difficult to reconcile with the average interstellar grain population (Weingartner & Draine 2001a), but we must keep in mind that the dust grains entering the solar system over a time scale of a few years are sampling a tiny region of the interstellar medium of order a few AU in size. It is possible that the solar system just happens to be passing through a region in the local interstellar cloud that has been enhanced in the abundance of large grains due to radiation-driven grain drift.

1.10.2 Star-forming Regions

Various processes could alter the gas-to-dust ratio in the material forming a star:

(1) Motion of dust through gas can result from gravitational sedimentation of dust grains in star-

forming clouds (Flannery & Krook 1978). This could lead to enhanced abundances in stars of those elements that are depleted into dust in star-forming clouds.

(2) Star formation is accompanied by ambipolar diffusion of magnetic field out of the contracting gas cloud. Charged dust grains, while not perfectly coupled to the magnetic field, will tend to drift outward, resulting in reduction of the abundances of the depleted elements in the star-forming core (Ciolek & Mouschovias 1996).

(3) Gravitational sedimentation in an accretion disk can concentrate dust at the midplane. Gammie (1996) has suggested "layered accretion," in which viscous stresses are effective along the surface layers of the disk, but the midplane is a quiescent "dead zone" as far as the magnetorotational instability is concerned. This could suppress stellar abundances of depleted elements.

(4) In thick disks, small bodies orbit more rapidly than the gas, with gas drag leading to radial infall of these bodies. This could enhance stellar abundances of depleted species.

(5) Before accretion terminates, a massive star may attain a pre-main sequence luminosity high enough for radiation pressure to drive a drift of dust grains away from it. This would suppress stellar abundances of depleted elements.

Given these competing mechanisms, the net effect could be of either sign, but, as pointed out by Snow (2000), it would not be suprising if stars had abundances that differed from the overall abundances of the interstellar medium out of which they formed, and it would also not be surprising if the resulting abundances depended on stellar mass. In this connection it is interesting to note that the study by Sofia & Meyer (2001) finds that abundances of Mg and Si in B stars appear to be significantly below the abundances of these elements in young F and G disk stars, or in the Sun; they conclude that the abundances in B stars do not provide a good representation of interstellar abundances.

1.11 Ion Recombination on Dust Grains

As discussed by Jenkins (2004), determinations of elemental abundances from interstellar absorption-line observations may require estimation of the fraction in unobserved ionization states, such as Na II, K II, or Ca III. Such estimates require knowledge of the rates for ionization and recombination processes. Neutral or negatively charged dust grains provide a pathway for ion neutralization that for some cases can be faster than ordinary radiative recombination with free electrons (Weingartner & Draine 2002).

1.12 Summary

This Symposium has been concerned with the origin and evolution of the elements. The main points of the present paper are as follows:

(1) The chemical composition of interstellar dust remains uncertain. PAH molecules are present, and a substantial fraction of the grain mass most likely consists of amorphous silicate, but precise compositional information still eludes us.

(2) The grain size distribution is strongly constrained by observations of extinction, scaterring, and infrared emission, and extends from grains containing just tens of atoms to grains with radii $a \gtrsim 0.3\,\mu$m.

(3) Dust grains will drift through interstellar gas, and this transport process could produce local variations in the dust/gas ratio.

(4) The dust mass required to account for interstellar extinction using homogeneous spherical grains exceeds that inferred from depletion studies (Jenkins 2004) by a factor ~ 1.5.

(5) Dust grains could possibly deplete a significant fraction of interstellar D. This mechanism should be considered as a possible explanation for observed variations in the interstellar D/H ratio.

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