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Interstellar Dust Models and Evolutionary Implications

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Abstract. The wavelength dependences of interstellar extinction and polarization, supplemented by observed elemental abundances and the spectrum of infrared emission from dust heated by starlight, strongly constrain dust models. One dust model that appears to be consistent with observations is presented. To reproduce the observed extinction, the model consumes the bulk of interstellar Mg, Si, and Fe (in amorphous silicates), and a substantial fraction of C (in carbonaceous material), with size distributions and alignment adjusted to match observations. The composition, structure, and size distribution of interstellar grains is the result of injection of dust from stellar outflows into the interstellar medium, followed by destruction, growth, coagulation, and photoprocessing of interstellar grains. The balance among these poorly-understood processes is responsible for the mix of solid material present in the ISM. Most interstellar grain material present in the diffuse interstellar medium must be grown in the interstellar medium. The amorphous silicate and carbonaceous materials that form the bulk of interstellar dust must therefore be the result of grain growth in the presence of ultraviolet radiation. Dust in high-z systems such as J1148+5251 is also produced primarily in the interstellar medium, with supernova-produced dust contributing only a small fraction of the total dust mass.

1. Introduction

Trumpler (1930) and Lindblad (1935), recognized that reddening of distant stars was produced by submicron particles present in interstellar space, but over 70 years later we continue to work to determine the composition, shape, and size distribution of interstellar dust. Despite substantial advances in out understanding of interstellar physics, the problem is far too difficult for an *ab initio* approach. We do not know enough about physical conditions in stellar outflows (where some grains are formed) and the interstellar medium (where grains undergo modification), and our understanding of the physical and chemical processes occuring on grain surfaces and within grains is very limited. We cannot predict with any confidence how grain materials will evolve over hundreds of Myr in the ISM. We need to use what physics we know, but observations must guide us.

Almost all of the observational information concerning interstellar dust arises from interaction of electromagnetic radiation with dust: scattering, absorption, and emission. The first "detection" of interstellar dust was through extinction of starlight: Herschel (1785) remarked on the absence of stars in certain portions of the Milky Way (*"An Opening in the Heavens"*), although he did not understand its cause. Over a century later, Barnard (1907) noted that the neighborhood of ρ Oph was an example of "an apparently absorbing medium."

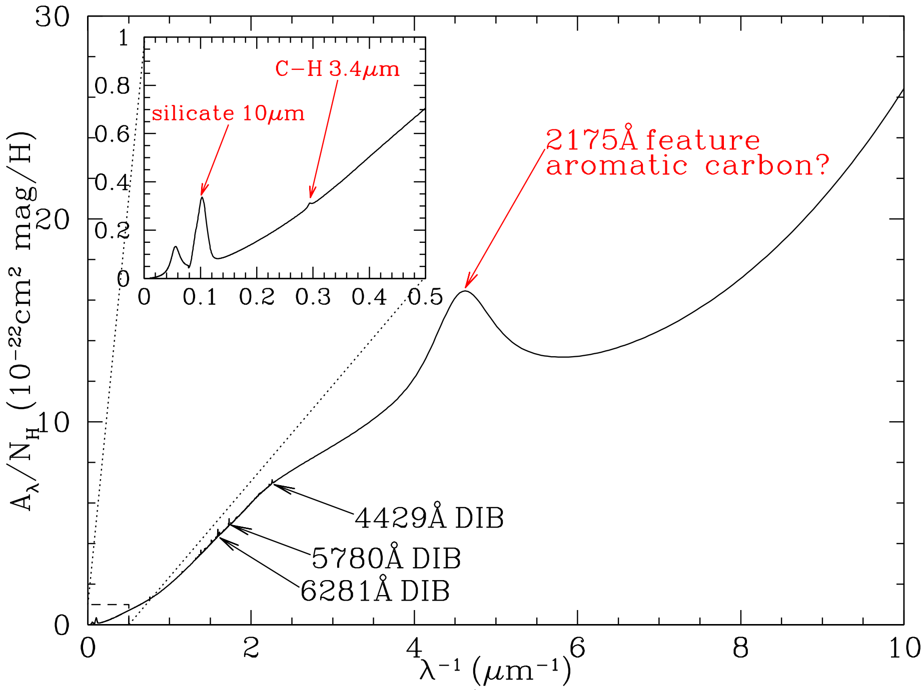

Figure 1. Average extinction vs. λ^{-1} for dust in interstellar diffuse clouds. For $\lambda^{-1} > 1\mu\text{m}^{-1}$, this is based on the parameterization of extinction by Fitzpatrick (1999), with addition of 77 strongest diffuse interstellar bands (DIBs) from Jenniskens & Desert (1994). Three of the strongest DIBs are labelled.

We now study scattering, absorption, and emission of radiation by interstellar dust at wavelengths ranging from Å (X-rays) to cm (microwaves).

2. Observational Constraints

2.1. Extinction

Wavelength-dependent extinction of starlight—the so-called "extinction curve"—remains the principal source of information about interstellar dust. Interstellar extinction has been studied on many sightlines at wavelengths between about 2μm and 0.1μm. On sightlines with sufficient column density, it is possible to study the extinction at wavelengths as long as $\sim 20\mu$m. An average extinction curve is shown in Figure 1.

The extinction curve contains spectral features that constrain the composition of the dust. The strongest feature by far is a broad "bump" peaking near 2175Å. The strength of this feature requires that it be produced by a substance composed of high-abundance elements, such as C, Mg, Si, or Fe (Draine 1989). The position of the feature, and its width, are strongly suggestive of $\pi \rightarrow \pi^*$ excitations in aromatic carbon, such as graphite or polycyclic aromatic hydrocarbons. Some authors (e.g., Draine & Li 2007) think that the feature is produced by the large population of polycyclic aromatic hydrocarbons that is required to explain a number of infrared emission features.

The extinction curve in Fig. 1 shows a conspicuous feature near 10μm that can be confidently attributed to Si-O stretching modes in amorphous silicates; a companion feature at 18μm is attributed to O-Si-O bending modes. The absence of fine structure in the profile indicates that the silicate material is amorphous—Kemper et al. (2005) place an upper limit of 2% on the crystalline fraction.

There is a weak absorption feature at 3.4μm that is attributed to the C-H stretch in hydrocarbon material. The nature of the hydrocarbon material is controversial: from the profile shape and strength, Pendleton & Allamandola (2002) estimate that the carbonaceous material is ∼85% aromatic and ∼15% aliphatic, whereas Dartois et al. (2004) conclude that *at most* 15% of the carbon is aromatic.

Finally, we note that the extinction curve in Fig. 1 actually contains ∼200 weak but detected spectral features—the "diffuse interstellar bands," or DIBs. 86 years after the first DIBs were reported by Heger (1922), it is embarassing to have to admit that not a single one has yet been identified.

The extinction curve shows a smooth rise from the near IR to the vacuum UV. A broad range of grain sizes is required to reproduce this: the rapid rise in extinction shortward of 1500Å requires very large numbers of $a < 0.02\mu$m grains, but the extinction in the visible requires that most of the grain mass be in grains with sizes $0.05\mu\text{m} < a < 0.3\mu$m. The overall strength of the extinction per H nucleon requires that the grains providing the bulk of the extinction be based on high-abundance elements such as C, O, Mg, Si, and Fe.

Extinction curves vary from one sightline to another. Figure 1 shows an average extinction curve, but grain models must be able to account for observed sightline-to-sightline variations in the wavelength-dependence of extinction.

2.2. Other Evidence

In addition to the wavelength-dependent extinction, a modern dust model must also be consistent with a wide range of other observations of electromagnetic radiation absorbed, scattered, or radiated by dust:

- Polarization of starlight by interstellar grains.
- Scattering of starlight by grains (reflection nebulae, diffuse galactic light).
- Small-angle scattering of X-rays by interstellar grains.
- Infrared and submm emission from interstellar grains heated by starlight.
- Polarization of the infrared and submm emission from dust.
- Microwave emission from dust.

In addition to the above, we can study the interstellar grains that are entering the heliosphere today (Landgraf et al. 2000; Krüger et al. 2007), and we can analyze presolar grains trapped 4.5 Gyr ago in primitive meteorites and comets.

Our estimates of the total interstellar abundances of elements such as C, Mg, Si, and Fe, plus direct measurement of gas-phase abundances using absorption lines, tell us how much of each element appears to be locked up in solid grains. Gas-phase abundances of species such as Si, Ca, and Ti are observed to vary from one sightline to another, which implies that depletion from the gas must be able to occur relatively rapidly; a successful grain model must provide enough surface area for depletion of Si^+, Ca^+, and Ti^+ to take place rapidly.

The observed variability of gas-phas D/H from sightline to sightline is best understood if D is actually depleting onto dust grains (Draine 2004, 2006a) and evidence for this is now strong (Prochaska et al. 2005; Linsky et al. 2006; Lallement et al. 2008). A dust model must contain a component capable of trapping a substantial fraction of the D present in the ISM. The PAHs may be able to accomplish this (Draine 2006a).

In general, dust grains play a crucial role in interstellar chemistry, and a successful dust model should eventually be able to "predict" the rate for formation of interstellar H_2 via reactions on grain surfaces. Photoelectrons emitted by interstellar grains make a major contribution to heating of interstellar gas, and a successful grain model must be in quantitative agreement with heating rates inferred from observations of interstellar gas.

3. A Model Using Amorphous Silicate and Carbonaceous Grains

Current modeling techniques do not allow us to "invert" the observational constraints to arrive at a grain model. Constrained by elemental abundances, all sensible grain models consist predominantly of carbonaceous and amorphous silicate material, but there are various candidates for the carbonaceous material. For example, Zubko et al. (2004) consider models involving varying amounts of PAHs, graphite, 3 different types (AC, BE, ACH2) of amorphous carbon, and an organic refractory material with composition $C_{25}H_{25}O_5N$.

Here we will focus on one particular model, in which the carbonaceous material in ultrasmall particles is assumed to have the optical and thermal properties of PAHs, while the larger carbonaceous grains are assigned the optical properties of graphite. If polarization is not of interest, the particles amay be approximated as spheres. For these materials, Weingartner & Draine (2001, hereafter WD01) found size distributions that reproduce the extinction in various regions of the Milky Way, and in the Large and Small Magellanic Clouds. For current estimates of solar and interstellar abundances, the WD01 size distributions use somewhat more C, Mg, and Si than is nominally available, but one should keep in mind that (a) there are modeling uncertainties (the grains are certainly not solid spheres), (b) the actual interstellar abundances of C, Mg, Si, and Fe are uncertain, (c) gas-phase abundances of C have recently been revised downward (Sofia & Parvathi 2009), increasing the amount of carbon inferred to be in dust: it now appears that only $\sim 1/3$ of the C is in the gas, and $2/3$ is in the dust.

The PAH-graphite-amorphous silicate model satisfactorily reproduces interstellar extinction (see WD01), but it can also be tested in other ways. A dust grain illuminated by starlight will absorb energy, which will be reradiated in the infrared. The infrared emission spectrum will depend upon both the temperature of the grain and its infrared opacity.

Large $a \gtrsim 0.02\mu$m grains in the local starlight background will be heated to a more-or-less steady temperature 15–20K. However, very small grains (1) absorb photons much less frequently, and (2) have very small heat capacities, so that one absorbed photon can raise the grain to a high temperature, followed by very rapid cooling. Because of this, one cannot speak of an average temperature for very small grains—instead, one must determine temperature distribution function (dP/dT), where dP is the probability of finding the grain

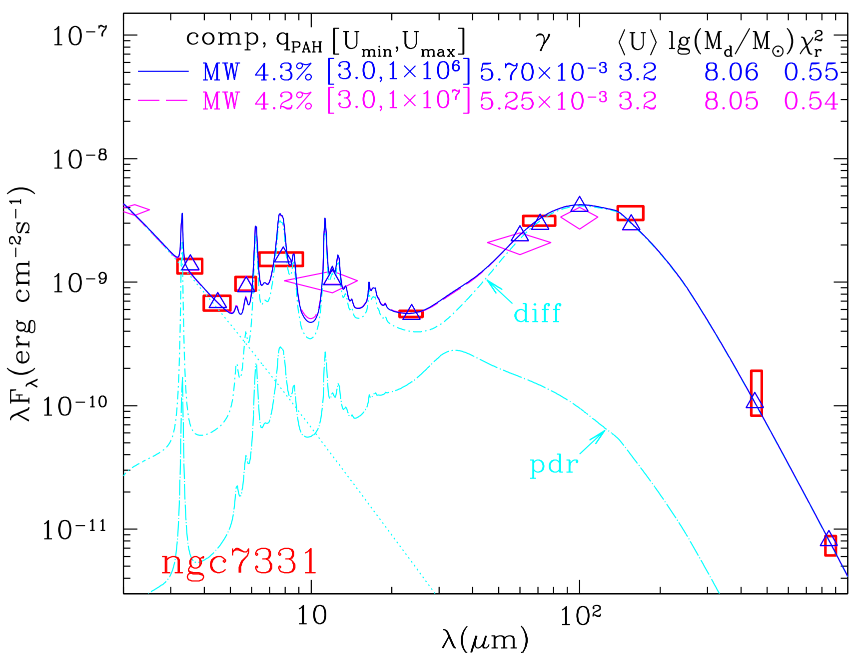

Figure 2. Global emission from NGC 7331 (from Draine et al. 2007). Symbols are 2MASS, Spitzer, IRAS, and SCUBA photometry. The solid curves is generated by the DL07 dust model, which requires a dust mass $1.1 \times 10^8 M_\odot$ to reproduce the observed emission spectrum.

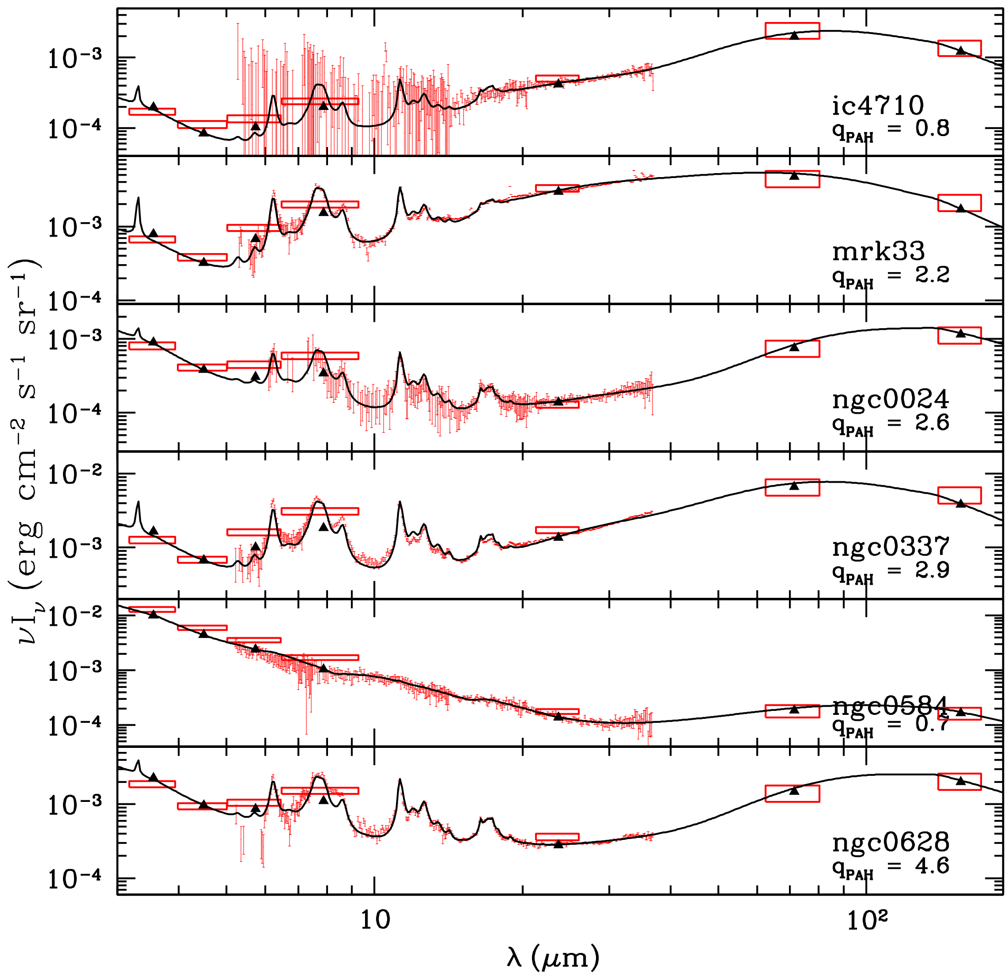

Figure 3. Emission from central regions of 6 SINGS galaxies. Error bars are for 5–33μm IRS spectra (Smith et al. 2007). Rectangles are IRAC and MIPS photometry. Solid line is model consisting of starlight plus emission from dust heated by starlight. The DL07 physical grain model is able to reproduce both the PAH features and the IR continuum for diverse galaxies, but with different PAH fractions $q_{\rm PAH}$ and different starlight intensity distributions. From Draine et al. (2009).

in the temperature interval $[T, T + dT]$. The infrared emission is given by

$$\frac{I_\nu}{N_{\rm H}} = \sum_{{\rm comp}\,i} \sum_{{\rm size}\,j} \frac{n_{ij}}{n_{\rm H}} \int dT \left(\frac{dP}{dT}\right)_{ij} B_\lambda(T) C_{{\rm abs},ij}(\lambda) \qquad (1)$$

To calculate the emission from a grain model that includes very small grains, one must first find $(dP/dT)_{ij}$ for the different compositions i grain sizes j that are present in the model. For large grains, $dP/dT \rightarrow \delta(T - \bar{T})$, where δ is the Dirac delta function, but for small grains dP/dT has a tail extending to high energies.

The DL07 grain model uses the WD01 size distribution for all except the PAHs; the size distribution of the PAHs was adjusted to try to reproduce the $\lambda < 25\mu$m infrared emission. DL07 have solved for the temperature distribution functions dP/dT for different grain sizes and composition, and have calculated the resulting infrared emission spectrum for various intensities of the starlight heating the grains.

The diffuse ISM away from the Galactic plane in the Milky Way has been measured by COBE-DIRBE (Dwek et al. 1997; Arendt et al. 1998), and by COBE-FIRAS (Finkbeiner et al. 1999). The emission predicted for the DL07 grain model is in good agreement with the observed diffuse emission from high-latitude regions in the Milky Way.

If we assume that grains in other galaxies are like grains in the Milky Way, we can test the grain model by comparing it to the emission observed from other galaxies. The Spitzer Infrared Nearby Galaxy Survey (SINGS, Kennicutt et al. 2003) consists of 75 nearby galaxies observed with all of the instruments on Spitzer Space Telescope (Werner et al. 2004). Draine et al. (2007) have used the DL07 dust models to estimate the dust content and starlight intensities for 65 of the SINGS galaxies. Figure 2 shows the observed SED for one example, the well-observed Sb galaxy NGC 7331. With suitable assumptions for the starlight heating the dust, the DL07 dust model closely reproduces the observed infrared and submm emission.

Modeling the IR emission from NGC 7331 yields an estimated dust mass $M_{\rm dust} = 1.1 \times 10^8 M_\odot$. The H I 21cm emission give an HI mass $M({\rm HI}) = 1.0 \times 10^8 M_\odot$, and the CO 1→0 luminosity gives an estimated H_2 mass $M(H_2) = 1.6 \times 10^{10} M_\odot$ (for an assumed CO "X factor" $4 \times 10^{22}{\rm cm}^{-2}\,{\rm K\ km\ s}^{-1}$), resulting in a dust-to-H mass ratio $M_{\rm dust}/M_{\rm H} = 0.043$, reasonably close to the expected value ~ 0.007, especially when one considers the uncertainties in estimation of the H_2 mass from the CO 1→0 luminosity.

4. Polarization of Starlight and Polarized IR-Submm Emission

WD01 showed that a model based on amorphous silicate and carbonaceous grains, including PAHs, could reproduce observations of extinction in the Milky Way, LMC, and SMC, and DL07 showed that these same dust models could reproduce observations of infrared emission.

In addition to interstellar extinction, a dust model should be able to reproduce observations of polarization of starlight by aligned dust grains. The infrared emission from aligned dust grains will be polarized, and microwave and

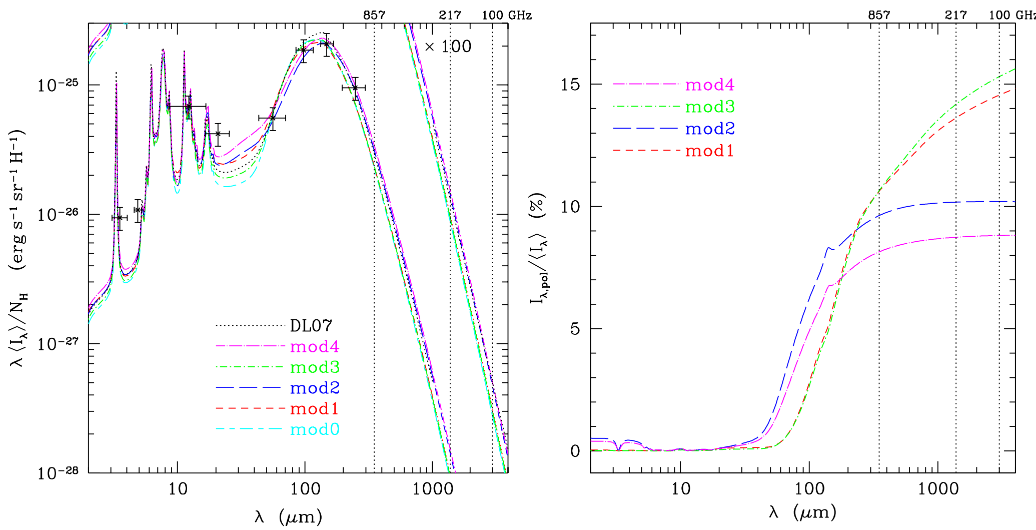

Figure 4. *Left:* Infrared emission vs. wavelength λ for models (mod1–mod4) that reproduce extinction and polarization (**?**). Emission from the spherical grain model of Draine & Li (2007, =DL07). Crosses show the emission per H for local high-latitude dust observed by DIRBE (Dwek et al. 1997; Arendt et al. 1998). *Right:* Linear polarization vs. λ for emission perpendicular to the local magnetic field.

submillimeter polarimetry has advanced to the point where it is beginning to be possible to measure the polarized emission from the diffuse interstellar medium. For computational convenience, the WD01 and DL07 models assumed spherical grains, and therefore couldn't say anything about polarization.

Early modeling of starlight polarization at optical wavelengths approximated the grains by infinite cylinders (Greenberg & Hong 1974), but improved numerical methods and faster computers allowed Kim & Martin (1995) to model the grains as spheroids. Advances in polarimetric techniques at submm to cm wavelengths now allow detection of polarized emission from the diffuse interstellar medium (e.g. Page et al. 2007) and theorists should now make predictions for the degree of polarization that is expected for different dust models.

In addition to reproducing the wavelength-dependent extinction, a dust model must first reproduce the polarization of starlight as a function of wavelength. All dust models must have aligned, nonspherical grains containing amorphous silicates, because the interstellar silicate feature is known to produce polarization in extinction (Smith et al. 2000). If carbonaceous material is present in a separate grain population, at this time there is no evidence that such grains are aligned. Absence of polarization in the 3.4μm C-H stretch feature suggesting that the carbonaceous particles (at least those responsible for the 3.4μm feature) may *not* be aligned (Chiar et al. 2005).

Using models based on carbonaceous grains (including PAHs) and amorphous silicate grains with various assumptions about (1) the shapes of the grains and (2) whether or not the carbonaceous grains are aligned, **?** are able to find size distributions and alignment functions (degree of alignment as a function of grain size) that are consistent with observations of interstellar extinction and starlight polarization. Figure 4 (*left*) shows the infrared emission from their models when the dust is heated by the local interstellar radiation field. The models are all in good agreement with the far-infrared emission per H nucleon observed by DIRBE (Dwek et al. 1997; Arendt et al. 1998).

Fig. 4 (*right*) shows that the different models predict quite different degrees of polarization, and with different dependences on wavelength. This is good news—it means that upcoming multiwavelength measurements of linear polarization by *Planck* should be able to reject some (or perhaps all!) of these models.

5. Where Do Interstellar Grains Come From?

The evolution of interstellar dust involves a complex interplay of many poorly-understood processes, in an arena (the interstellar medium) that we also have a very incomplete picture of. *Ab initio* approaches to the evolution of interstellar dust are therefore premature.

Under these circumstances, the best approach to understanding the evolution of interstellar dust is to first determine what kind of dust is present in the interstellar medium *today.* Then we can try to construct an evolutionary scenario that is consistent with the grains that are observed to be present today.

To summarize: Observations of interstellar gas-phase abundances ("depletions"), extinction, polarization, and emission by interstellar dust, and models that are able to reproduce those observations, tell us that:

1. The abundant elements Mg, Si, Fe reside primarily in dust.
2. Perhaps 2/3 of C is in dust.
3. The Si is predominantly in amorphous silicate material. Based on available abundances, the composition is likely to be (approximately) $Mg_{1.1}Fe_{0.9}SiO_4$.
4. There is a substantial population of PAHs that contains ∼10-20% of the interstellar C in the Milky Way; ∼4-5% of the total grain mass is contributed by PAHs in the Milky Way and other star-forming galaxies with ∼solar metallicity (Draine et al. 2007).

Whatever the processes of interstellar grain evolution, they must be able to account for the above facts.

5.1. Mass Budget for the Milky Way ISM

Figure 5 illustrates the overall flow of mass into and out of the ISM. The mass of interstellar gas in the Milky Way is $\sim 5\times10^9 M_\odot$, divided approximately equally between atomic and molecular gas. Gas is being converted into stars at a rate of $\sim 3M_\odot/\mathrm{yr}$. If there were no source of gas, the ISM would be consumed on a relatively short timescale $\sim 5\times10^9 M_\odot/(3\,M_\odot \mathrm{yr}^{-1}) \approx 1.7\times 10^9$ yr. However, there is return of material to the ISM from stars via various kinds of stellar outflows (stellar winds, planetary nebulae, novae, supernovae) and, in addition, there is evidence for infall of low metallicity gas. The rates are uncertain, particularly for infall, but it appears (see Figure 5) that the net rate

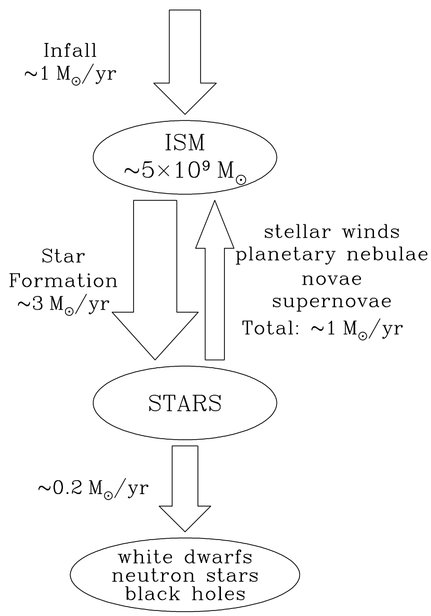

Figure 5. Baryon budget for the Milky Way disk (see also Table 1).

at which the ISM is losing mass is $\sim 1M_\odot$/yr, so that the characteristic decay time is of order 5×10^9 yr, which seems a plausible number for a galaxy that has been making stars in the disk at a more-or-less steady rate over the last ~9 Gyr (Rocha-Pinto et al. 2000).

6. Production of Stardust

Some of the stellar outflows returning matter to the ISM are dusty. Outflows from cool oxygen-rich red giants contain silicate grains, and the outflows from cool carbon stars contain solid carbonaceous grains, in some cases with SiC as one of the carbon-bearing materials. The ejecta that form planetary nebulae are generally dusty. Some novae produce dust, but the net contribution from novae appears to be small.

At least some stardust comes from supernovae: supernova-produced dust grains have been identified in meteorites, and the internal extinction and IR emission from some young supernova remnants is evidence for dust formation. Supernovae have even been described as "dust factories" (Sugerman et al. 2006). However, the average mass of dust per SN does not appear to be large: the Type II SN 1987a produced $\lesssim 8 \times 10^{-4} M_\odot$ of dust (Ercolano et al. 2007). The current record-holder for dust production is the Type II SN 2003gd, which produced $\lesssim 0.02M_\odot$ of dust (Sugerman et al. 2006). There is as yet no evidence of dust formation in Type Ia SNe. While only a very small number of SNe have as yet been studied, it appears that SNe produce, on average, $\sim 0.01M_\odot$, condensing $\lesssim 10\%$ of the condensible elements. It should also be kept in mind that the dust that has been detected in these supernovae is moving at high speeds ($\sim 10^3\,\mathrm{km\ s^{-1}}$), and is expected to undergo erosion by sputtering and possible destruction in grain-grain collisions when it is eventually decelerated to the low velocities of the quiescent interstellar medium. While dust production unquestionably occurs, "dust factory" may be a misnomer.

Table 1. Injection of Gas and Stardust from Stellar Sources

gas ($M_\odot$/yr)	dust ($M_\odot$/yr)	Stellar Source
0.4	0.002	Planetary Nebulae (~0.3/yr)
0.5	0.0025	Red Giant, Red Supergiant, C star winds
0.06	<0.0001?	OB, WR, other warm/hot star winds
0.25	0.0002?	SNe (1/100 yr, $\sim 10^{-2} M_\odot$ dust/SN?)
0.01	0.00001	Novae (100/yr, $10^{-7} M_\odot$ dust/nova?)
~1.2	**~0.005**	**All stellar sources**

An accurate inventory of the different sources of stardust is not available, but provisional estimates are offered in Table 1. The overall gas return rates from the different stellar sources in Table 1 can be estimated reasonably reliably, given our knowledge of the IMF (Kroupa 2001): (1) stars with initial masses above $\sim 8M_\odot$ become supernovae, leaving behind either neutron stars or black holes. (2) Initial masses between $\sim 0.9M_\odot$ and $\sim 8M_\odot$ leave behind white dwarfs of varying masses. (3) Stars with initial masses below $\sim 0.9M_\odot$ do not evolve on the timescales of interest.

We do not have a good understanding of either the stellar wind phenomenon itself, or the formation of dust in some stellar winds, so the estimates of dust injection are less reliable. The estimates for planetary nebulae and winds from cool stars assume that the dust mass is 0.5% of the gas mass, which corresponds to efficient condensation of the condensible elements. According to the estimates in Table 1, stardust is entering the ISM at a rate $\dot{M}_{\rm stardust} \approx 0.005 M_\odot/{\rm yr}$.

7. Stardust Lifetimes

Newly-made stardust moves away from its stellar source and begins a journey through the ISM. If nothing else happens, the grain will eventually find itself in a parcel of gas collapsing to form a new star. If this were the only process that removed grains from the ISM, the grain lifetime $\tau_{\rm d}$ would be the lifetime of material against star formation: $\tau_{\rm d} = \tau_{\rm SF} \approx M_{\rm ISM}/{\rm SFR} \approx 2 \times 10^9$ yr.

The ISM is a violent neighborhood, agitated by fast stellar winds and supernova explosions. A grain that is overrun by a fast shock is subject to sputtering by the shocked gas. Sputtering in shock waves has been studied by a number of authors. Draine & Salpeter (1979) found that $a = 0.1\mu$m silicate grains had $> 50\%$ of the grain material returned to the gas in radiative shocks with shock speeds $v_s > 200\,\mathrm{km\,s^{-1}}$.

We can estimate the global effects of SNe by a very simple argument. A supernova blastwave with initial energy $E_0 = 10^{51}$erg in gas with density $n_{\rm H} \approx$

$1\,\mathrm{cm}^{-3}$ is Sedov-like until the shock speed drops to $\sim 200\,\mathrm{km\,s}^{-1}$. During the Sedov phase,

$$Mv_s^2 \approx E_0 \tag{2}$$

and therefore the mass of gas shocked at shock speeds $> 200\,\mathrm{kms}^{-1}$ is

$$M(v_s > 200\mathrm{kms}^{-1}) \approx \frac{10^{51}\mathrm{erg}}{(200\,\mathrm{kms}^{-1})^2} \approx 1260 M_\odot \tag{3}$$

Thus one supernova can "clean" $\sim 1000\,M_\odot$ of ISM of dust. If $E_0 = 10^{51}$erg is a representative value for the kinetic energy of a SN, and the SN rate in the Milky Way disk is $\sim 1/(100\,\mathrm{yr})$, then the probability per unit time of an interstellar grain being overtaken by a $v_s > 200\,\mathrm{km\,s}^{-1}$ shock is

$$\tau_\mathrm{d}^{-1} \approx \frac{1260 M_\odot/100\,\mathrm{yr}}{5\times10^9 M_\odot} \approx \frac{1}{4\times10^8\mathrm{yr}} \quad . \tag{4}$$

There are other destructive processes as well, particularly grain-grain collisions in slower shock waves. Detailed studies (Barlow & Silk 1977; Draine & Salpeter 1979; Dwek & Scalo 1980; Jones et al. 1994) that try to take into account the complications of a multiphase interstellar medium find solid matter lifetimes $\tau_\mathrm{d} \approx 4\times10^8$yr, close to the simple estimate above.

To restate this: for a randomly-selected Si atom in a grain, the probability per unit time that it will be returned to the gas is $\tau_\mathrm{d}^{-1} \approx 1/(4\times10^8\,\mathrm{yr})$. In steady state, stardust injection = stardust removal, and we can estimate the mass of stardust that should be present in the ISM.

$$\dot{M}_\mathrm{stardust} \approx M_\mathrm{stardust}\left[\tau_\mathrm{SF}^{-1} + \tau_\mathrm{d}^{-1}\right] \quad , \tag{5}$$

from which we estimate $M_\mathrm{stardust} \approx 1.6\times10^6 M_\odot$. However, the total mass of refractory interstellar dust is $M_{rmismdust} \approx 0.005\times M_\mathrm{ISM} \approx 2.5\times10^7 M_\mathrm{sun}$. Thus we conclude that

$$\frac{M_\mathrm{stardust}}{M_\mathrm{ismdust}} \approx \frac{1.6\times10^6 M_\odot}{2.5\times10^7 M_\odot} \approx 0.06 \quad : \tag{6}$$

most interstellar dust is not stardust.

Stardust accounts for only $\sim 4\%$ of the total mass of interstellar dust.

Another way to approach the problem is to estimate the gas-phase abundance of Si. Let $f_{\star0}(\mathrm{Si})$ be the fraction of Si entering the ISM from stellar sources (stellar winds, planetary nebulae, supernovae...) that is in solid form. Because supernovae appear to condense $\lesssim 10\%$ of their condensibles into grains (Ercolano et al. 2007) and the winds from many stars (e.g., O stars) appear to be dustless, we may estimate $f_{\star_0}(\mathrm{Si}) < 0.5$. The fraction of interstellar Si that is in stardust will be

$$f_\star(\mathrm{Si}) = \frac{f_{\star0}(\mathrm{Si})}{1 + t_\mathrm{SF}/t_\mathrm{d}} \approx 0.2 f_{\star0}(\mathrm{Si}) \approx 0.1 \quad . \tag{7}$$

But in fact interstellar Si is almost always found to be strongly depleted, with $f(\text{Si}) \approx 0.9$ in dust. Therefore, we reach the same conclusion as before: most of the Si in interstellar grains is *not* in stardust— it must have been added to the grain *in the ISM*.

This is not a new result—Draine & Salpeter (1979) reached the conclusion that grain destruction was rapid and that regrowth of dust in the ISM was required to explain the observed depletions. The numbers basically haven't changed appreciably since then; the argument has been reiterated a number of times (e.g., Dwek & Scalo 1980; Draine 1990; Weingartner & Draine 1999; Draine 2006b). Nevertheless, some authors continued to hold the view that the solids in the interstellar medium were primarily formed in stars.

For example, a number of papers have argued that the low abundance of crystalline silicate material in the interstellar medium requires that crystalline stardust material must be amorphized by cosmic ray damage in the interstellar medium (e.g. Bringa et al. 2007). However, the low abundance of crystalline silicates in the ISM can be easily understood: (1) grain destruction reduces the abundance of stardust in the ISM, and (2) the silicate material grown in the ISM is amorphous.

Isotopically anomalous silicates found in interplanetary dust particles (IDPs) are presumably stardust. Techniques have recently been developed for study of stardust silicates in meteorites (e.g. Nguyen & Zinner 2004; Keller & Messenger 2008). Recent studies of stardust silicates identified in this way find that it is $\sim$80% amorphous, and $\sim$20% crystalline material (L. P. Keller 2008, talk given at this conference). If this 4:1 amorphous:crystalline ratio applies to the overall production of silicate stardust, then the observed upper limit of $\sim$2% on the crystalline fraction in the interstellar medium (Kemper et al. 2005) implies an upper limit of $2\% \times (4+1) = 10\%$ on the fraction of interstellar silicate material contributed by silicate stardust. This is in agreement with our estimate in eq. (7). The low crystalline fraction in interstellar silicates does not require that some of the crystalline material be amorphized—the expected destruction processes in the interstellar medium suffice to keep the crystalline fraction below the current upper limit.

8. Growth of Solid Material in the ISM

If most interstellar solid matter is not stardust, it follows that

most of the material in interstellar grains was formed in the ISM.

The growth of grain material takes place on the surfaces of already-present grains—a process also referred to as "depletion" of condensible elements from the gas. We know that this process takes place, because we observe different gas phase abundances of the "depletable" species.[1] The depletion process has three stages:

1. An atom or ion of the element must collide with a preexisting grain surface.
2. The atom must become bound to the grain material in a way that allows it to be retained in the presence of fluxes of ultraviolet radiation and reactive species such as atomic H and O.
3. The resulting grain material(s) will undergo heavy UV irradiation— whatever survives (or is produced by) UV photolysis will be what is present in the ISM today. Cosmic ray irradiation also occurs, but appears to be of secondary importance.

Step 1 is just a matter of kinetics: The rate for a given ion to hit a grain will be determined by the total geometric area provided by the grains—the surface area will be dominated by the smallest grains—and by the random velocities of atoms and ions and the possibly large velocities of grains relative to the gas[2]. In diffuse regions (where UV radiation is present) the ion-grain collision rate will be affected strongly by the charge state of the grains. Collisions between positively charged grains and ions such as Si^+ will be suppressed, but part of the grain population will be neutral, and the smaller PAHs are expected to have an appreciable fraction that are negative, with which ions will have enhanced collision rates.

Let $\Sigma_{\rm d,21} 10^{-21}{\rm cm}^2/{\rm H}$ = dust geometric cross section per H nucleon. From modeling the UV extinction, we know that $\Sigma_{\rm d,21} \gtrsim 1$. Let v_a be the velocity of an atom relative to the grains. The timescale $\tau_{\rm acc}$ for this atom to collide with a grain surface is

$$\tau_{\rm acc} = \frac{1}{n_{\rm H}\Sigma_d v_a} = 1.0\times 10^7{\rm yr}\left(\frac{30{\rm cm}^{-3}}{n_{\rm H}}\right)\frac{1}{\Sigma_{\rm d,21}}\left(\frac{{\rm km\ s}^{-1}}{v_a}\right) \quad . \tag{8}$$

This time is relatively short. In the case of ions, the accretion rate will be modified by Coulomb repulsion (by positive grains) or attraction (by negative grains). Weingartner & Draine (1999) discussed the kinetics of accretion of ions (Ti^+ was used as an example) onto grains in diffuse interstellar clouds, with attention to the charge distribution of the PAHs. They found that the very large surface area of PAHs resulted in a depletion rate

$$\tau_{\rm acc} \approx 2\times 10^5 {\rm yr} \quad . \tag{9}$$

The fact that this is a factor 50 smaller than eq. (7) can be attributed to two factors. First, the total surface area in small particles is considerably larger than

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[1] Mg, Al, Si, P, Cl, Ca, Ti, Cr, Fe, and Ni are the prime examples of elements whose gas-phase abundances show order-of-magnitude variations from one sightline to another, the result of depletion onto grains.

[2] Yan et al. (2004) conclude that MHD turbulence will cause $a > 0.04\mu$m silicate grains in the "cold neutral medium" ("CNM," with $n_{\rm H} \approx 30\,{\rm cm}^{-3}$, $T \approx 100\,{\rm K}$) to move relative to the gas with velocities $\gtrsim 1\,{\rm km/s}$, large compared to the mean thermal speed $(8kT/\pi m)^{1/2} = 0.27\,{\rm km/s}$ of a Si ion.

$10^{-21}\mathrm{cm}^2/\mathrm{H}$. Second, carbonaceous grains smaller than 10^{-6} cm and silicate grains smaller than 2×10^{-6} cm were negatively charged, with Coulomb focussing increasing the collision rates by large factors. Evidently depletion and grain growth can take place on time scales $\sim 2\times10^5$yr in ordinary HI clouds, with $n_\mathrm{H}\approx 30\,\mathrm{cm}^{-3}$.

We conclude that the low gas-phase abundances of elements such as Si and Ti can be understood based on rapid rates of depletion from the gas phase for the conditions found in ordinary HI clouds—the "cold neutral medium." The bulk of interstellar grain material is the result of accretion from the gas in the cold interstellar medium.

9. What Materials Form? Why Do Some Elements Not Deplete?

9.1. Thermal Desorption

In typical diffuse clouds, some elements (e.g., Ca, Al, Si, Fe) are heavily "depleted" from the gas, while others (e.g., S, Cu, Zn) show much less of a tendency to deplete (Jenkins 2004). To try to understand how this selectivity can occur, let's examine the steps in the depletion process.

Grains with radii $a \gtrsim 0.01\mu$m remain very cold in the diffuse ISM, with temperatures $T \lesssim 20$K. At these temperatures, almost any atom or ion impinging with a kinetic energy ~ 0.01eV is expected to have a high probability for "sticking" to the surface at least temporarily (where "temporarily" means long compared to the characteristic vibrational period $\sim 10^{-12}$s), with the exception of the inert gases such as He and Ne. Normal physisorption via van der Waals forces will bind species such as S, Cu, and Zn to grain surfaces with binding energies $B \sim 0.05$—0.2eV. Thermal desorption will take place with a probability per unit time $\sim \nu_0 \exp(-B/kT)$, with $\nu_0 \approx 10^{12}\mathrm{s}^{-1}$. For $B = 0.05\,\mathrm{eV}$ and a grain temperature $T = 20$K, the lifetime against thermal desorption would be $\sim 1\,\mathrm{s}$, whereas if $B = 0.10\,\mathrm{eV}$, the lifetime becomes 5×10^5 yr. Therefore if an atom is to remain on the grain surface long enough to matter, it must have a binding energy $B > 0.1\,\mathrm{eV}$. Unfortunately, the binding energies of the atoms of interest (C, Mg, Si, Fe) to surfaces of interest (amorphous silicate or carbonaceous materials) are not known, but it is plausible to imagine that those elements that do deplete are held to the grains surface by binding energies $B > 0.1\,\mathrm{eV}$.

9.2. Hydrogenation

We must now estimate some other rates. Consider one "surface site" on a grain, where some species X is adsorbed. The area of this surface site will be $A \approx 10^{-15}\mathrm{cm}^2$. This surface site is being bombarded by H atoms at a rate

$$n(\mathrm{H})\left(\frac{kT}{2\pi m_\mathrm{H}}\right)^{1/2} A = \frac{1}{30\,\mathrm{yr}}\left(\frac{n(\mathrm{H})}{30\,\mathrm{cm}^{-3}}\right)\left(\frac{T}{100\,\mathrm{K}}\right)^{1/2} \quad . \qquad (10)$$

The impinging H atoms might form chemical bonds with the adsorbate X; whether they will do so is not known (for some X there may be an energy barrier in the "reaction coordinate" necessary to produce XH, preventing reaction at low energies) but it does seem possible that incident H might result in hydrogenation of some physisorbed atoms, such as S. The resulting molecule might be ejected from the grain surface, or might remain there.

In H I clouds, O atoms are the third most abundant species in the gas (after H and He), and will collide with a surface site at a rate

$$n(\mathrm{O})\left(\frac{kT}{2\pi m_{\mathrm{O}}}\right)^{1/2} A = \frac{1}{3\times10^5\mathrm{yr}}\left(\frac{n_{\mathrm{H}}}{30\,\mathrm{cm}^{-3}}\right)\left(\frac{T}{100\,\mathrm{K}}\right)^{1/2} \quad . \tag{11}$$

9.3. Photodesorption or Photolysis by UV Radiation

Dust grains in diffuse clouds are exposed to diffuse starlight, including ultraviolet radiation from hot stars. The starlight intensity is such that, for example, a C atom in the gas (with ionization energy 11.26 eV) will be photoionized at a rate $\zeta(\mathrm{C}\rightarrow\mathrm{C}^+) = 3\times10^{-10}\,\mathrm{s}^{-1}$. Species on grain surfaces will in general have allowed transitions to excited states with $E < 13.6$ eV, and these transitions will also be excited by the starlight background, and we may assume a characteristic rate for UV excitation

$$\zeta \approx 10^{-10}\,\mathrm{s}^{-1} = \frac{1}{300\,\mathrm{yr}} \quad . \tag{12}$$

What happens when the adsorbed species (which might be an atom X, a hydride XH, an oxide XO, a hydroxide XOH, ...) absorbs a UV photon and makes a transition to an electronically excited state? The answer is: it depends. Some materials (e.g., stainless steel or quartz) can undergo heavy ultraviolet irradiation without being affected. Other materials (e.g., polyethylene) are chemically altered by UV irradiation. Some physisorbed or chemisorbed species will undergo photoexcitation to an electronic excited state that may actually be repulsive with respect to the surface, resulting in ejection in a time $\sim 10^{-13}$ s after being photoexcited. Laboratory studies of H_2O ice irradiated by Lyman α radiation (Westley et al. 1995) and mixed ices (**?**) show that the surface erodes at a rate consistent with ejection of molecules from the surface monolayer with a high yield per photoexcitation in the surface monolayer.

Thus we see that a species X residing on a grain surface will have a good chance of encountering an impinging H atom before anything interesting happens, but will be very unlikely to encounter any other impinging species (e.g, C, O, Si) before undergoing photoexcitation. The adsorbed species will undergo $\sim 10^4$ photoexcitations before a monolayer of material (other than adsorbed H) can be deposited on top of it.

Because photoexcitation happens so frequently, the only materials that *can* form by accretion in the diffuse ISM are those that are not destroyed or altered by ultraviolet irradiation— this is what selects for amorphous silicate material and carbonaceous material as the two condensates. There may be other materials present, of course—e.g., Fe oxides, or even metallic Fe—but observations of interstellar dust appear to be consistent with amorphous silicates containing most of the condensed material that is not carbonaceous.

Ultraviolet irradiation may also explain how it is possible for the interstellar medium to be able to grow two distinct grain materials—carbonaceous material and amorphous silicate material—out of a single gas mixture. One can imagine the following scenario: Suppose the grain population already has some amorphous silicate material exposed to the interstellar gaa. When Mg, Si, Fe, and O atoms arrive at the grain surface, they are able to grow additional amorphous silicate, adding one atom at a time. It may actually help to have ultraviolet radiation present, as the electronic excitations may allow chemical bonds to be rearranged to form amorphous silicate material as new O, Mg, Si, Fe atoms are added to the surface layer.

On the other hand, what happens when a C atom, for example, lands on the amorphous silicate surface? One can imagine that the C atom physisorbed on the amorphous silicate surface might undergo photoexcitation to an excited state that is repulsive, ejecting it from the surface. Or perhaps the C would become hydrogenated or oxidized, with the resulting CH or CO undergoing photodesorption from the surface. Such processes could keep the amorphous silicate carbon-free.

Similar processes may occur on exposed carbonaceous surfaces: impinging C atoms could grow new carbonaceous material, whereas impinging Mg, Si, Fe, etc. could be removed by some combination of reaction with impinging H or O, and photoexcitation by UV.

In this scenario, we can imagine the carbonaceous material and amorphous silicate material being in separate grains, or perhaps even as separate regions of a single grain. In the latter case, one would expect that when grain-grain collisions cause grains to shatter, the fragmentation would preferentially occur along interfaces between the two materials, leading to "pure" fragments.

Perhaps the interstellar grain population actually is dominated by two distinct grain types: amorphous silicate grains and some form of carbonaceous material.

10. Growth of Dust at High z: the example of J114816+525150

Observations of quasars and luminous galaxies at high redshift have detected large masses of dust in a number of systems (Wang et al. 2008). The prime example is the galaxy associated with the $z = 6.42$ QSO SDSS J114816+525150 (hereafter J1148+5251), with estimated dust mass $M_{\rm dust}$ ranging from $2 \times 10^8 M_\odot$ (Dwek et al. 2007) to $7 \times 10^8 M_\odot$ (Bertoldi et al. 2003a). Molecular gas appears to account for a large fraction of the $\sim 5 \times 10^{10} M_\odot$ dynamical mass (Walter et al. 2004). With $M_{\rm gas} < 5 \times 10^{10} M_\odot$, and $M_{\rm dust} \gtrsim 2 \times 10^8 M_\odot$, this system has a dust/gas mass ratio $M_{\rm dust}/M_{\rm gas} > 0.004$—comparable to or exceeding the Milky Way value $\sim$0.005.

The time available for stellar evolution prior to $z = 6.42$ is limited: if star formation began at $z = 10$, the oldest stars are only 400 Myr old at $z = 6.42$, and only massive stars will have been able to evolve— insufficient time for low-mass stars to evolve to the asymptotic giant branch which dominates production of stardust in the Milky Way. This has led a number of authors to propose that supernovae are responsible for the dust in high-z galaxies (e.g. Maiolino et al. 2004; Sugerman et al. 2006; Bianchi & Schneider 2007). Dwek et al. (2007) discuss the dust in J1148+5251 and conclude that supernovae would have to produce $\gtrsim 1 M_\odot$ of dust per supernova to explain the observations, but note that this is considerably in excess of what has been observed in SN ejecta.

J1148+5251 contains a large mass of molecular gas, detected in CO $J = 7 \rightarrow 6$, $6 \rightarrow 5$, and $3 \rightarrow 2$ (Bertoldi et al. 2003b; Walter et al. 2004) The CO that is observed, and the H_2 that must accompany the CO, is not supernova-produced: even if those molecules do form in the ejecta, they are efficiently destroyed by the reverse shock when the high-velocity ejecta are decelerated.

Instead, the H_2 must be formed by the mechanism that dominates H_2 formation in the Milky Way: catalysis on grain surfaces. Given that the massive stars present in these galaxies will destroy H_2 molecules—primarily through photodissociation—each H nucleon in the gas must, on average, have collided with grain surfaces many times in the age of this galaxy. Metal atoms and ions move only a few times more slowly than H, and will also collide with grain surfaces many times; if they stick, they will form new grain material. This is the process that dominates grain formation in the Milky Way, and there is no reason not to expect it to dominate growth of grain material in J1148+5251.

Supernovae are of course required to produce the metals that compose the grains, and to provide some supernova-condensed "stardust" to provide some surface area on which to grow more material in the ISM, but the bulk of the dust mass in high-z galaxies will be primarily the result of grain growth competing successfully with grain destruction in the ISM.

11. Summary

The principal points of this paper are as follows:

1. The principal observational constraints on models for the interstellar grain population are summarized. The observed wavelength dependence of extinction (Fig. 1) and polarization of starlight, together with elemental abundances (total and observed in the gas) continue to give the strongest constraints on what interstellar dust can be. Additional information is provided by infrared emission features at 3.3, 6.2, 7.7, 8.6, 11.3, 12.0μm that are identified as coming from PAHs following single-photon heating.

2. A grain model consisting of a population of amorphous silicate spheres and a population of carbonaceous grains, including PAHs, can reproduce the observed wavelength-dependent extinction by dust. This model also successfully reproduces the observed infrared emission from interstellar dust (Figs. 2, 3).

3. If the amorphous silicate and carbonaceous grains are given spheroidal shapes, the observed polarization of starlight can also be reproduced.

4. The infrared emission spectra calculated for these spheroidal grain models (Fig. 4) are consistent with the observed infrared emission from high-latitude regions in the Milky Way. The models predict different degrees of polarization as a function of wavelength—observations with *Planck* will test these predictions.

5. The evolution of interstellar grains in the Milky Way is discussed. Grain destruction in the interstellar medium is such that only $\lesssim$10% of the interstellar dust mass consists of "stardust" from stellar sources, including

supernovae. *The bulk of interstellar dust has been grown in the interstellar medium.*

6. The amorphous silicate and carbonaceous materials found in interstellar grains is the product of grain growth in the presence of strong ultraviolet radiation, that will photoexcite and possibly photodesorb species from the grain surface. The ultraviolet radiation may be key to maintaining separate populations of silicate and carbonaceous grains even though most grain growth occurs out of an average-composition ISM.

7. Dust in high-redshift systems such as J1148+5251 must be—and can be—predominantly the result of grain growth in interstellar clouds. A small amount of dust from supernovae is sufficient to initiate grain growth in the ISM.

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