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Perspectives on Interstellar Dust Inside and Outside of the Heliosphere

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Abstract Measurements by dust detectors on interplanetary spacecraft appear to indicate a substantial flux of interstellar particles with masses $> 10^{-12}$ g. The reported abundance of these massive grains cannot be typical of interstellar gas: it is incompatible with both interstellar elemental abundances *and* the observed extinction properties of the interstellar dust population. We discuss the likelihood that the Solar System is by chance located near an unusual concentration of massive grains and conclude that this is unlikely, unless dynamical processes in the ISM are responsible for such concentrations. Radiation pressure might conceivably drive large grains into "magnetic valleys". If the influx direction of interstellar gas and dust is varying on a ~ 10 yr timescale, as suggested by some observations, this would have dramatic implications for the small-scale structure of the interstellar medium.

Keywords Dust · Interstellar dust · Heliosphere · Interstellar matter

1 Introduction

The interstellar medium (ISM) consists of a partially-ionized, magnetized gas mixed with solid particles of dust. The ionization state and molecular fraction of the gas depend primarily on the gas density and the local intensity of ultraviolet radiation that can photodissociate molecules and photoionize molecules and atoms. The dust content is determined by the prior history of the gas, including injection of newly-formed dust in stellar winds and supernova explosions, grain destruction in violent events such as supernova blast waves, and grain growth in the interstellar medium by both vapor deposition and coagulation in dense regions.

While we do not know the properties of interstellar dust with precision, they are strongly-constrained by a variety of observations. The observed wavelength dependence of interstellar extinction—the so-called "reddening curve" (reviewed in Sect. 2)—provides strong constraints on both the composition and size distribution of interstellar dust. In the local regions

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of the Milky Way, interstellar dust is abundant, containing a large fraction of the elements (such as Mg, Si, and Fe) that can be incorporated into refractory solids. As discussed in Sect. 3, interstellar abundances therefore provide a strong constraint on grain models. The size distribution of interstellar grains can be inferred from the observed average reddening curve together with interstellar abundance constraints.

Microparticle impacts on detectors on Ulysses and Galileo have been interpreted as showing a flux of solid particles entering the Solar system from the local interstellar medium (Grun et al. 1993). In Sect. 3 we show that the population of large grains inferred from dust impact detectors on Ulysses and Galileo (Landgraf et al. 2000; Krüger et al. 2007; Krueger and Gruen 2008) is incompatible with average elemental abundances in the ISM. In Sect. 4, we show that such a large grain population would result in wavelength-dependent extinction very different from what is observed.

The Ulysses and Galileo data, if correctly interpreted, imply that the Solar System is, by chance, located in a very atypical spot in the ISM, with an overabundance of very large grains. The likelihood of such a scenario is discussed in Sect. 5. In Sect. 6 we comment on suggestions that the interstellar dust inflow vector might have changed appreciably over only ∼5 yrs. Our conclusions are summarized in Sect. 7.

2 Dust in the Diffuse Interstellar Medium

In the Milky Way and many other galaxies, a substantial fraction of the "refractory elements" in the ISM are in solid materials, in submicron dust particles. At least on large scales, the dust and gas are well-mixed, with the density of dust tending to be proportional to the density of gas.

The properties of the dust—size distribution, shapes, composition—are inferred from a wide range of observations (for a review, see Draine 2003) including: wavelength-dependent extinction and polarization of starlight, light scattering in the visible and ultraviolet, small-angle scattering of X-rays, thermal emission from infrared to submm wavelengths, and microwave radiation from spinning dust. Studies of the strength and wavelength-dependence of interstellar extinction $A_\lambda \equiv (2.5/\ln 10)\tau_{\rm ext}(\lambda) = 1.086\tau_{\rm ext}(\lambda)$ provide strong constraints on the size distribution and composition of interstellar dust. Figure 1 shows an empirical parameterization of the extinction by dust in "diffuse clouds" (Cardelli et al. 1989; Fitzpatrick 1999). A "diffuse cloud" is simply a region with visual extinction $A_{\rm V} \lesssim 1$ mag; most of the interstellar H I is in such regions. The interstellar material surrounding the heliosphere consists of diffuse H I, and it was natural to expect that the interstellar dust outside the heliosphere would be typical "diffuse cloud" dust—typical in both its size distribution and its abundance relative to the gas.

The wavelength-dependence of A_λ is known to vary from one sightline to another. Extinction curves are often characterized by $R_V \equiv A_V/(A_B - A_V)$. Average diffuse clouds have $R_V \approx 3.1$ but R_V can be as small as ~ 2.2 in some diffuse clouds (e.g., $R_V = 2.22 \pm 0.14$ toward HD 210121: Fitzpatrick 1999) and can reach values as large as ~ 5.8 in dense regions (e.g., $R_V = 5.8 \pm 0.6$ toward HD 36982: Fitzpatrick 1999). The extinction law shown in Fig. 1 is intended to be an average curve for diffuse clouds, with $R_V \approx 3.1$. The most notable characteristic of the extinction curve in Fig. 1 is the continuing rise into the vacuum ultraviolet; this requires that the size distribution be such that the total surface area of the dust is dominated by very small grains with radii $a \lesssim 200$ Å. The second notable characteristic is the prominent "bump" in the extinction at $\lambda \approx 2175$ Å. While this feature has not yet been identified with complete certainty (see, e.g., Draine 1989), it is thought

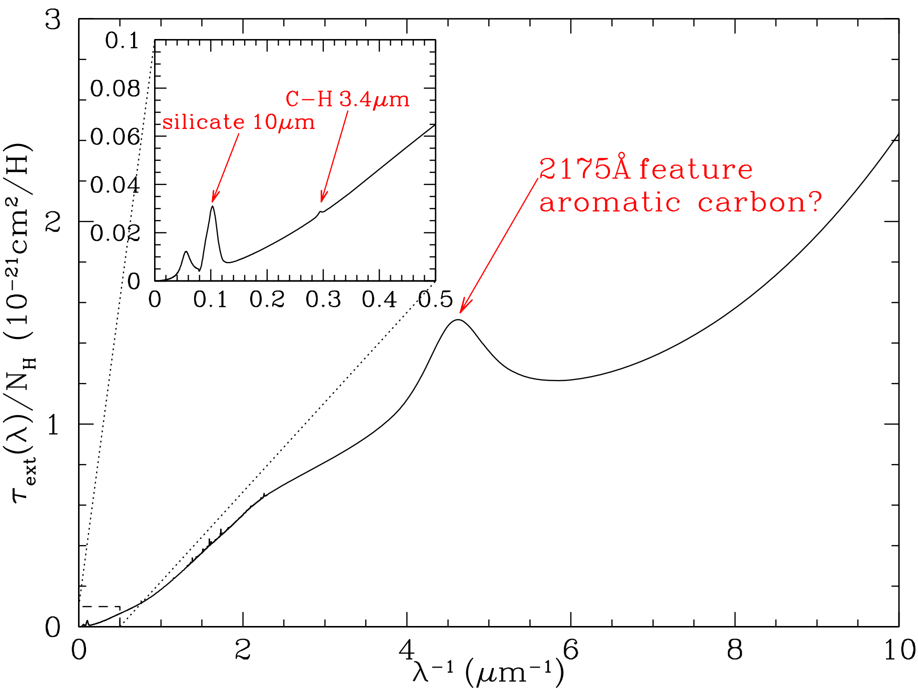

Fig. 1 The average observed extinction per H nucleon, as a function of inverse wavelength $1/\lambda$, in diffuse regions of the Milky Way. The prominent "bump" at $\lambda \approx 2175$ Å is probably due to $\pi \rightarrow \pi^*$ electronic transitions in sp^2-bonded (aromatic) carbon. The strong infrared extinction features (see *inset*) are produced by the Si–O stretching mode (9.8 μm) and the O–Si–O bending mode (18 μm). There is also a weak feature at 3.4 μm due to the C–H stretch in aliphatic (chainlike) hydrocarbons

to be produced by $\pi \rightarrow \pi^*$ electronic transitions in aromatic carbon, such as the carbon in graphite or in polycyclic aromatic hydrocarbons (PAHs). The 2175 Å bump traces only the aromatic carbon in particles with masses $m \lesssim 10^{-16}$ g: the feature is suppressed in larger grains. The 2175 Å feature therefore gives only a lower bound on the carbon content of the dust population: $\gtrsim 15\%$ of interstellar carbon is in aromatic structures.

There are also two spectroscopic features in the infrared—strong absorption features peaking near 9.7 μm and 18 μm. These features are characteristic of Si–O stretching and O–Si–O bending modes in amorphous silicates. The strength of the features requires that most interstellar Si atoms be incorporated into these silicates, together with corresponding amounts of Mg, Fe, and O. Amorphous silicates and carbonaceous materials are together thought to account for the bulk of the mass of interstellar dust in diffuse clouds. In dense and dark clouds, ices are also present, but the heliosphere is not located near a dark cloud, hence ices are not expected to be present in the dust entering the solar system from the ISM.

As discussed in Sect. 3, observations of the elements that are "depleted" from the gas phase in interstellar clouds provide an indication of what elements are in grains—the bulk of the mass of interstellar dust is contributed by the elements C, O, Mg, Si, and Fe. Based on the spectroscopic evidence in Fig. 1, it can be concluded that the dominant materials are some form of amorphous silicate (with composition $\sim MgFeSiO_4$) and some mixture of carbonaceous materials—PAHs, amorphous carbon, graphite, and perhaps even diamond.

Table 1 Dust Mass per H from Milky Way Abundances. $(N_X/N_H)_\odot$ and $(N_X/N_H)_{gas}$ are the abundances of element X, by number, relative to H in the Sun and in the gas phase of a "standard" interstellar cloud (see text). $M_{X,dust}/M_H$ is the mass of element X in dust relative to the total mass of H

X	$(N_X/N_H)_\odot$ (ppm)[a]	$(N_X/N_H)_{gas}/(N_X/N_H)_\odot$[a]	$M_{X,dust}/M_H$
C	247	0.57	0.0013
N	85	0.72	0.0003
O	490	0.73	0.0021
Mg	38	0.08	0.0008
Al	3[b]	$\lesssim$0.1[c]	0.0001
Si	32	0.05	0.0009
Ca	2[b]	0.0002[d]	0.0001
Fe	29	0.007	0.0016
Ni	2	0.004	0.0001
total			0.0073

[a]Jenkins (2004) except as noted

[b]$(N_X/N_H)_\odot$ from Grevesse and Sauval (1998)

[c] assumed

[d]Savage and Sembach (1996)

3 Models for Interstellar Dust: Extinction vs. Elemental Abundances

Observations of the spectra of recently-formed stars, together with absorption lines produced by interstellar gas, have led to estimates of elemental abundances in the local interstellar material. Abundances of many elements relative to hydrogen in the ISM can also be deduced from emission lines from H II regions. Although the Sun was formed out of the ISM 4.5 Gyr ago, the elemental abundances in the ISM today appear to be close to those in the solar photosphere, and "solar abundances" are generally considered to be a good guide to interstellar abundances, although "solar abundances" are themselves uncertain: e.g., recent estimates of O/H in the solar photosphere range from (457 ± 56) ppm (Asplund et al. 2004) to (730 ± 100) ppm (Centeno and Socas-Navarro 2008).

The second column of Table 1 lists the solar abundances of the elements that are sufficiently abundant to contribute 1% or more of the mass of interstellar dust. Elements such as Ti do not appear in Table 1 because they are too rare: the abundance of Ti, by mass, is only about 0.3% of the abundance of Fe. Therefore, even though most interstellar Ti is in fact locked up in grains, Ti is not a major grain constituent.

The third column gives observed gas-phase abundances, relative to solar, in "standard" interstellar diffuse clouds, such as the well-studied cloud on the line-of-sight to the bright star ζ Oph. The gas-phase abundance of C appears to be only ∼57% of the total C abundance, implying that ∼43% of the carbon is sequestered in grains. For elements such as Mg, Si, or Fe the "depletions" are more severe, with 90% or more of the material locked up in grains.

Based on these observations alone, we can estimate the mass of interstellar dust: ∼0.73% of the mass of the hydrogen in a "standard" cloud. It is important to recognize that "solar" abundances of elements such as C, Mg, Si, and Fe remain uncertain, and interstellar abundances might be a bit higher than solar abundances, but it is difficult to imagine that the

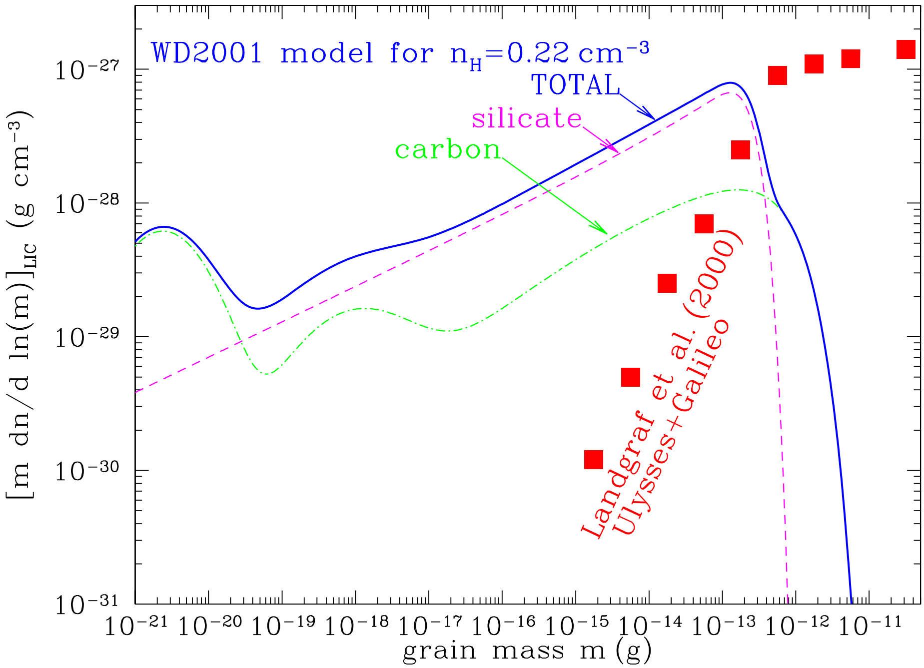

Fig. 2 The mass distribution from Weingartner and Draine (2001a) scaled to the density $n_H \approx 0.22\ cm^{-3}$ of the local interstellar cloud. The peak near $\sim 3 \times 10^{-21}$ g consists of PAHs. Also shown is the mass distribution estimated from impacts on Ulysses and Galileo (Landgraf et al. 2000). No correction for "filtration" by the heliospheric magnetic field has been applied. For $5 \times 10^{-13} < m < 3 \times 10^{-11}$ g the mass flux observed by Ulysses and Galileo is far above that expected for interstellar dust (see text)

total mass of dust in "standard" diffuse clouds could be much more than ∼1.0% of the total hydrogen mass.

Various authors have obtained dust grain size distributions that reproduce the observed extinction per H as shown in Fig. 1, subject to the constraint that the mass of the dust in the model should be consistent with the "observed" mass given in Table 1 (e.g., Mathis et al. 1977; Draine and Lee 1984; Weingartner and Draine 2001a; Zubko et al. 2004). This turns out not to be an easy task: models that reproduce the observed extinction—even when trying to also minimize the total grain mass—tend to consume 100% or more of the "available" material. Modest discrepancies between the mass in the dust model and the "observed" dust mass in Table 1 would not be unexpected, given uncertainties in the observations, and given that the theoretical models make simplifying assumptions, e.g., typically assuming spherical grains. Overall, one draws the conclusion that the bulk of the interstellar grain mass is in dust grains with masses $\lesssim 5 \times 10^{-13}$ g—these grains are *needed* to produce the observed extinction, and there isn't much dust mass "left over" once the observed extinction has been reproduced.

Assuming that the interstellar grain population consists of two distinct compositions—amorphous silicate grains and carbonaceous grains—Weingartner and Draine (2001a, hereafter WD01) found size distributions for these two components that would produce extinction close to the observed extinction curve in Fig. 1, and which would incorporate amounts of C, Mg, Si, and Fe approximately consistent with current estimates of elemental abundances in the ISM. The same dust model, heated by starlight, is consistent with observa-

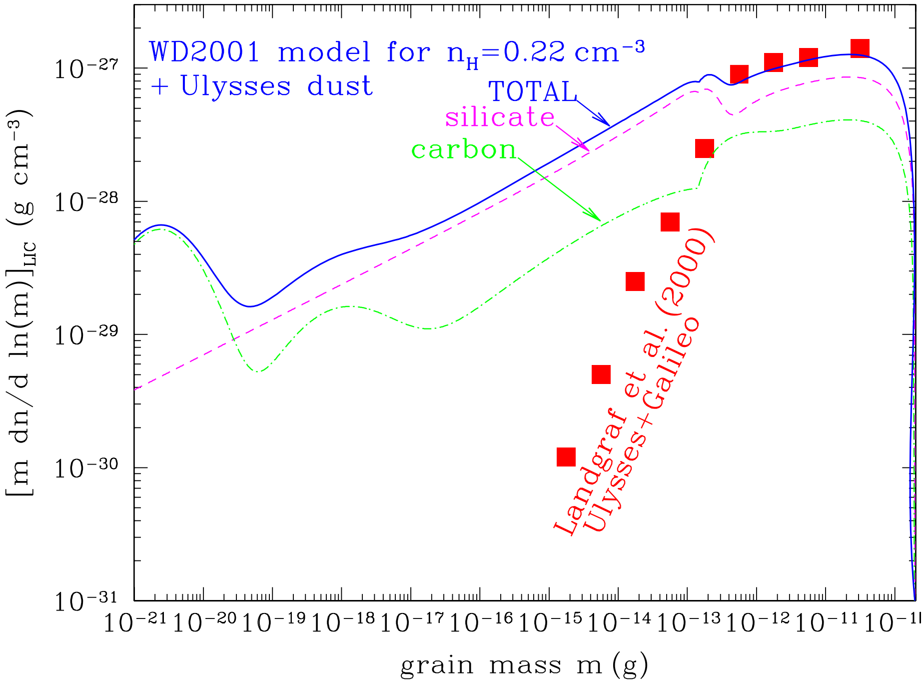

Fig. 3 The mass distribution from Weingartner and Draine (2001a) plus the "big grain" component from the Ulysses and Galileo measurements. This model has a dust/H mass ratio of 0.028, much larger than the value 0.010 of the WD01 size distribution in Fig. 2

tions of infrared emission from the Milky Way and similar galaxies (Draine and Li 2007; Draine et al. 2007). The resulting mass distributions are shown in Fig. 2, for an H nucleon density $n_H = 0.22\ cm^{-3}$, the value currently estimated for the very local ISM based on observations of inflowing He^0 (Lallement et al. 2004) and photoionization models for the nearby ISM (Slavin and Frisch 2007).

Also shown in Fig. 2 is the mass distribution of particles entering the heliosphere from the local ISM as estimated by Landgraf et al. (2000) from the dust impact detectors on Ulysses and Galileo. Because the magnetic field of the heliosphere is expected to substantially deflect incoming particles with masses $m \lesssim 3 \times 10^{-13}$ g, the fact that the Landgraf et al. (2000) results fall well below the WD2001 model for $m < 10^{-13}$ g is not surprising. However, the reported flux of $m \gtrsim 3 \times 10^{-13}$ g particles is quite unexpected if the local ISM has a dust/gas ratio typical of diffuse regions in our Galaxy.

First of all, there is the question of overall mass: as seen from Table 1, current estimates for solar and interstellar abundances would allow M_{dust}/M_H of only 0.0073. Given uncertainties in both measured abundances and grain modeling, it can be argued that the WD2001 dust model ($M_{dust}/M_H \approx 0.010$—a factor 1.4 greater than the total in Table 1) is within tolerances. However, extending the size distribution to include the Ulysses results, as in Fig. 3, raises M_{dust}/M_H to 0.028–3.9 times higher than the estimated total in Table 1. This is incompatible with our current understanding of elemental abundances in the general ISM.

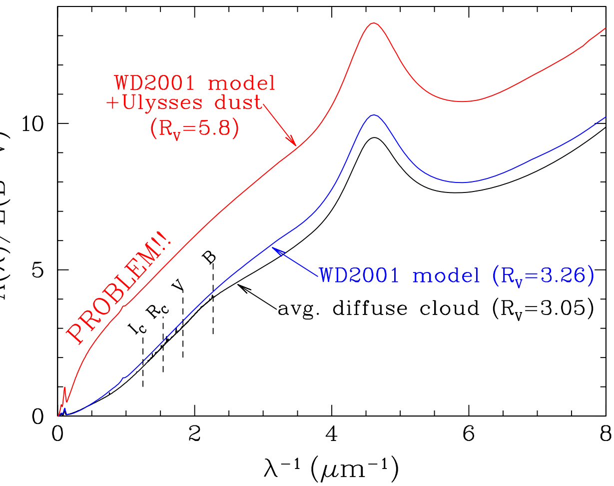

Fig. 4 Reddening law calculated for the mass distribution of Fig. 3 (note: $E(B-V) \equiv A(B) - A(V)$, where $A(\lambda)$ is the extinction at wavelength λ). The large grains contribute substantial amounts of additional extinction, and the resulting reddening curve differs strongly from observed reddening: $A(\lambda)/E(B-V)$ exceeds observed values by factors 1.5 – 2 for the commonly-observed B, V, R, and I bands

4 Contribution of Massive Grains to Extinction

If the massive grains detected by Landgraf et al. (2000) were part of the general interstellar grain population, they would have conspicuous effects on the interstellar extinction. To see this, we have taken the WD01 size distribution, and added to it an additional population of carbonaceous and silicate particles so as to approximately reproduce the Landgraf et al. (2000) size distribution at $m > 3 \times 10^{-13}$ g. We arbitrarily assume that 2/3 of the added mass is contributed by amorphous silicates and 1/3 by graphite. The adopted size distribution is shown in Fig. 3. Approximating the particles as spheres, the extinction as a function of wavelength has been calculated for the extended size distribution of Figure 3. The resulting "reddening curve" $A(\lambda)/E(B-V)$ is shown in Fig. 4.

On suitable sightlines, $A(\lambda)/E(B-V)$ can be determined observationally to accuracies of $\sim 10\%$ for $0.5 \lesssim (\lambda/\mu\text{m})^{-1} \lesssim 3$. The reddening law shown in Fig. 4 is well outside the range of what is observed (see, e.g. Mathis 1990). The synthetic curve in Fig. 4 has $R_V \approx 5.8$—such large values of R_V are not seen in diffuse clouds, being found only in regions with $A_V \gtrsim 2$.

It does not seem possible for the dust in the general ISM to have the size distribution for $m \gtrsim 3 \times 10^{-13}$ g *reported by* Landgraf et al. *(*2000*):* (1) as shown in Sect. 3, there are simply not enough atoms of C, Mg, Si, and Fe to constitute such a large mass in dust, and, (2) as seen here, if such dust were pervasive, the wavelength-dependence of interstellar extinction would be totally unlike what is actually observed.

5 Could the Dust in the Local ISM Be Atypical?

We have shown above that the large-grain population reported by Landgraf et al. (2000) cannot be pervasive. However, it is important to realize that the dust detectors on Ulysses and Galileo have only probed a tiny portion of the ISM: a cylindrical volume with diameter ~10 AU, and length increasing by ~5 AU/yr due to the solar-system's motion of 26.2 km/s relative to the local ISM (Möbius et al. 2004). We have therefore probed only a "microscopic" sample of the ISM—how representative do we expect this sample to be?

5.1 Turbulent Mixing in the ISM

MHD turbulence appears to be pervasive in the ISM. Although not understood in detail, the turbulence appears to be the result of "driving" by energetic phenomena on large scales $L_{\rm max}$—e.g., H II regions, stellar winds, supernova explosions. The turbulent cascade to smaller scales appears to approximately follow the "Kolmogorov" power-law scaling, with the velocity differences on length-scale L varying as

$$v_L \approx v_{\rm max}(L/L_{\rm max})^{1/3} \quad \text{for } L_{\rm diss} < L < L_{\rm max}, \tag{1}$$

where $L_{\rm diss}$ is the length scale below which dissipation is dominant. Because of the magnetic field, the turbulence is anisotropic, but the scaling law (1) approximately applies to turbulent motions perpendicular to the magnetic field.

Observations of turbulence within ~ 100 pc are more-or-less consistent with $v_{\rm max} \approx 10\ {\rm km\ s}^{-1}$ and $L_{\rm max} \approx 100$ pc. Nonuniformities on a scale L will be erased on timescales

$$\tau_{\rm diff} \approx \frac{L}{v_L} \approx \frac{L^{2/3} L_{\rm max}^{1/3}}{v_{\rm max}} \approx 0.5 \left(\frac{L}{\rm pc}\right)^{2/3} \ {\rm Myr}, \tag{2}$$

where we have adopted $v_{\rm max} \approx 10\,{\rm km\ s}^{-1}$ and $L_{\rm max} \approx 100$ pc. A mixing timescale of $\lesssim$Myr is short relative to Galactic timescales. Therefore we do not expect to find small-scale abundance inhomogeneities unless they were very recently injected, or unless some specific mechanism sustains them. What injection mechanisms might produce local enhancements in the population of large dust particles?

5.2 Enrichment by Supernova Explosions?

One possible source of inhomogeneity is Type II supernova explosions following core collapse in massive stars. Each such explosion enriches the nearby ISM with $\sim 5\ M_\odot$ of heavy elements, a fraction of which may be in grains. Hydrodynamic instabilities in the supernova remnant will mix these heavy elements with a mass $M_{\rm mix}$ of the ISM. The normal ISM has a heavy-element mass fraction $Z \approx 0.02$; this will be enhanced by $\Delta Z \approx 0.05(10^2\ M_\odot/M_{\rm mix})$. For the average density $\langle n_{\rm H}\rangle \approx 1\ {\rm cm}^{-3}$ of the ISM in the solar neighborhood, this corresponds to a lengthscale $L_{\rm mix} \approx 14\ {\rm pc}(M_{\rm mix}/10^2 M_\odot)^{1/3}$ and from (2), we would expect inhomogeneities on this length scale to be erased in a time

$$\tau_{\rm diff} \approx 2.9(M_{\rm mix}/10^2 M_\odot)^{2/9}\ {\rm Myr} \tag{3}$$

The supernova rate/volume in the Galactic disk is $S \approx 10^{-13}\ {\rm pc}^{-3}\ {\rm yr}^{-1}$. The probability that a SN exploded within a distance $L_{\rm mix}$ within a time $\tau_{\rm diff}$ is only $\sim L_{\rm mix}^3 S \tau_{\rm diff} \approx 10^{-3}$. It is therefore very improbable that the local interstellar cloud has been heavily enriched by a recent SN explosion. The Local Bubble is believed to have been caused by one or more SN explosions over the past 10–15 Myr, but these were located at a distance of ~ 100 pc (Fuchs et al. 2006). The strongest argument against enrichment by SN ejecta is the fact that the gas-phase abundances of Mg and Fe appear to show normal depletions relative to solar abundances (Redfield and Linsky 2008).

5.3 Wake of an Evolved Star?

Cool AGB stars have dusty winds that may pollute the ISM with fresh grain material—for example, the wind from Mira = o Ceti (Martin et al. 2007). What is the likelihood that a recent passage by an AGB star left behind a concentration of large grains that might account for the excess of large particles seen by Ulysses?

Consider a star moving at speed $v_\star$ relative to the ISM, losing mass at a rate $\dot{M}$. It will leave behind a wake, with radius R_w, filled with gas with density n_w and temperature T_w. Mass conservation and balance with the interstellar pressure $p_{\rm ISM}$ give

$$n_w 1.4 m_{\rm H} \pi R_w^2 v_\star = \dot{M}, \tag{4}$$

$$n_w k T_w = p_{\rm ISM}. \tag{5}$$

These two equations can be solved for the wake radius

$$R_w = \left[\frac{\dot{M}}{1.4 m_{\rm H}\pi v_\star}\frac{T_w}{p_{\rm ISM}/k}\right]^{1/2} = 0.13\ {\rm pc}\left[\frac{\dot{M}_{-6}}{v_{\star,6}}\frac{T_{w2}}{(p_{\rm ISM}/k)_{5000}}\right]^{1/2},$$

$$\dot{M}_{-6} \equiv \frac{\dot{M}}{10^{-6} M_\odot\,{\rm yr}^{-1}}, \quad v_{\star,6} \equiv \frac{v_\star}{10\ {\rm km\ s}^{-1}}, \quad T_{w2} \equiv \frac{T}{100\ {\rm K}},$$

$$\left(\frac{p_{\rm ISM}}{k}\right)_{5000} \equiv \frac{p_{\rm ISM}/k}{5000\ {\rm cm}^{-3}\ {\rm K}}. \tag{6}$$

The trailing wake will be mixed with the ISM by turbulent diffusion on a time given by (3):

$$\tau_{\rm diff} \approx 0.5(R_w/{\rm pc})^{2/3}\ {\rm Myr} \approx 0.13\left[\frac{\dot{M}_{-6}}{v_{\star,6}}\frac{T_{w2}}{(p_{\rm ISM}/k)_{5000}}\right]^{1/3}\ {\rm Myr}. \tag{7}$$

If the duration of the mass loss phase is longer than $\tau_{\rm diff}$, the wake volume will be

$$V_w \approx \pi R_w^2 v_\star \tau_{\rm diff} \approx 0.07\left[\frac{\dot{M}_{-6}T_{w,2}}{(p_{\rm ISM}/k)_{5000}}\right]^{4/3} v_{\star,6}^{-1/3}{\rm pc}^3. \tag{8}$$

The *total* rate of stellar mass loss in the Milky Way is $\sim 1\ M_\odot\,{\rm yr}^{-1}$, e.g., 10^6 stars, each with $\dot{M}_{-6} \approx 1$. If $\sim 10^6$ stars are randomly-distributed in a disk of full-thickness ~ 200 pc and radius 12 kpc, then the stellar density is $n_\star \approx 1 \times 10^{-5}\ {\rm pc}^{-3}$, and the nearest-neighbor distance is $n_\star^{-1/3} \approx 50$ pc. [The distance to Mira, $D = 107$ pc, is in rough agreement with our estimate for $n_\star^{-1/3}$.] With $n_\star \approx 10^{-5}\ {\rm pc}^{-3}$, the fraction of the volume occupied by "wakes" is very small:

$$n_\star V_w \approx 7 \times 10^{-7}\left[\frac{\dot{M}_{-6}T_{w,2}}{(p_{\rm ISM}/k)_{5000}}\right]^{4/3} v_{\star,6}^{-1/3}\quad. \tag{9}$$

It is therefore *extremely* unlikely that the Solar System would by chance be located today within such a stellar wake; this conclusion will not be changed for any plausible variation of uncertain parameters such as $\dot{M}_{-6}$, $T_{w,2}$, or $v_{\star,6}$.

5.4 Dynamical Concentration of Massive Grains?

We have seen above that it is highly unlikely that the Solar System is by chance passing through gas that was recently enriched in very large grains from either a supernova explosion

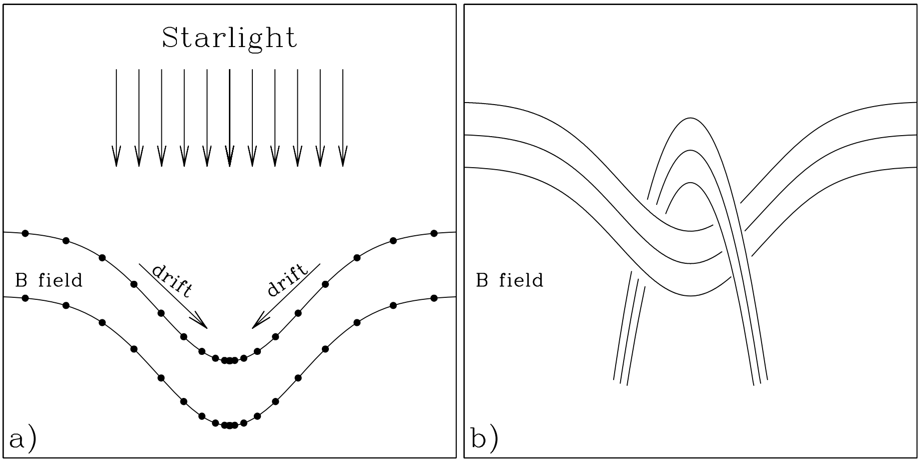

Fig. 5 (**a**) Radiation pressure-driven drift of dust grains along magnetic field lines could concentrate grains in magnetic "valleys" (see text). (**b**) Tangled magnetic fields could produce magnetic valleys

or an evolved star. What other process might produce the anomalous concentration of dust grains that appears to be present in the portion of the ISM we are now passing through?

Dust grains and gas atoms are subject to different forces, and in general the dust grains will *drift* relative to the gas. Charged dust grains are coupled to the magnetic field, which inhibits drift across magnetic field lines, but the grains are free to drift *along* field lines. Drift velocities resulting from radiation pressure and other effects of anisotropic starlight have been discussed by Weingartner and Draine (2001b). The drift velocities are not large, but can attain $\sim 0.5\,\mathrm{km\,s^{-1}}$ in the "warm neutral medium" conditions characteristic of the region the Solar System is now moving through (see Figs. 17, 18 of Weingartner and Draine 2001b). If sustained for long enough, these drifts might result in variations in the dust/gas ratio.

One possible scenario for concentrating dust is illustrated in Fig. 5a. If field lines are bent, radiation pressure could push grains into magnetic "valleys", as shown. If the width and depth of the "valley" are both of size L_B, then dust might accumulate on a time scale

$$t_{\mathrm{accum}} \approx \frac{L_B}{v_{\mathrm{drift}}} \approx 10^3\,\mathrm{yr}\left(\frac{L_B}{100\ \mathrm{AU}}\right)\left(\frac{0.5\,\mathrm{km\,s^{-1}}}{v_{\mathrm{drift}}}\right). \quad (10)$$

Magnetic stresses will act to try to straighten the field lines. Radiation pressure acting on the grains, if strong enough, could keep the field deformed, and could even cause the field deformation to grow, in a manner akin to the Parker instability, except with radiation pressure on dust playing the role of gravity on gas. However, this would require balancing the magnetic force per volume $\sim \nabla(B^2/8\pi) \approx B^2/8\pi L_B$ with the radiation pressure force per volume $\kappa\rho J_{\mathrm{rad}}/c$, where κ is the dust opacity, ρ is the dust mass density, and J_{rad} is the net flux of starlight. With the magnetic force/volume scaling as $1/L_B$, and parameters appropriate to the Milky Way, it does not appear that radiation pressure on dust could deform the magnetic field on length scales $L_B \lesssim 10$ pc. However, local field curvature might be maintained by magnetic stresses if the magnetic field is tangled, as shown in Fig. 5b.

If radiation-pressure-driven drift is responsible for concentrating very large grains, it should also have acted to concentrate the $m \approx 10^{-13}$ g grains that are thought to dominate the grain size distribution in the average interstellar medium (recall Fig. 2), as their drift velocities will be similar to those of larger grains. It is not clear that the “filtration” effects in the heliosphere will be able to suppress the flux of these particles to the values observed by Ulysses and Galileo.

6 Structure of the Very Local ISM

Recent analyses of microparticle impacts on the Ulysses spacecraft appear to indicate that the impacting dust velocity vector in heliocentric coordinates has shifted by 30° over the 15 years of observation (Krüger et al. 2007). The interstellar dust mass flux at 4–5 AU also appears to have varied by a factor ~ 3 over 1992–2006. These variations might be due to solar-cycle-related changes in the interplanetary B field at $\gtrsim 5$ AU (Landgraf et al. 2003; Krüger et al. 2007), but variations in such electromagnetic “filtration” would be expected to result in variations in velocity vector and flux as a function of grain size, with electromagnetic deflection expected to be minimal for $m \gtrsim 2 \times 10^{-12}$ g. Surprisingly, size-dependence of the velocity vector is not evident in the data (Krüger et al. 2007), so we must consider the possibility that the grain mass flux impinging on the heliosphere is variable. Since 15 years of observation corresponds to a spatial scale of only ~ 83 AU, variations in the grain flux incident on the heliosphere would require substantial variations in both grain density and velocity over length scales of only tens of AU. Such small-scale variations in the dust density in the local interstellar medium, if present, would appear to require an active mechanism, such as described in Sect. 5.4, to maintain it. While slow dust drift relative to the gas might account for density variations, one would not expect large velocity variations in a quiescent medium (Weingartner and Draine 2001b, estimated $v_{\rm drift} \lesssim 0.5\ {\rm km\ s^{-1}}$).

It is interesting to note that the velocity of the inflowing He^0 does not coincide with the velocity of two closest interstellar clouds: the “Local Interstellar Cloud” (LIC) and “Cloud G”: the velocity of the local He^0 is close to the *average* of the LIC and G cloud velocity vectors (Redfield and Linsky 2008). In view of this, it is natural to consider the possibility that the heliosphere might, by chance, be located in the narrow shock transition where the two clouds interact: the time-dependence of the mass flux and velocity of inflowing atoms and dust grains may be revealing structure in a multifluid shock transition layer.

7 Summary

The size distribution of interstellar grains entering the heliosphere, as inferred from observations by Ulysses and Galileo (Landgraf et al. 2000; Krüger et al. 2007) cannot be typical of the general interstellar medium, as can be demonstrated by two independent arguments:

1. The required abundance of elements in grains would substantially exceed what is available in the interstellar medium.
2. If such a size distribution were generally present, it would produce an interstellar “reddening law” very different from what is observed.

Therefore, if the size distribution of local interstellar dust does have the large grain population reported by Landgraf et al. (2000), the dust grain/gas ratio in the interstellar medium must be quite nonuniform. The length scale characterizing these nonuniformities is not known. If the velocity vector of the incoming dust flow is actually changing over time scales of only years—one possible explanation for the variations in the directions of impacting particles reported by Krüger et al. (2007)—this would require that the dust velocity vary over lengthscales of only tens of AU. Such small scale structure was not expected.

Mechanisms that might account for such nonuniformity are considered. It seems extremely unlikely that the Sun is passing through a region that has recently been enriched with dust from a stellar source. The least unlikely scenario may involve concentration of dust in certain regions, and removal of dust from other regions, by dynamical processes. One possible mechanism involving anisotropic starlight driving dust grains along deformed magnetic field lines is outlined. Whether this can compete with the diffusive effects of turbulent mixing is far from clear, however.

It is important to carry out additional observations to confirm the enhanced grain size distribution, and to confirm the time-dependence of the density and velocity vector of the inflowing dust and gas. If the reported density of large grains, and the time-dependence of the inflow, are confirmed, this may require revision of our understanding of the small-scale structure of the ISM. Absorption line studies seem to suggest that, by coincidence, the heliosphere is just now passing through the transition zone—possibly a shock transition—between the "Local Interstellar Cloud" and "Cloud G". If so, the flow into the heliosphere offers the opportunity to study the small-scale structure in this transition zone. The Ulysses observations indicate that this region is heavily enriched with large dust particles, although why this should be so remains unclear.

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