Can Fluffy Dust Alleviate the “Subsolar” Interstellar Abundance Problem?

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ABSTRACT

What might be the most appropriate set of interstellar reference abundances of chemical elements (both in gas and in dust) relative to hydrogen has been a subject of much discussion in the past decade. While historically the Sun has been taken as the reference standard, it has recently been suggested that the interstellar abundances might be better represented by those of B stars (because of their young ages) which are just $\sim 60$–$70\%$ of the widely adopted solar values (“subsolar”). On the other hand, the most recent estimates of the solar carbon and oxygen abundances are also close to those of B stars. If the interstellar abundances are indeed “subsolar” like B stars or the newly-determined solar C,O values, there might be a lack of raw material to form the dust to account for the interstellar extinction. In literature it has been argued that this problem could be solved if interstellar grains have a fluffy, porous structure since fluffy grains are more effective in absorbing and scattering optical and ultraviolet starlight than compact grains (on a per unit mass basis). However, we show in this work that, using the Kramers-Kronig relation, fluffy dust is not able to overcome the abundance shortage problem. A likely solution is that the abundances of refractory elements in stellar photospheres may under-represent the composition of the interstellar material from which stars are formed, resulting either from the possible underestimation of the degree of heavy-element settling in stellar atmospheres, or from the incomplete incorporation of heavy elements in stars during the star formation process.

Subject headings: dust, extinction — ISM: abundances

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### 1. Introduction

Elements in the interstellar medium (ISM) generally exist in the form of gas or dust. The interstellar gas-phase abundances of elements can be measured from their optical and ultraviolet (UV) spectroscopic absorption lines. The elements “missing” from the gas phase are bound up in dust grains – this phenomenon is often called “interstellar depletion”. The determination of the dust-phase abundances (“depletion”) is indirect and more complicated. One usually relies on the interstellar extinction modeling or the solid-state spectral feature analysis. Both methods require an explicit assumption of the nature (e.g. grain composition, size and geometry) and the physical characteristics of the grains (e.g. their optical properties and the strengths of their characteristic vibrational bands usually determined from their laboratory analogs). More commonly, the dust-phase abundance of an element is derived by assuming a reference abundance – total abundance of this element (both in gas and in dust) for the ISM\(^1\) – and then from which subtracting off the observed gas-phase abundance.

Interstellar depletions allow us to extract important information about the composition and quantity of interstellar dust (see §2.11 in Li 2004a): (1) The fact that Si, Fe, Mg, C, and O are depleted in low density clouds indicates that interstellar dust must contain an appreciable amount of Si, Fe, Mg, C and O. Indeed, all contemporary interstellar dust models consist of both silicates and carbonaceous dust (see Li 2004b for a review). (2) From the depletion of the major elements Si, Fe, Mg, C, and O one can estimate the gas-to-dust mass ratio to be $\sim 165$ (see Li 2004a), if the interstellar abundances are assumed to be those of the solar values of Holweger (2001). (3) In addition to the silicate dust component, there must exist another dust population, since silicates alone are not able to account for the observed amount of extinction relative to H although Si, Mg, and Fe are highly depleted in the ISM. Even if all Si, Fe, and Mg elements of solar abundances of Holweger (2001) are locked up in submicron-sized silicate grains, they can only account for $\sim 60\%$ of the total observed optical extinction (see Li 2004a).

Apparently, in interstellar depletion and dust composition studies the knowledge of interstellar reference abundances is critical. Historically, the solar abundances have been taken to represent the total interstellar abundances. But we note that the published solar abundances have undergone major changes over the years and are still subject to major systematic uncertainties. This is demonstrated in Table 1 in which the widely used solar abundances over the past 3 decades for the dust-forming elements C, O, Mg, Si and Fe are tabulated. Most notably, the most recent estimates of the solar C ($[\text{C}/\text{H}]_\odot \approx 245$ ppm; \(1\)In astrophysical literature, the total abundance of elements are also known as “standard abundances”, “interstellar abundances”, and “cosmic abundances”.}
Allende Prieto, Lambert, & Asplund 2002) and O abundances ([O/H]⊙ ≈ 457 ppm; Asplund et al. 2004) are significantly reduced from their earlier values.

Using the gas-phase abundances measured by the *Copernicus* satellite for the ζ Ophiuchi sightline (Morton et al. 1973) and the solar abundances of Cameron (1973; see Table 1) as the reference abundances, Greenberg (1974) found that the observed depletion of C, N, and O is significantly greater than could be accommodated by the dust under any reasonable models.\(^{2}\) Twenty years later, Sofia, Cardelli, & Savage (1994) found that the interstellar depletions are lowered for C, N, and O if B stars are used as the reference standard. They argued that the solar system may have enhanced abundances of many elements, and therefore the solar abundances (of Anders & Grevesse 1989) are not representative of the interstellar abundances.

Snow & Witt (1996) analyzed the surface abundances of B stars and field F and G stars and found that not only C, N, and O but also Si, Mg, and Fe and many other elements are underabundant in these stars. This led them to suggest that the interstellar abundances are appreciably subsolar (≈60%–70% of the solar values compiled by Anders & Grevesse 1989). It is worth noting that the most recent estimates of the solar C ([C/H]⊙ ≈ 245 ppm; Allende Prieto et al. 2002) and O abundances ([O/H]⊙ ≈ 457 ppm; Asplund et al. 2004)\(^{3}\) are also “subsolar”, just ≈50%–70% of the Anders & Grevesse (1989) values and close to the “subsolar” interstellar abundances originally recommended by Snow & Witt (1996). These reductions in the amounts of heavy elements available for grains have turned the former surplus of raw materials (Greenberg 1974) into a shortage and therefore have profound significance for the nature of interstellar dust (Snow & Witt 1996).

If the interstellar abundances are indeed “subsolar” like B stars or the newly-determined solar values, there is clearly a crisis for interstellar grain modeling; in particular, this places severe challenges to the interstellar extinction modeling\(^{4}\) and the interpretation of the interstellar abundances of many elements.

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\(^{2}\)Whittet (1984) argued that the *Copernicus* determinations of the C, N, and O depletions for ζ Oph were subject to systematic errors arising in the gas-phase abundance analysis and the depletions toward many other stars are actually substantially lower.

\(^{3}\)The substantial drop in [O/H]⊙ is of particular interest: the original ≈851 ppm (Anders & Grevesse 1989) was considered too large to be accounted for in the ISM if the solar abundance is taken to be the interstellar reference standard (Mathis 1996). This was one of the major motivations to invoke subsolar interstellar abundances.

\(^{4}\)Most grain models require more elements to be tied up in dust than available if the interstellar abundances are indeed significantly subsolar (see Snow & Witt 1995, 1996).
sterstellar 9.7 \mu m feature which is generally attributed to amorphous silicate dust\(^5\) – this is often referred to as interstellar abundance “budget crisis” (e.g. see Kim & Martin 1996).

In the context of these reduced reference abundances, Mathis (1986) re-investigated the composite interstellar dust model and found that fluffy grains consisting of small silicates, oxides, amorphous carbon derived from burning benzene (“BE”), and vacuum with a volume fraction of \(\sim 45\%\) could account for the observed interstellar extinction and satisfy the much tighter abundance constraints. Other dust models invoking compact grains require more elements than available (Li & Greenberg 1997, Weingartner & Draine 2001, Li & Draine 2001, Zubko, Dwek, & Arendt 2004). By comparing the observed dust-to-gas ratio of the \(\zeta\) Oph sightline with that expected from the reduced depletions, Snow & Witt (1996) concluded that the dust in this sightline must have a fluffy, porous or fractal structure.

However, can fluffy dust really alleviate the subsolar interstellar abundance budget crisis? We will explore this issue in terms of the Kramers-Kronig relations (Purcell 1969), using the most recently determined (subsolar) B star abundances (Sofia & Meyer 2001; see Table 1) as the reference standard.\(^6\) It is found in this paper that the Kramers-Kronig relations readily rule out the B star abundances as the interstellar reference abundances since the available elements are insufficient to account for the observed interstellar extinction, independent of specific grain models and grain fluffiness. It is also found that if the Sun (of Holweger 2001) or the field F and G stars (of Sofia & Meyer 2001) are used as the reference standard, the dust depletion is not inconsistent with the interstellar extinction. However, given that even the elemental abundances of our own Sun are not well determined, we are not at a position to conclude that the Sun or the field F and G stars reference abundances are to be preferred; after all, if the solar Mg, Si, and Fe elements are also close to these of B

\(^5\)The amount of Si (relative to H) required to deplete in dust to account for the observed 9.7 \mu m feature strength \(\Delta r_{9.7 \mu m}/A_V \approx 1/18.5\) in the local diffuse ISM is

\[
\left[ \frac{\text{Si}}{\text{H}} \right] = \frac{\Delta r_{9.7 \mu m}}{N_H} \frac{1}{\kappa_{\text{sil}}^{\text{abs}}(9.7 \mu m) \mu_{\text{sil}}} = \frac{\Delta r_{9.7 \mu m}}{A_V} \frac{A_V}{N_H} \frac{1}{\kappa_{\text{sil}}^{\text{abs}}(9.7 \mu m) \mu_{\text{sil}}}
\]

where \(\kappa_{\text{sil}}^{\text{abs}}(9.7 \mu m)\) is the silicate mass absorption coefficient at \(\lambda=9.7 \mu m\), \(A_V\) is the visual extinction, and \(N_H\) is the hydrogen column density, \(\mu_{\text{sil}}\) is the silicate molecular weight. With \(\kappa_{\text{sil}}^{\text{abs}}(9.7 \mu m)\approx2850 \text{ cm}^2 \text{ g}^{-1}\) and \(\mu_{\text{sil}}\approx172 \mu H\) for amorphous olivine MgFeSiO\(_4\), the local diffuse ISM \((A_V/N_H\approx5.3 \times 10^{-22} \text{ mag cm}^2)\) requires \(\text{Si/H}=35 \text{ ppm}\), significantly exceeding the B star Si/H abundance (\(\approx 18.8 \text{ ppm}\); Sofia & Meyer 2001). But also see Mathis (1998) who argued that composite fluffy spheroids with axis ratios greater than 2 could explain the observed silicate features even if the interstellar abundances are subsolar.

\(^6\)Although the most recently determined solar C and O abundances are in good agreement with those of B stars, and both are substantially lower than the widely adopted Anders & Grevesse (1989) solar values, for simplicity we customarily call the B star and new solar (C, O) abundances “subsolar.”
stars as the newly determined solar C and O abundances, the solar abundances would also fall short in accounting for the interstellar extinction.

2. Constraints from the Kramers-Kronig Relations

As shown by Purcell (1969), the Kramers-Kronig relations can be applied to the interstellar space sparsely populated by interstellar grains. Let $\tau_{\text{ext}}(\lambda)$ be the extinction optical depth at wavelength $\lambda$ and $\tau_{\text{ext}}(\lambda)/N_{\text{H}}$ be the extinction per H nucleon. The Kramers-Kronig relations can be used to relate $\int_0^\infty \tau_{\text{ext}}(\lambda)/N_{\text{H}} \, d\lambda$ to the total volume occupied by dust per H nucleon $V_{\text{dust}}^{\text{tot}}/H$ through

$$\int_0^\infty \frac{\tau_{\text{ext}}(\lambda)}{N_{\text{H}}} \, d\lambda = 3\pi^2 F \frac{V_{\text{dust}}^{\text{tot}}}{H},$$

where the dimensionless factor $F$ is the orientationally-averaged polarizability relative to the polarizability of an equal-volume conducting sphere, depending only upon the grain shape and the static (zero-frequency) dielectric constant $\epsilon_0$ of the grain material (Purcell 1969; Draine 2003a).

Let $P$ be the volume fraction of vacuum (“fluffiness” or “porosity”) contained in a fluffy grain. Let $[X/H]_{\text{ISM}}$ be the total interstellar abundance of element X relative to H, $[X/H]_{\text{gas}}$ be the amount of X in gas phase, $[X/H]_{\text{dust}}$ be the amount of X contained in dust (obviously we have $[X/H]_{\text{dust}} = [X/H]_{\text{ISM}} - [X/H]_{\text{gas}}$), and $\mu_X$ be the atomic weight of X. Let there be $N$ dust species in a composite fluffy grain; let $\rho_j$ be the mass density of dust species $j$; let $f_{X,j}$ be the fraction of element X locked up in dust species $j$. For a chosen set of interstellar reference abundances, the total volume of interstellar dust per H nucleon can be estimated from the interstellar depletions

$$\frac{V_{\text{dust}}^{\text{tot}}}{H} = \sum_{j=1}^N \sum_X f_{X,j} \left( [X/H]_{\text{ISM}} - [X/H]_{\text{gas}} \right) \frac{\mu_X}{(1-P) \rho_j}$$

where the first summation is over all possible dust species and the second one is over all condensable elements.\(^7\)

\(^7\)Eq.(3) actually slightly overestimates the total dust volume since the $1/(1-P)$ enlarging factor has also been applied to the ultrasmall grains [e.g. polycyclic aromatic hydrocarbon molecules (PAHs) responsible for the 3.3, 6.2, 7.7, 8.6 and 11.3 $\mu$m “unidentified infrared” (UIR) emission features], which are separated from the bulk, composite fluffy grains which contain most of the mass. Although small PAHs are expected to be planar (and thus “highly flattened”), their static dielectric constants $\epsilon_0$ are not large (e.g. $\epsilon_0 \approx 2.3$ for benzene), therefore the $F$ factors for PAHs will be in the order of unity and their contribution to the
The interstellar extinction per H nucleon $\tau_{\text{ext}}(\lambda)/N_H$ is known for a limited range of wavelengths. For the diffuse ISM, the mean extinction per H nucleon $\tau_{\text{ext}}(\lambda)/N_H$ is fairly well-determined from the far UV to infrared (IR): $0.1 \mu m \lesssim \lambda \lesssim 30 \mu m$ (Draine 2003b). For $30 \mu m \lesssim \lambda \lesssim 1000 \mu m$ we will adopt the theoretical $\tau_{\text{ext}}(\lambda)/N_H$ values calculated from the silicate-graphite-PAH model which has been shown to successfully reproduce the observed interstellar extinction from the far-UV to mid-IR and the observed IR emission (Weingartner & Draine 2001, Li & Draine 2001). Since $\tau_{\text{ext}}(\lambda)$ is a positive number for all wavelengths, the integration of $\tau_{\text{ext}}(\lambda)/N_H$ over a finite wavelength range can be used to obtain a lower bound on $F/\left(1 - P\right)$

$$\left(\frac{F}{1 - P}\right)_{\text{min}} = \frac{\int_{912 \text{ A}}^{1000 \mu m} \tau_{\text{ext}}(\lambda)/N_H d\lambda}{3\pi^2 \sum_j N X \int_{X \text{,j}} \left([X/H]_{\text{ISM}} - [X/H]_{\text{gas}}\right) \mu X / \rho_j}. \quad (4)$$

At a first glance of Eqs.(2,3), there appears to be no problem for dust models with subsolar interstellar abundances to account for the interstellar extinction, provided that the dust is sufficiently fluffy (i.e., the porosity $P$ is sufficiently large). However, one should keep in mind that for a composite fluffy grain, the increase in the total dust volume $V_{\text{dust}}^{\text{tot}}$ will be offset by a decrease in $F$ since the effective static dielectric constant becomes smaller when the dust becomes more porous which leads to a smaller $F$ (see Fig. 1 in Purcell [1969] and Fig. 15 in Draine [2003a]).

For the diffuse ISM, the integration of the mean extinction over the wavelength range $912 \text{ A} \leq \lambda \leq 1000 \mu m$ is approximately $\int_{912 \text{ A}}^{1000 \mu m} \tau_{\text{ext}}(\lambda)/N_H d\lambda \approx 1.37 \times 10^{-25} \text{ cm}^3/\text{H}$. If we adopt the B star abundances as the reference standard and subtract the observed gas-phase abundances (see Table 2 in Sofia 2004), we obtain $[C/H]_{\text{dust}} = [C/H]_{\text{ISM}} - [C/H]_{\text{gas}} \approx 60$ parts per million (ppm), $[\text{Mg/H}]_{\text{dust}} \approx 21$ ppm, $[\text{Si/H}]_{\text{dust}} \approx 16.8$ ppm, and $[\text{Fe/H}]_{\text{dust}} \approx 27.5$ ppm. It is reasonable to assume that all the dust-phase Si atoms are incorporated into amorphous olivine silicates with a stoichiometric composition of MgFeSiO$_4$. This also consumes 16.8 ppm Mg and Fe. We take the remaining 4.2 ppm Mg to be depleted in MgO, and the remaining 10.7 ppm Fe evenly tied up in FeO, Fe$_2$O$_3$, and Fe$_3$O$_4$. We will assume the 60 ppm dust-phase carbon to be bound up either in graphite or in amorphous carbon. Therefore, from Eq.(4) we obtain $(F/\left[1 - P\right])_{\text{min}} \approx 2.07$ if the carbon is in the form of graphite, or $(F/\left[1 - P\right])_{\text{min}} \approx 1.94$ if the carbon is in the form of “BE” amorphous carbon. In doing so, we take the mass density of amorphous olivine MgFeSiO$_4$, MgO, FeO, Fe$_2$O$_3$, right-hand-side of Eq.(2) will not be large, after all, in the silicate-graphite-PAHs interstellar grain model (Weingartner & Draine 2001; Li & Draine 2001) the PAH population takes over only $\approx 6.1\%$ of the total grain volume (and $\approx 4.6\%$ of the total grain mass).
Fe₃O₄, graphite, and amorphous carbon to be 3.5, 3.58, 5.7, 5.25, 5.18, 2.24, and 1.8 g cm⁻³, respectively.

For a composite fluffy grain consisting of small amorphous silicates, oxides (MgO, FeO, Fe₂O₃, and Fe₃O₄), and graphite or amorphous carbon particles, we use the Bruggeman effective medium theory (Bohren & Huffman 1983; Ossenkopf 1991) to calculate its effective static dielectric constants $\varepsilon_{\text{eff}}$. The static dielectric constants of the constituent dust materials of the composite grain adopted in this work are: $\varepsilon_0 \approx 10$ for amorphous olivine (Draine & Lee 1984), $\varepsilon_0 \approx 9$ for MgO (Roessler & Huffman 1998), $\varepsilon_0 \approx 16$ for Fe₂O₃ (Steyer 1974), $\varepsilon_0 \approx 160$ for amorphous carbon (Rouleau & Martin 1991), and $\varepsilon_0 \rightarrow \infty$ for FeO, Fe₃O₄ and graphite (in the calculation, we take $\varepsilon_0 = 10^{300}$ to represent $\varepsilon_0 \rightarrow \infty$; it is found that there is not much difference among the model results obtained using $\varepsilon_0 = 10^{100}$, $\varepsilon_0 = 10^{200}$, or $\varepsilon_0 = 10^{300}$).

Interstellar grains are nonspherical as indicated by the detection of interstellar polarization. For simplicity, we approximate these nonspherical grains by prolates or oblates. Interstellar polarization modeling suggests that interstellar grains are modestly elongated: Lee & Draine (1985) found that the 3.1 µm ice polarization feature of the Becklin-Neugebauer (BN) object is best fit by $a/b = 1/2$ oblates, where $a$ ($b$) is the semiaxis along (perpendicular to) the symmetry axis; similarly, Hildebrand & Dragovan (1995) also found that $a/b = 1/2$ oblates provide the best match to the 9.7 µm silicate polarization feature of the BN object; using ice-coated core-mantle grains, Greenberg & Li (1996) found that $a/b = 3$ prolates are preferred in explaining the 9.7 and 18 µm silicate polarization features of this object.

For a composite fluffy grain of a given porosity $P$ and a given elongation $a/b$, we first calculate its effective static dielectric constant $\varepsilon_{\text{eff}}^0$ and then calculate the $F$ factor. In Figure 1 we show the model-predicted $(F/ (1 - P))_{\text{mod}}$ as a function of $P$ obtained for spheres ($a/b = 1$) and prolates ($a/b = 2, 3, 5$) using the B star abundances as the interstellar reference standard. It is seen that even for $a/b = 5$, the model values $(F/ (1 - P))_{\text{mod}}$ are always below the lower limit $(F/ (1 - P))_{\text{min}}$; no matter what chemical form the carbon takes (graphite or amorphous carbon). Similar results are obtained for oblate grains. This indicates that if the total interstellar abundances are those of the B stars, there are not enough raw materials to make the dust producing the interstellar extinction, unless the grains are highly elongated or flattened ($a/b > 6.1$ for prolates or $b/a > 5.7$ for oblates).

It is also seen in Figure 1 that the model value of $F/ (1 - P)$ first increases with $P$ and reaches its maximum at $P \approx 0.35$–0.55, depending on the grain shape, and then decreases. This explains why in the latest version of the composite dust model – to make the most economical use of the heavy elements – Mathis (1996) arrived at a porosity of $P \approx 0.45$, in
contrast to the original value of $P \approx 0.8$ (Mathis & Whiffen 1989). For $P > 0.8$, the model-predicted values of $F/(1-P)$ are insensitive to grain shape. This is because for grains with a porosity $P > 0.8$, their effective static dielectric constants becomes smaller than $\sim 1.8$, while the $F$ factor is insensitive to grain shape when $\epsilon_0 < 2$ (see Fig. 1 of Purcell [1969] and Fig. 15 of Draine [2003a]).

3. Discussion

Using the Kramers-Kronig relations, we have shown in §2 that the B star abundances as the interstellar reference standard fall short in accounting for the interstellar extinction, no matter how fluffy the dust is or what precise chemical form the dust takes, unless the dust is highly elongated or flattened. Mathis (1996) suggested that the interstellar extinction could be accounted for if the dust has a fluffy, porous structure, consisting of small silicates, amorphous carbon, and oxides with vacuum comprising $\sim 45\%$ of its volume. But Dwek (1997) argued against this suggestion on the basis of the fluffy dust model emitting too much in the far-IR to be consistent with that observed for the diffuse ISM and the neglect of PAHs in the model (which are required to explain the “UIR” emission bands). While the Dwek (1997) argument involves estimating the relatively uncertain UV and optical interstellar radiation field times the otherwise unobserved absorption (in contrast to extinction) of the grains (cf. Mathis 1998), the discussion presented in this work is more robust since essentially no assumptions are made in using the Kramers-Kronig relations to rule out the B star abundances as the interstellar reference standard. The only assumption made in our analysis is that all the dust-phase Si atoms, with a similar number of Fe and Mg atoms, are locked up in amorphous olivine silicates (MgFeSiO$_4$) and the remaining Fe and Mg atoms form oxides.

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8The reason why our model-predicted $F/(1-P)$ peaks at $P \approx 0.55$ for spherical grains consisting silicates, oxides and amorphous carbon (see Fig.1) while it is at $P \approx 0.45$ in the Mathis (1996) model lies in the fact the B star abundances and the interstellar gas-phase abundances we are using are somewhat different from those adopted in Mathis (1996).

9Jones (1988) found that although the introduction of a porous structure to a grain does increase its UV and far-UV absorption (per unit dust mass) compared to its compact counterpart, its long wavelength absorptivity is reduced. This is expected from the Kramers-Kronig relation which indicates that the integration of the extinction cross sections over the entire wavelength range should be proportional to the total dust volume $V$ times the $F$ factor, unless the dust is both extremely elongated and conducting, $VF$ for porous grains does not differ much from that for compact grains of the same mass. The enhanced short-wavelength absorptivity of porous dust revealed in Jones (1988) also explains why porous dust emits more in the far-IR: the dust absorbs more at short wavelengths, and the absorbed energy must be radiated away at long wavelengths!
But we have also considered silicates in the form of amorphous pyroxene \((\text{Mg}_{1-x}\text{Fe}_x\text{SiO}_3)\) and amorphous olivine \([\text{Mg}_{2(1-x)}\text{Fe}_{2x}\text{SiO}_4]\) with various Fe fraction \(0 \leq x \leq 1\) and even with some of the Si atoms in SiO\(_2\). It is found that the conclusion of this work remains unchanged, unless an appreciable fraction of the Fe atoms are in the form of metallic iron needles.\(^\text{10}\)

We have also considered the F and G star abundances or the Holweger (2001) solar abundances (see Table 1) as the interstellar reference standard. We take all the dust-phase Mg, Si, and Fe atoms to be in amorphous silicates and assign four O atoms for the average of the Mg, Si, Fe abundances (based on olivine). We take all the C atoms remaining from the gas to form graphite. The Kramers-Kronig relations place a lower bound of \([F/(1 - P)]_{\text{min}} \approx 0.97\) for models using the F and G star abundances and \([F/(1 - P)]_{\text{min}} \approx 0.96\) for models using the solar abundances. As shown in Figure 2, the model-predicted values of \(F/(1 - P)\) always exceed the lower limit \([F/(1 - P)]_{\text{min}}\) except for very porous dust with \(P > 0.92\), indicating that the F and G star abundances or the solar abundances are not inconsistent with the interstellar extinction.

If we do not adopt the Holweger (2001) solar abundances but the most recently determined solar values of C (Allende Prieto et al. 2002) and O (Asplund et al. 2004), and assume that the solar abundances of other elements like Mg, Si and Fe are also close to those of B stars like C and O, the solar abundances would also fall short in accounting for the interstellar extinction.\(^\text{11}\) Given that even the elemental abundances of our own Sun are still subject to major systematic uncertainties, we are not at a position to conclude that the solar or F and G star abundances are a more preferable reference standard for the ISM.

It is very possible that the abundances of refractory elements in stars and in the ISM are different, namely, there does not exist any set of abundances of refractory elements derived from stellar atmospheres, minus the measured gas-phase abundances of these elements in the diffuse ISM, can yield the number of dust atoms implied by interstellar extinction. Various physical processes such as radiation pressure, ambipolar diffusion, and gravitational sedimentation occurring during the early stages of star formation (Draine 2004; Snow 2000)

\(^{10}\) However, the survival of metallic iron grains in the ISM is questionable. According to Jones (1990), in the ISM which is comparatively rich in atomic oxygen, iron grains will undergo rapid oxidation to iron(II)oxide (FeO) and subsequently magnetite (Fe\(_3\)O\(_4\)) and even haematite (Fe\(_2\)O\(_3\)) on time-scales of the order of \(10^6\) yr; the reaction of metallic iron particles with sulphur in the ISM will lead to their rapid degradation to sulphide and even sulphate.

\(^{11}\) The latest solar abundances compiled by Asplund, Grevesse, & Sauval (2005) have C and O close to those B stars, but Mg, Si and Fe close to those of Holweger (2001). See Table 1. If we adopt those of Asplund et al. (2005), the interstellar extinction can be accounted for by modestly elongated \((a/b \sim 2\text{--}3)\) grains with a vacuum volume fraction of \(\sim 40\text{--}60\%\).
can act to prevent grains from being incorporated into stars and, therefore, lead to lower abundances of heavy elements in stars than in the ISM out of which they have formed. Alternatively, the stellar *photospheric* abundances of heavy elements may under-represent the composition of the star, due to the possible underestimation of the degree of heavy-element settling in stellar atmospheres. The latter is also indicated by the inconsistency between the most recent solar abundance determinations and the helioseismological results (Bahcall et al. 2004).

However, there does exist some evidence for the subsolar nature of the interstellar abundances: some noble gases have subsolar abundances in the ISM (e.g. Cardelli & Meyer [1997] found that krypton has an interstellar abundance of 60% of solar; neon was found to be $\sim 75\%$ solar in the ISM [Takei et al. 2002]). Since noble gases are not likely to be depleted onto dust, the abundances of noble gases in the ISM should reflect the total interstellar abundances. The problem of what might be the most appropriate set of interstellar reference abundances is still awaiting a solution, but it is unlikely for the ISM to have abundances as low as those of B stars since otherwise there will not be enough material to make the dust needed to explain the observed interstellar extinction.

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Fig. 1.— Model-predicted $(F/ [1 - P])_{mod}$ as a function of porosity $P$ for spherical (solid lines) or prolate composite fluffy grains consisting of (a) small silicates, oxides, and graphite; or (b) small silicates, oxides, and amorphous carbon with an elongation of $a/b = 2$ (dotted lines), $a/b = 3$ (dashed lines), and $a/b = 5$ (dot-dashed lines), using the B star abundances as the interstellar reference standard. The horizontal long-dashed lines plot $(F/ [1 - P])_{min}$, the lower limit on $(F/ [1 - P])$ required by the interstellar extinction (see Eq.[4]).
Fig. 2.— Same as Fig. 1a but for models (a) with the F and G star abundances or (b) with the solar abundances as the interstellar reference standard.
Table 1: Solar and stellar abundances for the dust-forming elements C, O, Mg, Si and Fe (relative to $10^6$ hydrogen atoms).

| Object     | C    | O    | Mg   | Si   | Fe   | References          |
|------------|------|------|------|------|------|---------------------|
| Sun        | 370  | 676  | 34   | 32   | 34   | Cameron 1973        |
| Sun        | 417  | 692  | 39.9 | 37.6 | 38.8 | Cameron 1982        |
| Sun        | 363  | 853  | 38.5 | 35.8 | 32.3 | Anders & Grevesse 1989 |
| Sun        | 331  | 676  | 38   | 35.5 | 31.6 | Grevesse & Sauval 1998 |
| Sun        | 391  | 545  | 34.5 | 34.4 | 28.1 | Holweger 2001       |
| Sun        | 245  | 490  | -    | -    | -    | Allende Prieto et al. 2002 |
| Sun        | -    | 457  | -    | -    | -    | Asplund et al. 2004 |
| Sun        | 245  | 457  | 33.9 | 32.3 | 28.2 | Asplund et al. 2005 |
| F,G stars  | 358  | 445  | 42.7 | 39.9 | 27.9 | Sofia & Meyer 2001  |
| B stars    | 190  | 350  | 23   | 18.8 | 28.5 | Sofia & Meyer 2001  |