astro-ph seminar 2021.01.27 (担当:大澤)

The efficiency of grain growth in the diffuse interstellar medium

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Grain growth by accretion of gas-phase metals is a common assumption in models of dust evolution, but in dense gas, where the timescale is short enough for accretion to be effective, material is accreted in the form of ice mantles rather than adding to the refractory grain mass. It has been suggested that negatively-charged small grains in the diffuse interstellar medium (ISM) can accrete efficiently due to the Coulomb attraction of positively-charged ions, avoiding this issue. We show that this inevitably results in the growth of the small-grain radii until they become positively charged, at which point further growth is effectively halted. The resulting gas-phase depletions under diffuse ISM conditions are significantly overestimated when a constant grain size distribution is assumed. While observed depletions can be reproduced by changing the initial size distribution or assuming highly efficient grain shattering, both options result in unrealistic levels of far-ultraviolet extinction. We suggest that the observed elemental depletions in the diffuse ISM are better explained by higher initial depletions, combined with inefficient dust destruction by supernovae at moderate ($n_H \sim 30\,cm^{-3}$) densities, rather than by higher accretion efficiences.

Key words:
dust, extinction – ISM: evolution

Background

SNのshockなどにより、銀河のダストは a few 100 Myr 程度で破壊されてしまう

ISM における gas accretion によって dust mass を増やすモデルが広く認識されてきた。

↔ accretion の効率の高い dense gas では icy mantle になってしまい、ISM でまた gas phase に戻ってしまうという指摘

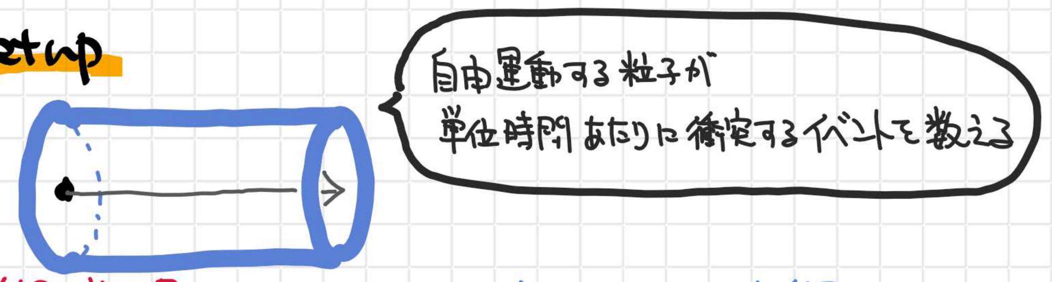
→ CNM での gas accretion の可能性が議論されてきた (Zhukovska et al. 2016, 2018)

密度が低いので効率が低いが、小さいダストは負に帯電しているので Coulomb attraction で実効的な断面積を boost できる

Zhukovska et al. (2016, 2018) ではうまく説明できたと報告。↔ gas accretion で重要な小さいダストのサイズ進化を解いていない

本研究ではダストのサイズ進化を考慮に入れて計算する

Setup



ダストの質量増加量 = ダストに衝突したSi原子の総質量

$$4\pi a^2\, da\, \rho f_{Si} = D(a) \times \pi a^2 v_{Si}\, dt\, n_{Si} m_{Si} \rightarrow \frac{da}{dt} = \frac{n_{Si} m_{Si} < v_{Si} >}{4 \rho f_{Si}} \times D(a)$$

ダスト半径の増加　　Coulomb attraction による boost

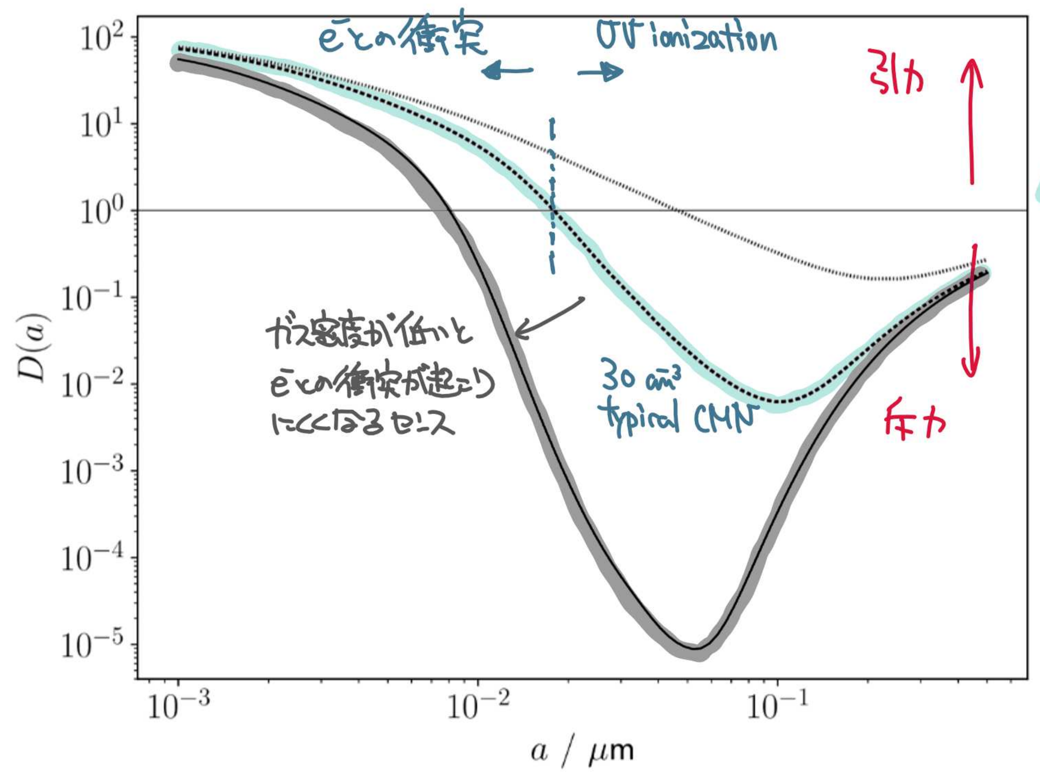


Figure 1. Coulomb focusing factor versus grain size for $T = 100\,K$, $x_e = 0.0015$ and $n_H = 5$ (solid line), 30 (dashed line) and $100\,cm^{-3}$ (dotted line). The thin solid line marks $D(a) = 1$, i.e. no net attraction or repulsion.

For typical CNM conditions, small grains tend to be negatively charged and thus attract positive ions, but beyond a radius of $\sim 0.01\,\mu m$ grains instead become positively charged and $D(a) < 1$.

Table 1. Model parameters

Parameter	Value	Unit
Gas density n_H	30	cm^{-3}
Gas temperature T	100	K
Electron fraction x_e	0.0015	
Grain density ρ	3.13	$g\,cm^{-3}$
Silicon mass fraction f_{Si}	0.165	-
Silicon elemental abundance ϵ_{Si}	3.24×10^{-5}	-
Initial depletion $[Si/H]_{gas}$	−0.5	-
Dust destruction timescale τ_{dest}	350	Myr
Maximum grain size a_{max}	0.25	μm
Minimum grain size a_{min}	0.005	μm

MRN分布 (Maximum / Minimum grain size)

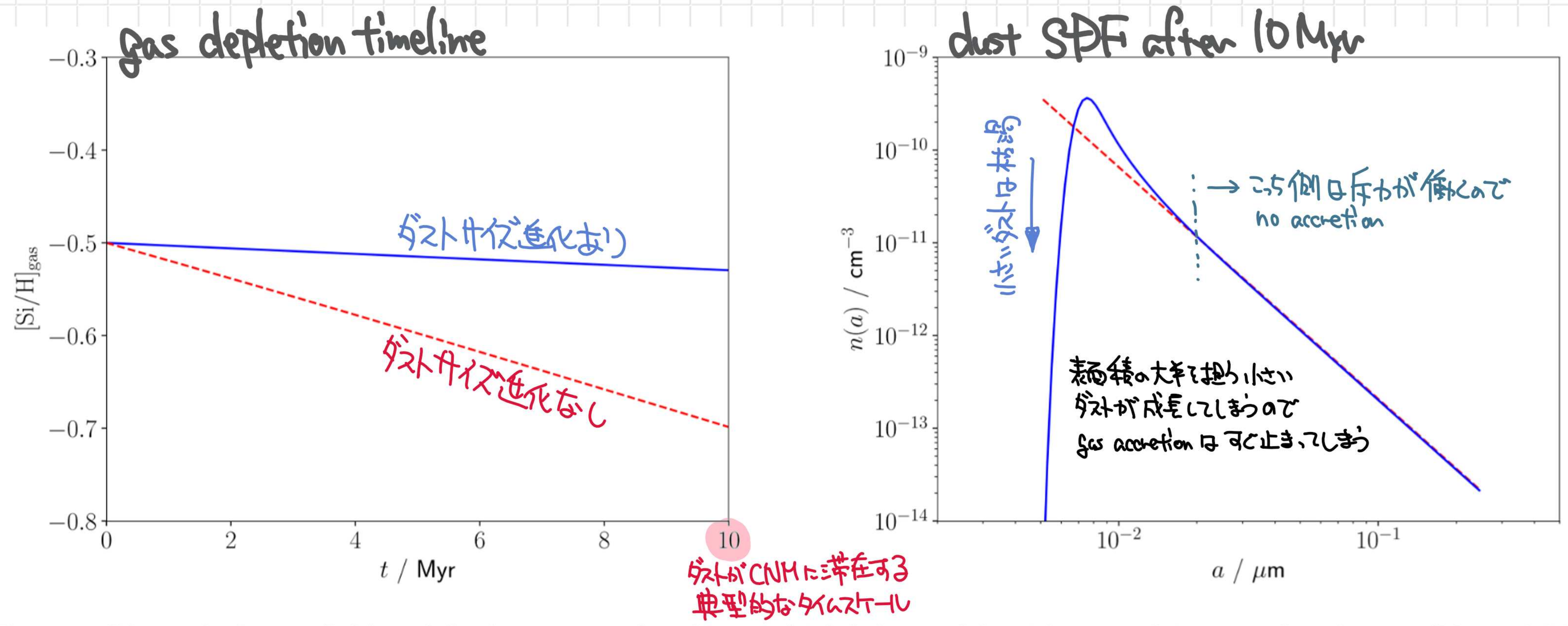
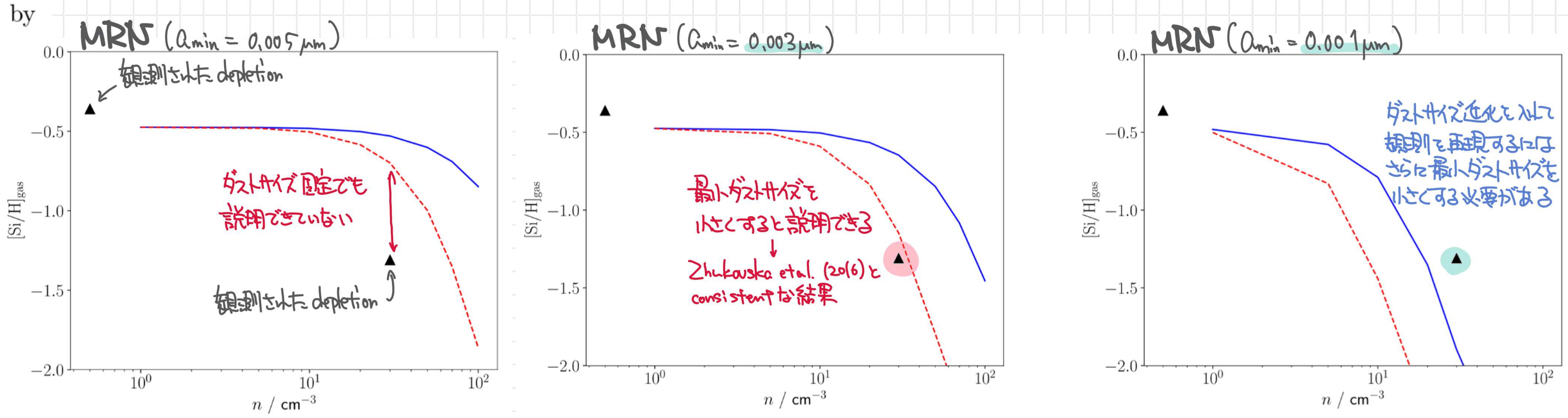
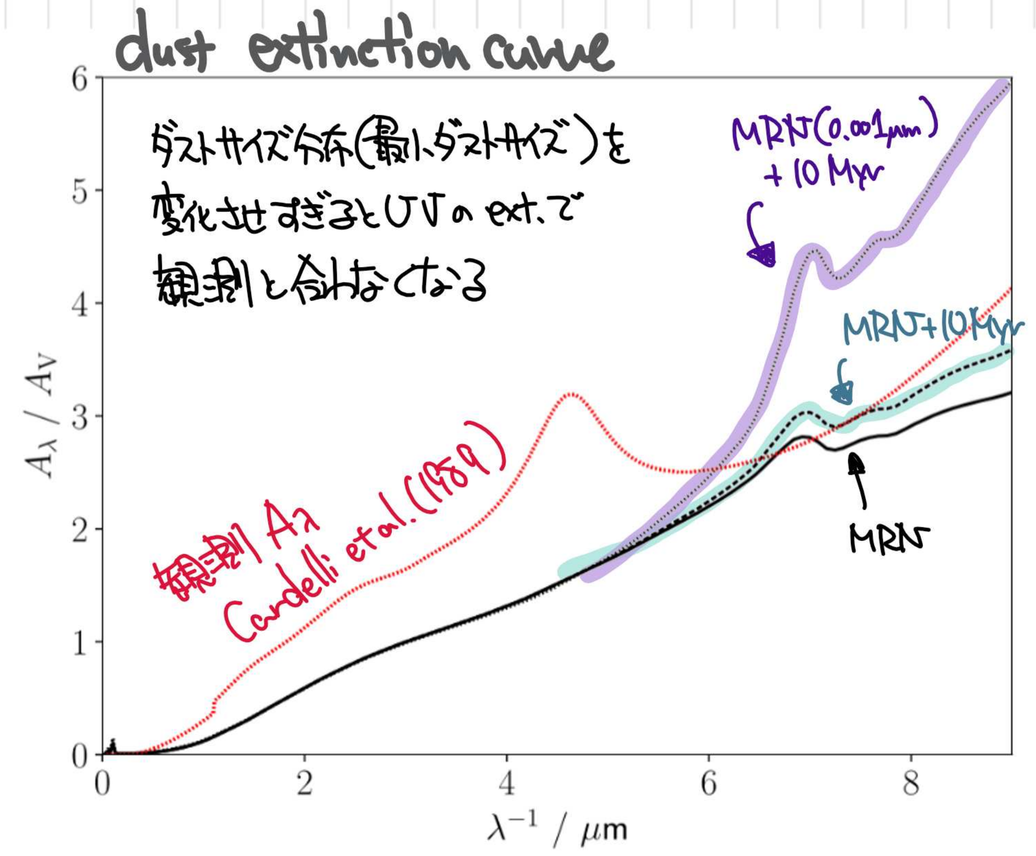
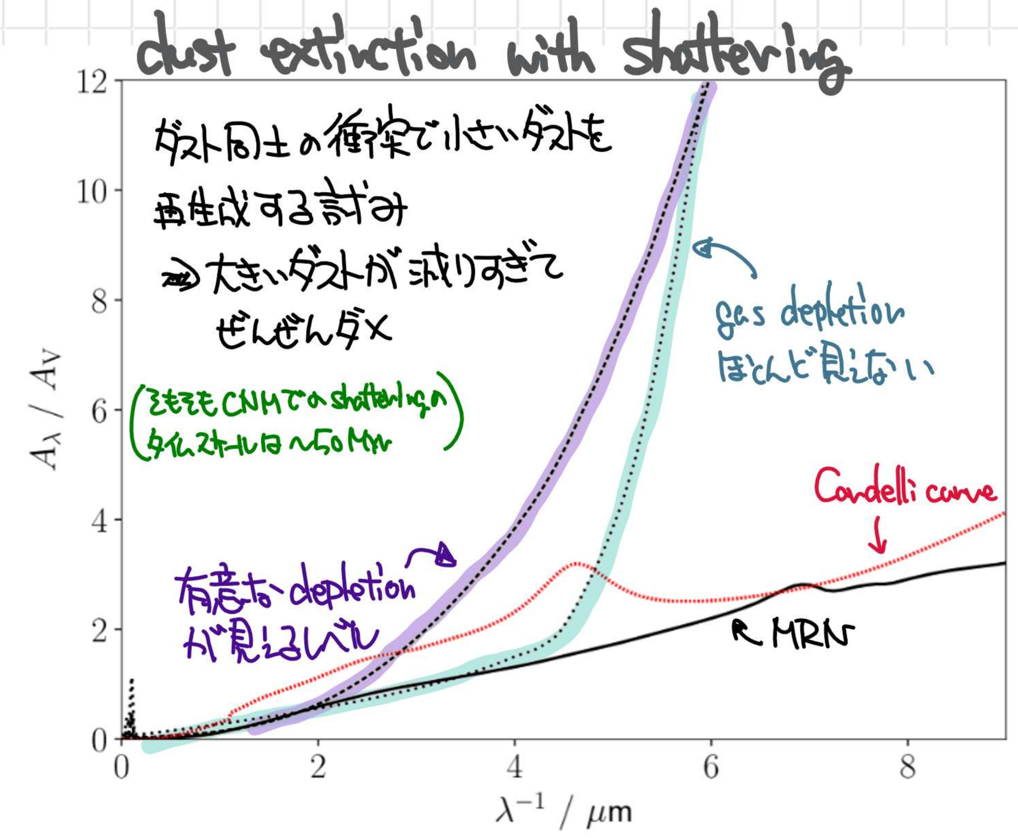


Figure 2. Silicon depletion (left) and final grain size distribution (right) for models with an evolving size distribution (blue solid lines) or for a constant MRN distribution (red dashed lines), for $n_H = 30\,cm^{-3}$ and $T = 100\,K$.







5 CONCLUSION

Efficient accretion of gas-phase metals by small, negatively-charged dust grains has been proposed as an explanation for elemental depletion patterns observed in the CNM (Zhukovska et al. 2016, 2018). We have demonstrated that once the evolution of the size distribution is properly accounted for, this becomes impossible, as the growth in dust mass is halted once the small grains grow large enough to become positively charged. Increasing or replenishing the number of small grains, such as by altering the initial size distribution or invoking efficient grain shattering, results in far-UV extinction curves incompatible with anything observed along Galactic sightlines. We suggest that relatively high levels of depletion in the CNM, rather than being a sign of efficient grain growth, are actually indicative of the survival of dust grains in initially highly-depleted material from a (presumably) denser phase of the ISM.