From our Galaxy to Distant DLAs: The Condensation of Gas-Phase Elements onto Interstellar Dust Grains

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Logarithmic depletion of element $X$ from the gas phase

$$[X / H] = \log\left(\frac{X}{H}\right)_{obs} - \log\left(\frac{X}{H}\right)_{stellar}$$

Reference Abundance: solar or B stars

Number density of element $X$ in dust relative to hydrogen

$$(X_{dust}/H) = (X/H)_{\odot} \left(1 - 10[X_{gas}/H]\right)$$
What has been Known for some Time

• Depletions vary from one location to the next
  – Sightlines with low average density $N(H)/d$ have less depletion
  – Gas at high velocity displacements have less depletion: grains have been disrupted

• Depletions vary from one element to the next
  – Depletion strengths are greatest for elements that can form refractory compounds and are small for those that can only form volatile compounds
An Interpretation of Milky Way ISM Gas-Phase Abundances Reported in the Literature

• Basic Tactic:
  – Adopt protosolar abundances as a reference standard
  – Ignore the sightline properties and characterize depletions of elements with respect to each other, recognizing that the severity of depletions differ from one element to the next and from one region of space to the next.

Underlying Strategy

• Basic premise:
  ➢ All elements deplete together in some systematic fashion, but by differing degrees that change from one region to another and from one element to the next.
  ➢ Propose a single parameter $F_*$ that expresses a general level of depletion along a sight line.

($F_*$ is much like $<n(H)>$ that has been used in the past.)
Another basic premise: Differences in how the elements respond to changes in $F^*$ are represented by other parameters specific to each element.
For element $X$:

$$\left[ \frac{X_{gas}}{H} \right] = B_X + A_X \left( F_* - z_X \right)$$
The Buildup of Dust Grains

Conventional Formula:

\[
\left( \frac{X_{dust}}{H} \right) = \left( \frac{X}{H} \right) \left( 1 - 10^{\frac{X_{gas}}{H}} \right)
\]

|A_x| is a rate constant for element condensation
The Buildup of Dust Grains

Differential Element Contributions:

\[
\frac{d(X_{\text{dust}} / H)}{dF_*} = -(\ln 10) A_X \left( \frac{X_{\text{gas}}}{H} \right) F_*
\]

\(|A_X|\) is a rate constant for element condensation
The quantities $\log(\text{gas} / \text{H})$ into Equation (21), we define that $X^* = A_X / \sigma_{X/\text{H}}$.

If we substitute the right-hand side of Equation (21), we define that $X^* = A_X / \sigma_{X/\text{H}}$.

Terms of the number of atoms per H atom that condense onto the grain can be treated separately in Section 9.1. Method.

There are a number of applications where we can use the slopes of the logarithms of the consumption rates for the elements Fe, Ni, and Zn.

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Fortunately, this is usually not the case. Given that many sight lines follow the linear trends with $X^*$, again plotted as a function of $N_X^* / N_H$.

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Summary of Element Consumption Rates

(Mass of elements in dust)/(total element mass) = 0.20 (F* = 0)
0.54 (F* = 1)
Average Density of Dispersed Solids

Number of grains per unit area in a column of length $d$

$$\tau = N_g \pi a^2 Q_e$$

Optical depth over a distance $d$

Radius of each grain

Grain volume

Internal density

Refractive index at low freq.

Extinction efficiency factor


$$\langle \rho_g \rangle = \frac{N_g}{d} \times \frac{4\pi a^3}{3} \times \rho_s$$

$$\langle \rho_g \rangle = \frac{1}{3\pi^2} \times \frac{\int_0^\infty \tau d\lambda}{d} \times \left( \frac{m^2 + 2}{m^2 - 1} \right) \times \rho_s$$
Average Density of Dispersed Solids

Combine $A_v = 1.8 \text{ mag kpc}^{-1}$ with relative extinctions from 1000 Å to 20 μm

$\langle \rho_g \rangle = 1.8 \times 10^{-26} \text{ g cm}^{-3} = 0.006 \langle \rho_H \rangle$

$(\text{Mass of elements in dust})/(\text{total element mass}) = 0.20 (F_* = 0)$

$0.54 (F_* = 1)$
Depletion Trends against Condensation Temperatures

\[ A_x \]

\[ T_c \]

- Jenkins 2009
- Ritchey et al. 2018
Sightlines
Trends of Overall Depletion Strengths

Distance of the target away from the Galactic plane:
- $|z| \geq 500$ pc
- $|z| = 250$ pc
- $|z| = 100$ pc
- $|z| = 0$ pc

$F^*$ vs. $\log \langle n(H) \rangle$

1σ error in $F^*$:
- $\leq 0.02$
- $0.05$
- $0.10$
- $0.15$
- $0.30$
Trends of Overall Depletion Strengths

\[ \log F(H_2) = \frac{2N(H_2)}{2N(H_2) + N(H \, I)} \]
Some Notes about Specific Elements

Three noteworthy cases: S, O, and Kr
Sulfur

• A problem element: many investigators have proposed that S is undepleted.
• Results may be misleading ...

HD 41161: log N(H) = 21.16
Sulfur

• A problem element: many investigators have proposed that S is undepleted.

• Results may be misleading ...

HD 3827: log N(H) = 20.56
Sulfur

- A problem element: many investigators have proposed that S is undepleted.
- Results may be misleading ...

Inside the star’s H II region, H is fully ionized, but S is only singly ionized. This can raise the amount of S II without increasing H I.

\[ \text{He}^0 \quad \text{H}^0 \quad \text{S}^+ \quad \text{S}^0 \]

\[ \varepsilon \text{ CMa} \quad T_{\text{eff}} = 21,750 \text{ K} \]
The Consumption of Oxygen Compared to other Elements

• Conventional view: oxygen is mostly incorporated into refractory compounds such as silicates and oxides.

• Let’s examine whether or not this is consistent with our determinations of $d(X_{\text{dust}}/H)/dF^*$
The Consumption of Oxygen Compared to other Elements

At $F_\ast = 0.0$

\[
\frac{O}{Mg + Si + Fe} = 2.3
\]

The most oxygen-rich silicate, MgSiO$_3$, has a 3:2 ratio of O to other atoms.
The Consumption of Oxygen Compared to other Elements

At $F_\ast = 1.0$

$$\frac{O}{Mg + Si + Fe} = 16$$

The most oxygen-rich silicate, $MgSiO_3$, has a 3:2 ratio of O to other atoms.
The Consumption of Oxygen Compared to other Elements

• Conclusion: In addition to forming silicates, O must deplete by forming some other compound using another abundant element.
  – Various oxides of N? Unlikely, since N does not seem to deplete (at least not appreciably more than about $10^{-5}$ per H atom per unit change in $F_*$).
  – H$_2$O? Perhaps, but 3.05 μm ice feature only seen toward regions with extinctions much larger than those of the lines of sight in the UV absorption studies.
  – CO, CO$_2$ and O$_2$ are present in the ISM, but in amounts that are not sufficient to explain the depletion of O.
Perhaps very large grains (diam. >> 1μm) containing appreciable amounts of H$_2$O are present but not visible?
Partial correlations of O abundances relative to $H_{\text{total}}$ were investigated for the trends with $F_*$, $\log f(H_2)$ and $\log I/I_0$.

$O/H_{\text{total}}$ shows positive correlations with $\log f(H_2)$ and $\log I/I_0$, and a negative correlation with $F_*$. 

**Generalized depletion parameter**

**Relative starlight intensity**

**Fraction of hydrogen in molecular form**
Interpretation:
- Negative correlation with \( F_* \) no surprise, O follows other elements.
- Positive correlation with \( f(H_2) \) seems counterintuitive: stronger molecular environment might favor reactions that create O-bearing molecules.

A conjecture:
- \( f(H_2) \propto n_H n_g / I = \text{func}(F_*) / I \)
- If we could hold \( F_* \) and \( I \) constant, we’d expect \( f(H_2) \) to also remain constant.
- A variation in \( [O_{\text{gas}}/H] \) with \( f(H_2) \) indicates some factor(s) other than just \( F_* \) and \( I \) may influence \( f(H_2) \) – perhaps grain size distribution, where surface to volume ratios could influence production efficiency.
Krypton

• Chemically inert
• However, meteoritic studies and laboratory experiments indicate that heavy noble gases can bind to solids via enhanced physisorption.
• A negative correlation with $I/I_0$ may arise from the creation of active binding sites by UV radiation.

Ritchey et al. (2018)
Distant Absorption Line Systems

Basic Issues:

1. Absorption features in the spectrum of the quasar reveal column densities of the gas phases of various heavy elements and hydrogen.

2. Using the relationships of depletions seen in our Galaxy, can we interpret these outcomes in terms of a division between gas-phase and solid-phase abundances?

Background Quasar

Galaxy that produces a Damped Lyman-α (DLA) absorption system in the quasar spectrum
Our Objectives

1. For each absorption system, what is the overall metallicity of the gas \([M/H]\) compared to solar abundances?
2. What proportion of the matter in the gas has condensed onto dust grains?
3. What is the overall behavior of the above two properties in various systems as a function of \(z(\text{abs})\)?
How this can be done

• Basic strategy: use differences in the rates of element depletions to differentiate between the effects of dust formation and low overall metallicities.

• A complication from chemical evolution: One must be aware of abundance differences between α-process and Fe-peak elements.
Behavior of $\log(\text{Si/Fe})_\text{dust}$ vs metallicity

Behavior of $\log(\text{Si/Fe})_{\text{dust}}$ vs metallicity

Recipe: Start with Depletion Coefficients

The basic equation:

\[ \frac{X_{\text{gas}}}{H} = B_X + A_X (F^* - z_X) \]

<table>
<thead>
<tr>
<th>Elem. X</th>
<th>Log ((X/H)_\odot ) +12</th>
<th>(A_X)</th>
<th>(B_X)</th>
<th>(z_X)</th>
<th>(X_{\text{gas}}/H)_0</th>
<th>(X_{\text{gas}}/H)_1</th>
<th>(\chi^2)</th>
<th>(e_r)</th>
<th>Prob. worse fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>8.46 ± 0.04</td>
<td>-0.101 ± 0.229</td>
<td>-0.193 ± 0.060</td>
<td>0.803</td>
<td>-0.112 ± 0.194</td>
<td>-0.213 ± 0.075</td>
<td>3.7</td>
<td>8</td>
<td>0.881</td>
</tr>
<tr>
<td>N</td>
<td>7.90 ± 0.11</td>
<td>-0.000 ± 0.079</td>
<td>-0.109 ± 0.111</td>
<td>0.550</td>
<td>-0.109 ± 0.119</td>
<td>-0.109 ± 0.117</td>
<td>28.8</td>
<td>32</td>
<td>0.628</td>
</tr>
<tr>
<td>O</td>
<td>8.76 ± 0.05</td>
<td>-0.225 ± 0.053</td>
<td>-0.145 ± 0.051</td>
<td>0.598</td>
<td>-0.010 ± 0.060</td>
<td>-0.236 ± 0.055</td>
<td>75.0</td>
<td>64</td>
<td>0.164</td>
</tr>
<tr>
<td>Mg</td>
<td>7.62 ± 0.02</td>
<td>-0.997 ± 0.039</td>
<td>-0.800 ± 0.022</td>
<td>0.531</td>
<td>-0.270 ± 0.030</td>
<td>-1.267 ± 0.029</td>
<td>79.0</td>
<td>103</td>
<td>0.962</td>
</tr>
<tr>
<td>Si</td>
<td>7.61 ± 0.02</td>
<td>-1.136 ± 0.062</td>
<td>-0.570 ± 0.029</td>
<td>0.305</td>
<td>-0.223 ± 0.035</td>
<td>-1.359 ± 0.052</td>
<td>19.4</td>
<td>16</td>
<td>0.247</td>
</tr>
<tr>
<td>P</td>
<td>5.54 ± 0.04</td>
<td>-0.945 ± 0.051</td>
<td>-0.166 ± 0.042</td>
<td>0.609</td>
<td>0.296 ± 0.029</td>
<td>-0.649 ± 0.050</td>
<td>69.5</td>
<td>65</td>
<td>0.330</td>
</tr>
<tr>
<td>Cl</td>
<td>5.33 ± 0.06</td>
<td>-1.242 ± 0.129</td>
<td>-0.314 ± 0.065</td>
<td>0.609</td>
<td>0.442 ± 0.102</td>
<td>-0.809 ± 0.082</td>
<td>38.9</td>
<td>44</td>
<td>0.688</td>
</tr>
<tr>
<td>Ti</td>
<td>5.00 ± 0.03</td>
<td>-2.048 ± 0.062</td>
<td>-1.967 ± 0.033</td>
<td>0.430</td>
<td>-1.077 ± 0.043</td>
<td>-3.125 ± 0.049</td>
<td>50.7</td>
<td>43</td>
<td>0.195</td>
</tr>
<tr>
<td>Cr</td>
<td>5.72 ± 0.05</td>
<td>-1.447 ± 0.064</td>
<td>-1.508 ± 0.055</td>
<td>0.460</td>
<td>-0.827 ± 0.062</td>
<td>-2.274 ± 0.064</td>
<td>24.1</td>
<td>20</td>
<td>0.239</td>
</tr>
<tr>
<td>Mn</td>
<td>5.58 ± 0.03</td>
<td>-0.857 ± 0.041</td>
<td>-1.354 ± 0.032</td>
<td>0.520</td>
<td>-0.909 ± 0.038</td>
<td>-1.765 ± 0.038</td>
<td>106.3</td>
<td>83</td>
<td>0.043</td>
</tr>
<tr>
<td>Fe</td>
<td>7.54 ± 0.03</td>
<td>-1.285 ± 0.044</td>
<td>-1.513 ± 0.033</td>
<td>0.437</td>
<td>-0.951 ± 0.038</td>
<td>-2.236 ± 0.041</td>
<td>48.5</td>
<td>66</td>
<td>0.948</td>
</tr>
<tr>
<td>Ni</td>
<td>6.29 ± 0.03</td>
<td>-1.490 ± 0.062</td>
<td>-1.829 ± 0.035</td>
<td>0.599</td>
<td>-0.937 ± 0.051</td>
<td>-2.427 ± 0.043</td>
<td>30.7</td>
<td>34</td>
<td>0.630</td>
</tr>
<tr>
<td>Cu</td>
<td>4.34 ± 0.06</td>
<td>-0.710 ± 0.088</td>
<td>-1.102 ± 0.063</td>
<td>0.711</td>
<td>-0.597 ± 0.089</td>
<td>-1.307 ± 0.068</td>
<td>15.3</td>
<td>52</td>
<td>0.995</td>
</tr>
<tr>
<td>Zn</td>
<td>4.70 ± 0.04</td>
<td>-0.610 ± 0.066</td>
<td>-0.279 ± 0.045</td>
<td>0.555</td>
<td>0.050 ± 0.058</td>
<td>-0.551 ± 0.054</td>
<td>25.6</td>
<td>19</td>
<td>0.142</td>
</tr>
<tr>
<td>Ge</td>
<td>3.70 ± 0.05</td>
<td>-0.615 ± 0.083</td>
<td>-0.725 ± 0.054</td>
<td>0.690</td>
<td>-0.301 ± 0.078</td>
<td>-0.916 ± 0.059</td>
<td>12.4</td>
<td>24</td>
<td>0.925</td>
</tr>
<tr>
<td>Kr</td>
<td>3.36 ± 0.08</td>
<td>-0.166 ± 0.103</td>
<td>-0.332 ± 0.083</td>
<td>0.684</td>
<td>-0.218 ± 0.109</td>
<td>-0.384 ± 0.089</td>
<td>18.9</td>
<td>26</td>
<td>0.839</td>
</tr>
</tbody>
</table>
Recall that for any element $X$ in the ISM of our Galaxy, its depletion is given by:

$$[\frac{X_{\text{gas}}}{H}] = \log N(X) - \log N(H) - \log \left(\frac{X}{H}\right)_\odot - [M/H] = B_X + A_X(F - z_X)$$

But if the metallicity $[M/H]$ of some other system differs from that of our Galaxy, we must add a new term:

Rearrange Terms in this Formula
log \frac{N(X)}{N(H)} - \log \left( \frac{X}{H} \right)_\odot - B_x + A_x z_x = \left[ \frac{M}{H} \right] + F* A_x

These coefficients arise from a least squares best-fit equation for all X elements

\[ F^* = 0.90 \]

\[ [\text{M/H}] = 0.21 \pm 0.12 \]
SMC Sight Lines

Proof of concept:

Can we use interstellar absorption features to determine \([M/H]\) for the SMC, and if so, how does it compare with abundances in SMC stars?
SMC Sight Lines

How do their depletions compare to those of our Galaxy?
Depletion trends with $F_*$

Why do some of the SMC Depletions Differ from those of the Milky Way?

1. The stellar reference abundances of both $\alpha$- and Fe-peak elements in the SMC are uniformly lower than those of the Milky Way by $-0.65$ dex.

2. So why does a gas with a dilute mixture of heavy elements exhibit a slightly different depletion behavior for Ti and Mn compared to that of Fe?

3. A possible answer: an exception to point 1 is the abundance of C in SMC stars is even lower by an additional $-0.36$ dex. This anomalously low C abundance is supported by a deficiency in PAHs, compared to the Milky Way PAH abundance.
The Relative Lack of Carbon in low metallicity systems (distant DLAs)


Decreasing $F^*$

Kulkarni et al. (2016) P&SS, 133, 7
Mass Fractions of Heavy Elements in Dust

![Graph showing mass fractions of heavy elements in dust with a red cross marking the Milky Way region.](image-url)
The Mass of Dust Relative to that of Hydrogen
The Mass of Dust Relative to that of Hydrogen
Dust Surface Density and UV Opacity

Selection biases:
1. Not likely to record a spectrum of a quasar behind a galaxy with a large extinction.
2. Greater impact parameters are more likely to be sampled, and such locations in galaxies probably have lower than usual metallicities (and dust fractions).
3. However, there is no bias with regard to the Galaxy’s luminosity.

1 magnitude of extinction at 1400 Å
Summary

• UV Spectroscopy offers insights on the systematics of interstellar gas-phase abundances, which in turn informs us about the element constituents in solids
• There is a challenge in understanding the behaviors of oxygen and krypton
• From an almost universal pattern of depletions, we can use measurements of two or more elements to make corrections for depletions that are needed to derive element abundances in distant galaxies
• Depletion strengths and element abundances together reveal the absolute abundances of dust