CARBON-BEARING VOLATILES:
SURFACE ABUNDANCE ESTIMATES FROM EXOSPHERIC CONTENT CONSIDERATIONS.

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An exosphere of CO and CO2?

Detecteds of lunar exospheric ions by
the LADEE neutral mass spectrometer

- Ion Measurements have long indicated predominance of mass 28 ions (Al+, Si+, or CO+?)

Motivating Questions:
- What are the expected levels of carbon-bearing volatiles in the exosphere of the Moon?
- And, based on flux balance, what would be the distribution of adsorbed species on the surface of the grains?

If [CO+], then [CO]~10^4 cc
Expected carbon influx as the seed population for these exospheres

1) Solar wind:
   • A long-term average of the carbon to proton abundance in the solar wind is $\sim 2 - 3 \times 10^{-4}$ [von Steiger et al., 2000].
   • Assuming the average solar wind flux to be $2 \times 10^8$ ions cm$^{-2}$ s$^{-1}$, the carbon influx to the Moon is $4 - 6 \times 10^4$ ions cm$^{-2}$ s$^{-1}$

2) Micrometeoroids:
   • The carbon fraction in CI chondrites is 8.5 wt% [Lodders and Fegley, 1998].
   • Adopting a lower limit of the rate of micrometeoritic flux onto the Moon of $5.12 \times 10^{-17}$ gm cm$^{-2}$ s$^{-1}$ [Cintala, 1992] and an upper limit of $4.76 \times 10^{-16}$ gm cm$^{-2}$ s$^{-1}$ (Furi et al., 2012) the carbon influx, F, is: $8.8 \times 10^4 < F < 8.2 \times 10^5$ C atoms cm$^{-2}$ s$^{-1}$

Methane gas, Trapped {carbides, CO, CO$_2$}

CO, CO$_2$ gas
## Mobility of carbon volatiles

<table>
<thead>
<tr>
<th>Adsorbate</th>
<th>Adsorbent/Surface</th>
<th>E_{act} (eV)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>TiO$_2$ (100)</td>
<td>0.42</td>
<td>Linsebigler et al 1995</td>
</tr>
<tr>
<td>CO</td>
<td>TiO$_2$</td>
<td>0.45-0.5</td>
<td>Raupp and Dumesic 1985</td>
</tr>
<tr>
<td>CO</td>
<td>ZnO (powder)</td>
<td>0.36</td>
<td>Wang et al. 2007</td>
</tr>
<tr>
<td>CO coadsorbed with CO$_2$</td>
<td>ZnO (powder)</td>
<td>0.64</td>
<td>Wang et al. 2007</td>
</tr>
<tr>
<td>CO</td>
<td>Fe (100)</td>
<td>0.62, 0.88, 1.08</td>
<td>Benziger and Madix, 1980</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>MgO (100)</td>
<td>0.40</td>
<td>Meixner et al. 1992</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>ZnO (powder)</td>
<td>0.46-0.67</td>
<td>Xia et al. 2008</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>TiO$_2$</td>
<td>0.46</td>
<td></td>
</tr>
</tbody>
</table>

- **Major knowledge gap!**
- **Co-adsorbates influence the binding**
- New TPD experiments on lunar simulants and samples initiated at GSFC (Jason McLain)
Assume full vaporization of impactors (no contribution from trapped carbon in soil)

- Half CO, Half CO2
- $\tau(\text{CO}_2) = 4.95 \times 10^5$ s, $\tau(\text{CO}) = 1.3 \times 10^6$ s (quiet Sun, charge exchange and electron impact dissociation/ionization losses not accounted yet)
- $T_{iv} = 2000$ K here
- Recycled vapors assumed to stick
- Activation energy for desorption treated as free parameter, $E_b = 0.5$ and $E_b = 0.8$ eV (same for all soils)
- Pre_exponential = $1.0 \times 10^{13}$ /s

Migration calculations

Adopted 23 gridded Diviner temperature maps, Resolution 0.5x0.5 deg
* Coverage approaches or exceeds monolayer under such assumptions (must account for coverage dependence of $E_{act}$)
* Patchier polar volatile distribution as $E_{act}$ decreases
Assuming similar binding and source rates, we would expect significant amounts of CO to migrate to the poles as well (especially since its lifetime to dissociation is longer)
Polar CO$_2$ frosts

$E_b = 0.5$ eV

$log_{10}(adsCO_2)$ (cm$^{-2}$)

Time-dependent simulation run for 60 lunations
Sinks: dissociation/ionization, adsorbate sputtering
Diurnal variation of polar CO2 deposits

Log$_{10}$adsorbed CO2 (/cm$^2$) at Full Moon

Log$_{10}$adsorbed CO2 (/cm$^2$) at lunar phase=120 deg

DIVINER TEMPERATURE (K)
Detection methods:

1) Lunar Atmosphere Composition Experiment (LACE) NMS, ~25 deg North:
   possible detections of
   \[[\text{CO}]]_{\text{predawn}}=1.\times10^3 \text{ cc}, \[[\text{CO}_2]]_{\text{predawn}}=1.\times10^3 \text{ cc}, \[[\text{CH}_4]]_{\text{predawn}}=1.\times10^4 \text{ cc}
   “In all three cases, the signal increase began several hours before sunrise, and
   Continued to rise until the instrument became background saturated around sunrise”

1) Apollo UVS: \[[\text{CO}_g]]<14,000 \text{ cc} (Feldman and Morrison, 1991)

2) LRO LAMP: \[[\text{CO}_g]] <700 \text{ cc}, \text{polar nightside} (Cook et al. 2013)
Estimated Exospheric densities

\[ \log_{10}(\text{gasCO}_2) \, (\text{cm}^{-2}) \, \text{for} \, E_b = 0.8 \, \text{eV} \]

\[ \log_{10}(\text{gasCO}) \, (\text{cm}^{-2}) \, \text{for} \, E_b = 0.8 \, \text{eV} \]

Latitude (°)

Local Hour

Equatorial CO2 Density (lcc)

Equatorial CO Density (lcc)
Conclusions

* Significant CO and CO2 exospheric densities can be expected by the vaporization of micrometeoroids
* Estimates seemingly do not exceed known limits
* Can map global transport and deposition into poles at unprecedented 0.5x0.5 deg resolution
* Resulting polar deposits for CO and CO2 would really be “frosts” (1-10 ML)