CHEMISTRY OF THE OUTER SOLAR SYSTEM*

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Abstract. Data on the composition of the satellites of the outer planets and the composition and
structure of planetary atmospheres are briefly reviewed in light of simple models for the origin of the
solar system and the planets. Some crucial tests of present theories are suggested.

1. Introduction

Cameron's (1973) discussion of the origin and evolution of the outer planets shows
the necessity of considering compositional models in which a component of relatively
involatile material is admixed with a solar-composition volatile-rich component in
proportions which vary from planet to planet. For Jupiter, the solar component must
be at least a hundred times as massive as the volatile-poor component, with the mass
of the condensed component increasing with heliocentric distance. Uranus and Nep-
tune may contain comparable masses of the two components.

In Cameron's models, the temperature of accretion of condensed material decreases
steadily with heliocentric distance, and hence the composition of this component may
change with distance, being rocklike in the asteroid belt, but very rich in ice-forming
compounds beyond a few AU. The densities of the satellites of the outer planets may
provide direct evidence regarding the composition of condensed matter as a function
of distance from the Sun and from their primaries, and hence bear directly on the
present compositions of the planets themselves. In order to understand such composi-
tional trends we must determine the range of feasible accretion temperatures and neb-
ular pressures as a function of heliocentric distance, understand the chemistry of the
condensation-accretion process as a function of temperature and pressure, and thereby
relate the accretion conditions directly to an observable parameter, the density of the
satellite. Such an approach has already been applied with surprising success to the
terrestrial planets, and a philosophical predilection for searching for uniformities and
similarities in the processes forming diverse solar system bodies would suggest the
trial application of these methods to the outer solar system. We will therefore review
low temperature condensation-accretion models and their relevance to observable
properties of the satellites of the outer planets.

2. Low-Temperature Condensation

Our treatment of the chemistry of formation of objects in the outer solar system will

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be conditioned by the availability of only two types of observational evidence regarding their compositions: bulk density and atmospheric composition. We therefore will discuss the chemical behavior of a simplified set of elements taking only the most abundant and most volatile element groups into account. Table I, which presents the solar abundances of 15 selected abundant rock-forming and ice-forming elements, provides us with adequate compositional data on the parent material from which condensation occurred, the primitive solar nebula. The sources of data for this table are discussed in Lewis (1972a).

### TABLE I

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance (Si = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>28000</td>
</tr>
<tr>
<td>He</td>
<td>1780</td>
</tr>
<tr>
<td>O</td>
<td>16.6</td>
</tr>
<tr>
<td>C</td>
<td>10.0</td>
</tr>
<tr>
<td>N</td>
<td>2.4</td>
</tr>
<tr>
<td>Ne</td>
<td>2.1</td>
</tr>
<tr>
<td>Si</td>
<td>1.00</td>
</tr>
<tr>
<td>Mg</td>
<td>0.85</td>
</tr>
<tr>
<td>Fe</td>
<td>0.80</td>
</tr>
<tr>
<td>S</td>
<td>0.46</td>
</tr>
<tr>
<td>Ar</td>
<td>0.15</td>
</tr>
<tr>
<td>Al</td>
<td>0.071</td>
</tr>
<tr>
<td>Ca</td>
<td>0.060</td>
</tr>
<tr>
<td>Ni</td>
<td>0.050</td>
</tr>
<tr>
<td>Na</td>
<td>0.043</td>
</tr>
</tbody>
</table>

If accretion of condensed materials into large bodies (more than tens of meters) is slow relative to the cooling or heating rate of the nebula, then chemical equilibrium can be maintained between the nebular gases and condensed materials. In this case, the sequence of chemical events during cooling is moderately complex. If we consider the starting material to be sulfur-free rocky material at ~800 K, the sequence of major reactions occurring during cooling is

- (E1) $\sim 680 \text{ K } \text{Fe}^\circ + \text{H}_2\text{S} \rightarrow \text{FeS} \ (\text{H}_2\text{S} \text{ exhausted})$
- (E2) $\sim 500 \text{ K } \text{Fe}^\circ + \text{H}_2\text{O} \rightarrow \text{FeO} \ (\text{Fe}^\circ \text{ exhausted})$
- (E3) $\sim 500 \text{ K } \text{formation of tremolite} \ (\text{CaO} \text{ exhausted})$
- (E4) $\sim 400 \text{ K } \text{formation of hydrous Mg silicates} \ (\text{MgO} \text{ exhausted})$
- (E5) $\sim 170 \text{ K } \text{condensation of } \text{H}_2\text{O} \text{ ice} \ (\text{H}_2\text{O(g)} \text{ exhausted})$
- (E6) $\sim 110 \text{ K } \text{formation of } \text{NH}_3\cdot\text{H}_2\text{O(s)} \ (\text{NH}_3\text{(g)} \text{ exhausted})$
- (E7) $\sim 60 \text{ K } \text{formation of } \text{CH}_4\cdot\text{8H}_2\text{O(s)} \ (\text{H}_2\text{O(s)} \text{ exhausted})$
- (E8) $\sim 25 \text{ K } \text{CH}_4\text{(s) and Ar(s) condensation} \ (\text{CH}_4\text{(g)} + \text{Ar(g)} \text{ exhausted})$
- (E9) $\sim 8 \text{ K } \text{Ne(s) condensation} \ (\text{Ne(g)} \text{ exhausted})$
- (E10) $\sim 7 \text{ K } \text{H}_2\text{(s) condensation} \ (\text{H}_2\text{(g)} \text{ exhausted})$
- (E11) $\sim 1.0 \text{ K } \text{He(s) condensation} \ (\text{He(g)} \text{ exhausted})$