OBSERVATIONAL CONSTRAINTS ON THE EFFICACY OF A SOLID-STATE GREENHOUSE ON THE GALILEAN SATELLITES. Bruce M. Jakosky, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309-0392.

Absorption of solar energy at some depth beneath the solid surface of a body requires conduction of energy to the surface prior to its re-emission from the surface. As has been discussed for an icy surface by Clow (1) and by Brown and Matson (2), the result is for the subsurface to heat up sufficiently to allow conduction to the surface to occur; the subsurface temperature can then be greater than that of the surface, resulting in what Brown and Matson (2) have called a "solid-state greenhouse." We can obtain empirical estimates of the efficacy of such a process for the surfaces of the Galilean satellites by comparing the results of observations and thermal modelling of infrared temperatures for the two cases of eclipse cooling and diurnal temperature variations.

Modeling of the eclipse observations for Ganymede and Callisto by Hansen (3) and Cruikshank and Morrison (4) is straightforward. In each case, the cooling curve is indicative only of thermal conduction and emission from the surface, while the heating curve after eclipse is indicative also of the absorption of solar energy. Both heating and cooling curves are satisfactorily fit by the same model, which includes solar heating and thermal emission only at the surface. If a solid-state greenhouse were playing a role on these objects, the heating curve would require a larger thermal inertia than the cooling curve due to the larger depth to which the solar energy is applied.

Io and Europa both show non-uniform behavior at 10 and 20 µm, with post-eclipse heating taking longer than eclipse cooling (3,4). This difference, along with the difference between the cooling-derived thermal inertia and the heating-derived thermal inertia, could be due to a solid-state greenhouse on these objects. We can estimate the depth to which solar energy penetrates by comparing the cooling and heating curves (or, equivalently, the derived thermal inertias). Based on the data, the solar energy probably penetrates to about 2-4 times the eclipse cooling depth.

The thermal-conduction skin depth to which energy can conduct during a time of length \( P \) is approximately given by

\[
\delta = \sqrt{\frac{K P}{\rho C}},
\]

where \( K \), \( \rho \), and \( C \) are the thermal conductivity, density, and specific heat of the surface material, respectively. For the diurnal temperature variation, corresponding to changing insolation over the satellites' orbits, \( P \) is the orbital period. For the case of cooling and reheating during eclipse by Jupiter, \( P \) is the time during which the satellite is in eclipse. Table I shows the orbital periods and eclipse periods for each satellite, along with the resulting ratio of the orbital to the eclipse thermal skin depth (given by the square root of the ratios of the periods). The eclipse skin depths are between 0.1 and 0.25 of the diurnal skin depths. (If we included layering of the subsurface as indicated by both eclipse and diurnal measurements [see Hansen (3), Morrison and Cruikshank (4), and Spencer (5)], the eclipse skin depths would be an even smaller fraction of the diurnal skin depth.)
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For Ganymede and Callisto, with no significant solid-state greenhouse required or allowed by eclipse measurements, absorption of solar energy for the diurnal temperature variations must also occur on a depth which is very small compared to the diurnal thermal skin depth. Therefore, at diurnal timescales, there is no significant subsurface heating.

For Io and Europa, the depth of solar absorption appears to be comparable to that to which energy conducts over the course of a day. Therefore, solid-state greenhouse effects should be included in calculating the diurnal variation of surface and subsurface temperatures. Because the depth of solar absorption in each of these cases is comparable to the thermal skin depths, however, subsurface heating of the magnitude described by Matson and Brown (6) is probably not occurring; rather, subsurface temperatures may only be elevated by 10-20 K. Further, the requirement by Spencer (5) of a two-layer model to fit the Europa diurnal temperature variations may be mitigated somewhat when subsurface absorption of solar energy is included.

TABLE I. Thermal conduction skin depths for the Galilean satellites

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Diurnal Period (days)</th>
<th>Eclipse Period (days)</th>
<th>$\delta$(diurnal)</th>
<th>$\delta$(eclipse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Io</td>
<td>1.769</td>
<td>0.095</td>
<td>4.32</td>
<td></td>
</tr>
<tr>
<td>Europa</td>
<td>3.551</td>
<td>0.12</td>
<td>5.44</td>
<td></td>
</tr>
<tr>
<td>Ganymede</td>
<td>7.115</td>
<td>0.15</td>
<td>6.91</td>
<td></td>
</tr>
<tr>
<td>Callisto</td>
<td>16.689</td>
<td>0.20</td>
<td>9.13</td>
<td></td>
</tr>
</tbody>
</table>

References: