Energy Deposition by Swift Hadrons in Mixed Gas Targets: The Mean Excitation Energy of Planetary Atmospheres

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In many widely varying types of systems, energy is deposited by the collision of swift hadrons (typically H+ or He2+), with target molecules, resulting in the conversion of projectile kinetic energy to various types of energy in the target, through various processes. The ability to absorb energy from a hadronic projectile is referred to as the stopping power or linear energy transfer (LET), \(-\frac{dE}{dx}\), of the target species.

For a single component system, the stopping power for fast projectiles can be described in SI units by Bethe’s formulation [1].

\[
-\frac{dE}{dx} = n \frac{4\pi e^2 Z_i^2 Z_e}{mv^2} \ln \frac{2mv^2}{I_0}
\]  

(1)

Here, \(n\) is the scatterer density, \(Z_i\) is the projectile charge, \(Z_e\) is the target electron number, \(v\) is the projectile velocity and \(m\) and \(e\) are the electron mass and charge, respectively. The quantity \(I_0\) is the mean excitation energy of the target, and is the single materials quantity that describes the ability of the target to absorb energy from a projectile [1]. It is obtained as the first energy weighted moment of the dipole oscillator strength distribution of the target [1,2].

\[
\ln I_0 = \int \frac{dE}{E} \frac{dE}{dE} \frac{ln E}{dE} \frac{dE}{dE}
\]

(2)

It should be noted that the complete dipole oscillator strength distribution of the target, including all discrete and continuous transitions, is required.

In many situations, however, such as planetary atmospheres, [1] plasmas and warm, dense matter, the target can be composed of various components with various scatterer densities. In order to treat the stopping power of such a mixture, providing the components are non-interacting, each component would be treated separately and the results summed, as

\[
-\frac{dE}{dx} = \sum_{i=component} \left( \frac{dE}{dx} \right)_i
\]  

(3)

However, it would be more convenient to treat the mixture as a single substance as in eq.1, with its own mean excitation energy, \(I_{mix}^{0}\).

The stopping power for the mixture as a whole for a projectile of charge \(Z_i\) would then be

\[
\left( -\frac{dE}{dx} \right)_{mix} = n_{mix} \frac{4\pi e^2 Z_i^2 Z_e}{mv^2} \ln \frac{2mv^2}{I_0^{mix}}
\]  

(4)

Here, \(n_{mix}\) is a density of scattering centers, where \(n_{mix} = \sum n_i\).

\(Z_{mix}\) is the weighted average of the number of electrons per scatterer,

\[
Z_{mix} = \frac{\sum n_i Z_i}{n_{mix}}
\]

and \(I_0^{mix}\) is the mean excitation energy appropriate to the mixture. Such treatment would derive from a sum of stopping powers of the components, weighted by their relative density of scattering centers, as in eq. 3.

\[
\left( -\frac{dE}{dx} \right)_{mix} = \sum n_i \frac{4\pi e^2 Z_i^2 Z_e}{mv^2} \ln \frac{2mv^2}{I_0^{i}}
\]

(5)

Equating equations 4 and 5, one obtains

\[
\ln I_0^{mix} = \frac{\sum n_i Z_i \ln I_0^{i}}{\sum n_i Z_i}
\]

(6)

Thus, the mean excitation energy of the mixture of non-interacting components is simply the appropriate weighted average of the mean excitation energies of those components.

Applying the foregoing to the constituents of the atmospheres of the solar planets [5] and using the standard molecular mean excitation energies of Janni [6], a single mean excitation energy for each of the solar planetary atmospheres can be calculated. The molecular mean excitation energies used were: \(I_0^{CO} = 39.10eV\), \(I_0^{HI} = 20.40eV\), \(I_0^{CH} = 115.7eV\) and \(I_0^{Ar} = 102.35eV\).

Thus, the results for the mean excitation energies of the atmospheres for the solar planets are given in the Table 1.

It should be noted that trace atmospheric components (<1%) were not included, as inclusions make very small differences in the mean excitation energies of the atmosphere, and even smaller differences in the values of \(I_0\), which is the quantity that governs energy deposition by swift, massive particles in the atmospheres. For example, the mean excitation energy for Earth’s atmosphere, without including the 1% Ar is 101.89 eV, leading to a difference of 0.59 in \(I_0\) and 0.006 in \(ln I_0\).

Thus, energy deposition by auroral hadrons in planetary atmospheres, such as, for the many newly discovered Goldilocks planets, may be accurately estimated from the projectile flux and planetary composition.

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Received November 12, 2013; Accepted November 15, 2013; Published November 19, 2013


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Table 1: Mean excitation energies of the atmospheres of the solar planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Atmospheric composition</th>
<th>$I_x$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>98% He 2% H$^+$</td>
<td>38.59</td>
</tr>
<tr>
<td>Venus</td>
<td>96.5% CO$^+_2$ 3.5% N$^+$</td>
<td>102.24</td>
</tr>
<tr>
<td>Earth</td>
<td>78.1% N$^+_2$ 20.9% O$^+_2$ 1% Ar</td>
<td>102.48</td>
</tr>
<tr>
<td>Mars</td>
<td>95.3% CO$^+_2$ 2.7% N$^+_2$ 2% Ar</td>
<td>103.25</td>
</tr>
<tr>
<td>Jupiter, Saturn, Uranus, Neptune</td>
<td>89% H$^+$ 11% He</td>
<td>24.43</td>
</tr>
</tbody>
</table>

References

5. National Space Science Data Center’s Fact Sheet.