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Suggestion for Study of an Aspect of Energy Deposition by Auroral Particles in Planetary Atmospheres

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As the number and variety of known exoplanets approaches a thousand, the number and condition of the Cinderella planets (those possibly capable of supporting life) also grown. As it is generally agreed that a necessary condition for support of life is the presence of liquid water, one of the conditions necessary for a planet to be a Cinderella planet is that the surface temperature be appropriate.

The warming of a planetary atmosphere is exceedingly complicated due to both the variety of energetic particles interacting with, and depositing energy into, it, and the complicated chemical and physical composition of a planetary atmosphere [1]. Here, we wish to consider the theoretical description of one type of interaction, namely that of a fast, charged auroral particle, for instance a proton, alpha particle, or a pick-up ion, with those species relevant to planetary atmospheres [1]. The question to be addressed is thus "What is the energy deposition profile created by auroral particles traversing a planetary atmosphere?"

To simplify the problem, several assumptions should be made:

- The planet is non-magnetic, and thus the effect of the magnetosphere is ignored.
- The particles of type j enter the atmosphere with a velocity distribution in both speed and angle given by α_j.
- Each atomic, molecular, or ionic species i in the atmosphere has a density distribution measured radially outward from the center of mass of the planet, $n_i(h)$. The density of species i is the fractional density of scatterers at height h.
- Assume straight line trajectories, which is certainly not the case for *e.g.* protons colliding with heavy atoms.

The energy deposition per unit path length for a particle in a uniform distribution of scatterers, or the stopping power of the system is normally described by the projectile energy loss per unit path length, or stopping power:

$$-\frac{dE(v)}{dx} = nS(v) \qquad (1)$$

Where n is the density of scatterers, and $S(v)$ is the stopping cross section for a projectile with velocity v [2]. For a projectile of velocity v, then, in an atmosphere of mixed species of scatterers, each with a local density of $n_i(h)$ and stopping cross section $S_i(v)$, the total energy loss per unit path length at a particular distance h from the planet's center of mass will be:

$$\frac{dE(v,h)}{dx} = -n\sum_i n_i(h) S_i(v) \qquad (2)$$

The amount of energy lost along the path is an integral of dE/dx along the path. However, the velocity changes as the particle loses energy. One normally accounts for this by invoking the continuous slowing down approximation (CSDA). The range calculated in the CSDA is a very close approximation to the average path length traveled by a charged particle as it slows down to rest. Calculated in this approximation, the rate of energy loss at every point along the track is assumed to be equal to the same as the total stopping power at that point. Energy-loss fluctuations are neglected. The CSDA range is then obtained by integrating the reciprocal of the total stopping power with respect to energy. Thus, the energy lost by a particle moving a distance Δy through an atmosphere is

$$y_2 - y_1 = \int_{E_1}^{E_2} \frac{1}{dE/dx} dE \qquad (3)$$

so the energy deposited by the projectile along that path length is:

$$y_2 - y_1 = \int_{E_1}^{E_2} \frac{1}{n\sum_i n_i(h) S_i(v)} dE \qquad (4)$$

We note that the pathway of the ion through the atmosphere is not necessarily normal to the planet's surface, and thus something must be known about the distribution of trajectories of the incoming ions.

It is then necessary to determine the stopping cross section for a particular ion/target pair, which is generally expressed as a function of the particle velocity, as in Bethe-like theories [3], as:

$$S(v) = \frac{4\pi e^4 Z_1^2 Z_2}{mv^2} L(v) \qquad (5)$$

where Z_1 and Z_2 are the projectile charge and target electron number. The stopping number, $L(v)$, is normally written:

$$L(v) = L_0 + Z_1 L_1 + Z_1^2 L_2 \qquad (6)$$

which, using the Bethe [4], Lindhard [5,6], and Bloch [7] forms for L_0, L_1, and L_2, respectively, yields

$$L(v) = \ln\frac{2mv^2}{I_0} - C_1 v e^{-C_2 v} + Z_1 \cdot \frac{3\pi e^2 I_0}{2\hbar m v^3} \ln\frac{2mv^2}{I_0} - \frac{1.202 Z_1^2}{v^2} \qquad (7)$$

for the stopping number. Here the projectile velocity is given in units of the Bohr velocity.

The critical quantity here is the mean excitation energy of the target, I_0, which is defined [1] as the first energy weighted moment of the target dipole oscillator strength distribution (DODS):

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$$\ln I_0 = \frac{\int \frac{df}{dE} \ln E dE}{\int \frac{df}{dE} dE} \tag{8}$$

The mean excitation energy is characteristic of the target only, and has no dependence on the properties of the projectile ion. I_0 describes how easily a target molecule can absorb kinetic energy' from the projectile, primarily as electronic (including ionization) and vibrational (including fragmentation) excitation. (One should note parenthetically that if the target is in an excited electronic state before the collision, the projectile might absorb energy from the target [8]).

The energy deposited by these particles in the column of atmosphere is thus

$$y_2 - y_1 = \int_{E_1}^{E_2} \frac{1}{dE/dx} dE$$
$$= \int_{E_1}^{E_2} \frac{1}{n\sum_i n_i(h)\frac{4\pi e^4 Z_1^2 Z_2}{mv^2}\left[\ln\frac{2mv^2}{I_0} - C_1 v e^{-C_2 v} + Z_1 \cdot \frac{3\pi e^2 I_0}{2\hbar m v^3}\ln\frac{2mv^2}{I_0} - \frac{1.202 Z_1^2}{v^2}\right]} dE \tag{9}$$

Such a calculation of energy deposition would need to be carried out for each combination of auroral particle and target atmospheric molecule pair.

It is thus suggested that one aspect of energy deposition in planetary atmospheres, namely that of energy deposition by fast ions, could be investigated by using extant stopping power formulations. The usefulness of this approach is predicated on a detailed knowledge of the composition and distribution of the planetary atmosphere, and of the form and distribution of the impacting auroral particles.

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