State-to-State Modeling of High-Speed, Nonequilibrium Shocked Flows

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The high-speed movement of a body into and through a planetary atmosphere leads to the formation of a strong shock-wave in front of its forebody, with the downstream creation of a shocked plasma. Unlike shock-waves in astrophysical environments, which are essentially collision-free, high-speed shock-waves are driven through heavy-impact collisions. It is then necessary to accurately model the excitation processes behind the shock-wave, which ultimately leads to the formation of a relatively hot plasma (in the 10,000-100,000K range). This is typically a very complex task, as such so called "entry flows" take place in the rarefied upper layers of a planetary atmosphere. Atmospheric entry plasmas are therefore a specific class of low-pressure, high-temperature, heavy-impact collision plasmas where nonequilibrium effects are very significant (with strong departures of the plasma internal states from a Boltzmann distribution).

This work discusses the dominant energy exchange processes that lead to the formation of such a plasma, and the theoretical approaches that we have selected for adequately modeling such exchange processes. The outline of the main plasma formation processes is as follows:

- The translational energy is firstly transferred to the flow molecules internal modes through Translation-Vibration (T-V) processes, ultimately leading to the dissociation of the molecules. Such T-V processes can be adequately modeled using the semi-analytic Forced Harmonic Oscillator (FHO) theory.

- Zeldovich-type reactions (AB(v)+C→BC(w)+A) concurrently lead to the affirmation of new vibrationally excited molecular species. These can be appropriately described using published datasets issued from high fidelity particle trajectory methods over accurate potential energy surfaces.

- Vibration-Excitation (V-E) processes.lead to the heavy impact population of the excited states of the flow molecules and atoms. Simple analytical models such as the Landau-Zener and Rosen-Zener theories provide relatively accurate reaction rates, even when compared with more sophisticated methods.

- Finally, associative ionization processes of the type $A+B\text{->}AB^+ + e^-$ lead to the formation of the first free electrons in the flow. From there onwards, electron avalanche processes lead to the formation of a plasma downstream of the shock-wave, where the accurate databases of electron-impact reaction rates commonly utilized in the modeling of laboratory plasma sources can also be put to use in this case.

This work will be concluded by the application of this kind of detailed, high-fidelity kinetic models, to the real conditions of a high-speed entry into the Earth's atmosphere at a velocity of about 12km/s. The relative importance of the aforementioned processes will be discussed.

[1] M. Lino da Silva, V. Guerra, and J. Loureiro, Plasma Sources Sci. Technol. **18**, 034023 (2009)