Nonequilibrium radiation modeling for Huygens entry

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Motivation and approach

- How conservative is the assumption of a Boltzmann distribution for the excited states of CN and N_2 under Huygens entry conditions?

- The recent NASA Ames shock-tube measurements and modeling for CN have shown that:

  - At p_∞=133 Pa, the measured CN(B) population is close to the Boltzmann distribution, in good agreement with the CR model.

  - At p_∞=13 Pa (representative of Huygens entry), the measured CN(B) population is below the Boltzmann distribution, but the CR model does not quite predict the radiation decay.

- We have developed a new CR model for CN and N_2. We will compare it with the NASA AMES shock-tube experiments and apply it to Huygens nominal trajectory.

Nonequilibrium radiation modeling

nonequilibrium

1. Boltzmann in thermo-chemical nonequilibrium (ESA, NASA, EM2C)
   - $T=T_r$, $T_e=T_v=T_{ele}$.
2. Electronic CR model (NASA, EADS, EM2C)
   - $T=T_r$, $T_e=T_v$,
   - Kinetics of electronic states.
3. Vibrational-electronic CR model for air plasmas [Capitelli et al.] or [Pierrot, Chauveau, Laux],
   - $T=T_r$, T_e,
   - Kinetics of electronic and vibrational states.

Present CR model (20 reactions)

- Spontaneous emission

$CN(B) \rightarrow CN(X) + h\nu$

- Collisional (de)excitation with N_2

$CN(X) + N_2(X) \rightarrow CN(B) + N_2(X)$

- Resonant collisional (de)excitation with N_2

$CN(X) + N_2(X, v=11) \rightarrow CN(B) + N_2(X, v=0)$

- Electron impact (de)excitation

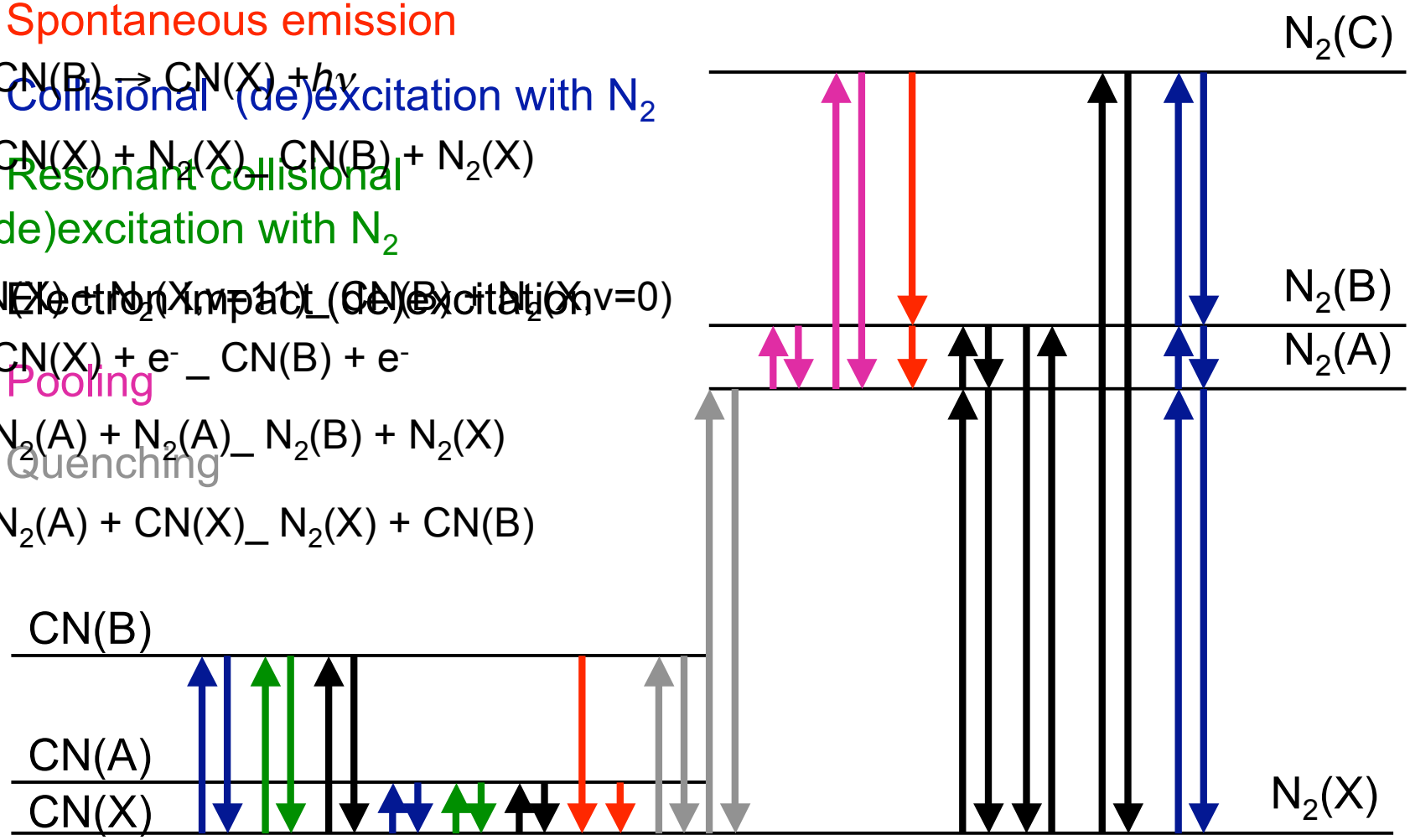
$CN(X) + e^- \rightarrow CN(B) + e^-$

- Pooling

$N_2(A) + N_2(A) \rightarrow N_2(B) + N_2(X)$

- Quenching

$N_2(A) + CN(X) \rightarrow N_2(X) + CN(B)$



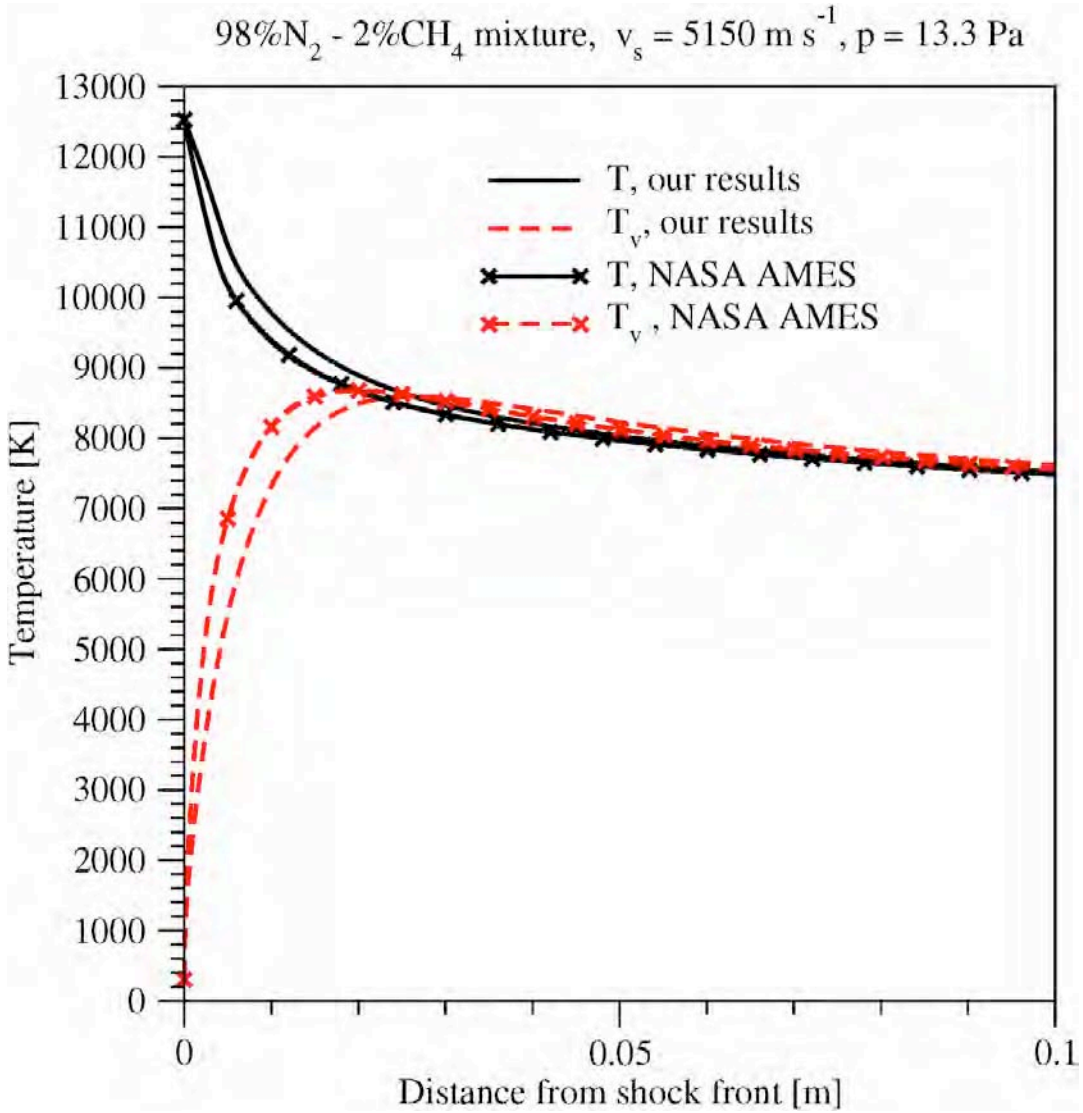
Shock-tube experiment

1. Flowfield
   - 1D solver for 2-temperature Euler equations .
   - Thermal nonequilibrium chemistry model (Gökçen).
2. Collisional-radiative model
   - CN(A,B), N_2(A,B,C) excited electronic states.
   - Lagrangian approach (more general than QSS).

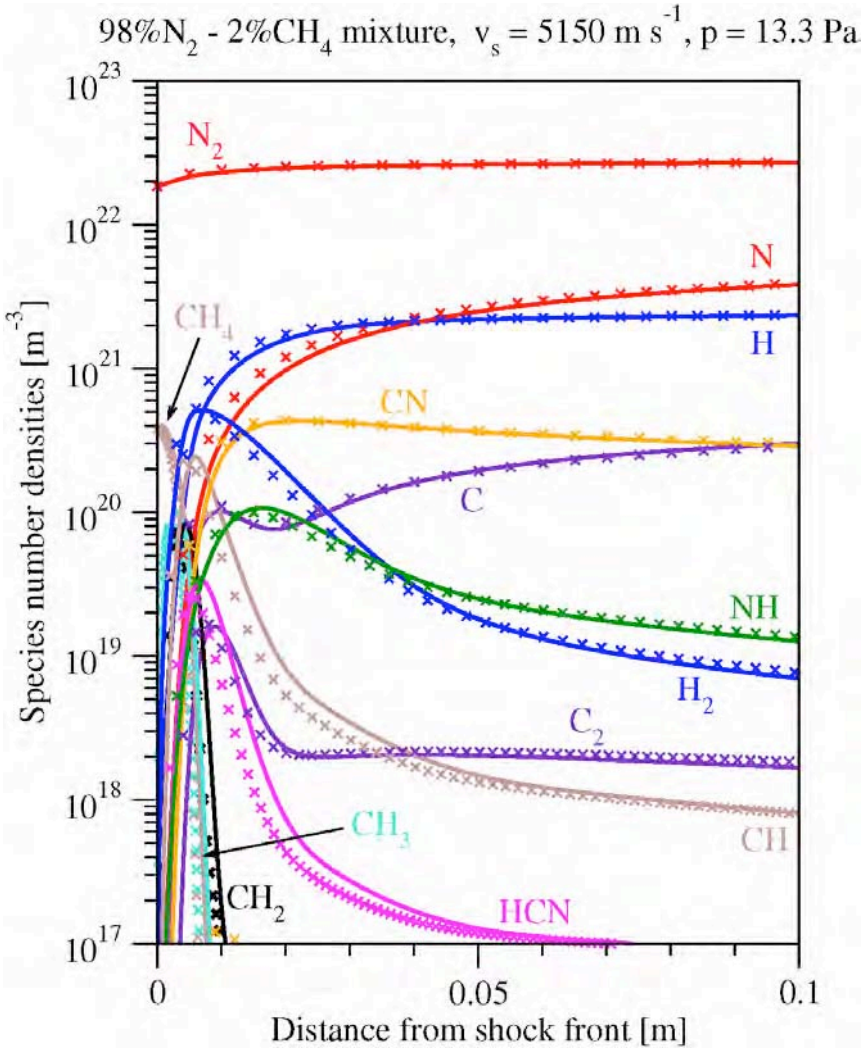
➡ Case 1, NASA-AMES, p = 13.3 Pa, u_s = 5150 m/s, 98% N_2, 2% CH_4.

➡ Case 2, NASA-AMES, p = 133.3 Pa, u_s = 5930 m/s, 91.4% N_2, 8.6% CH_4.

Shock-tube (temperatures)

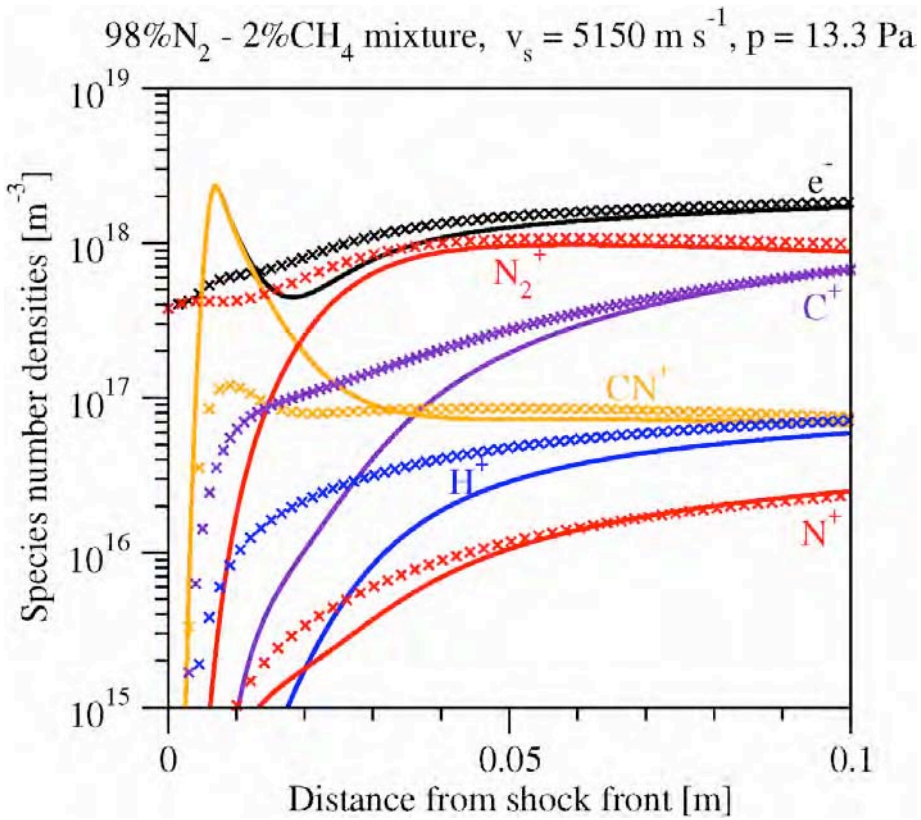


Shock-tube (composition)

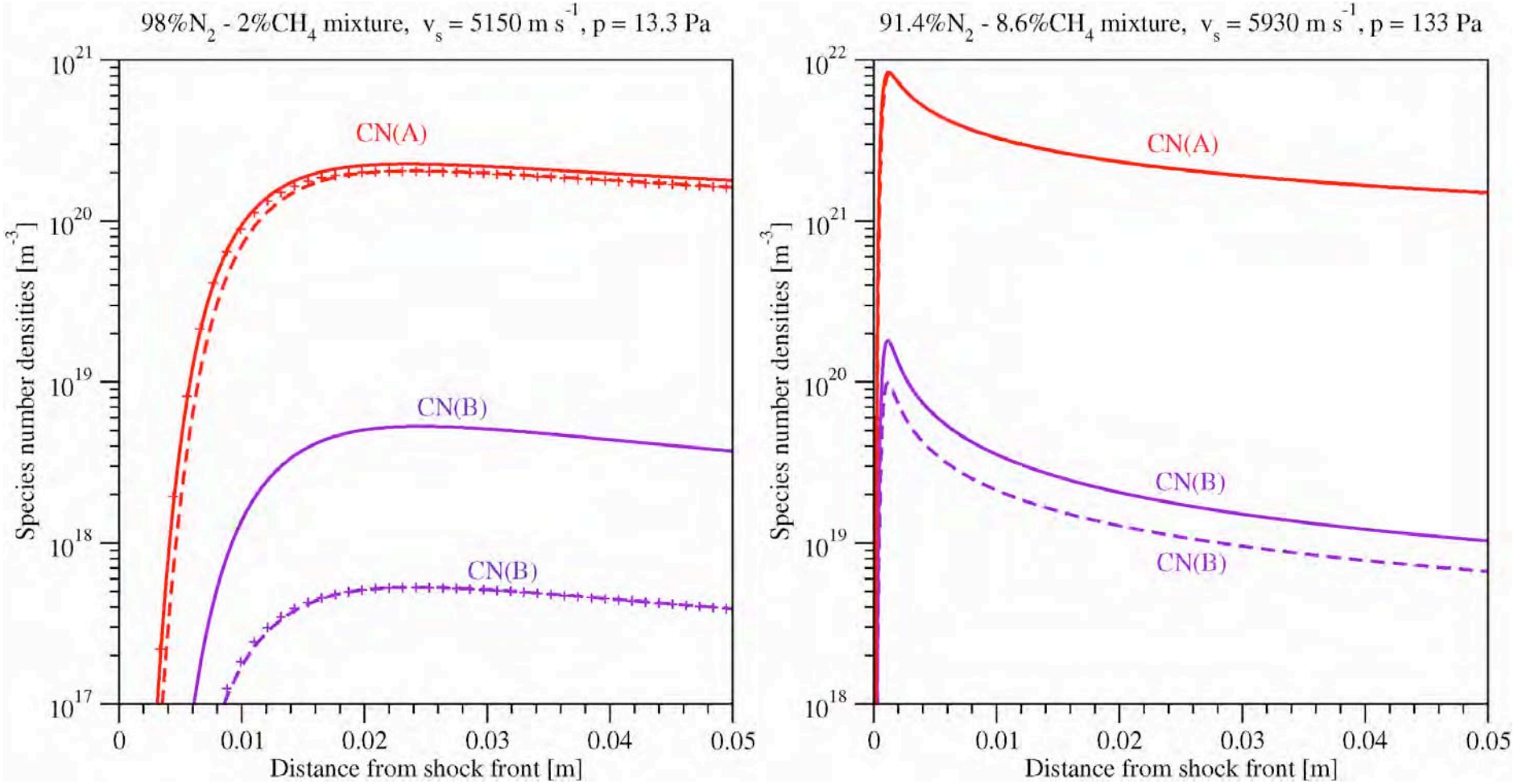


___NASA AMES,

— our results

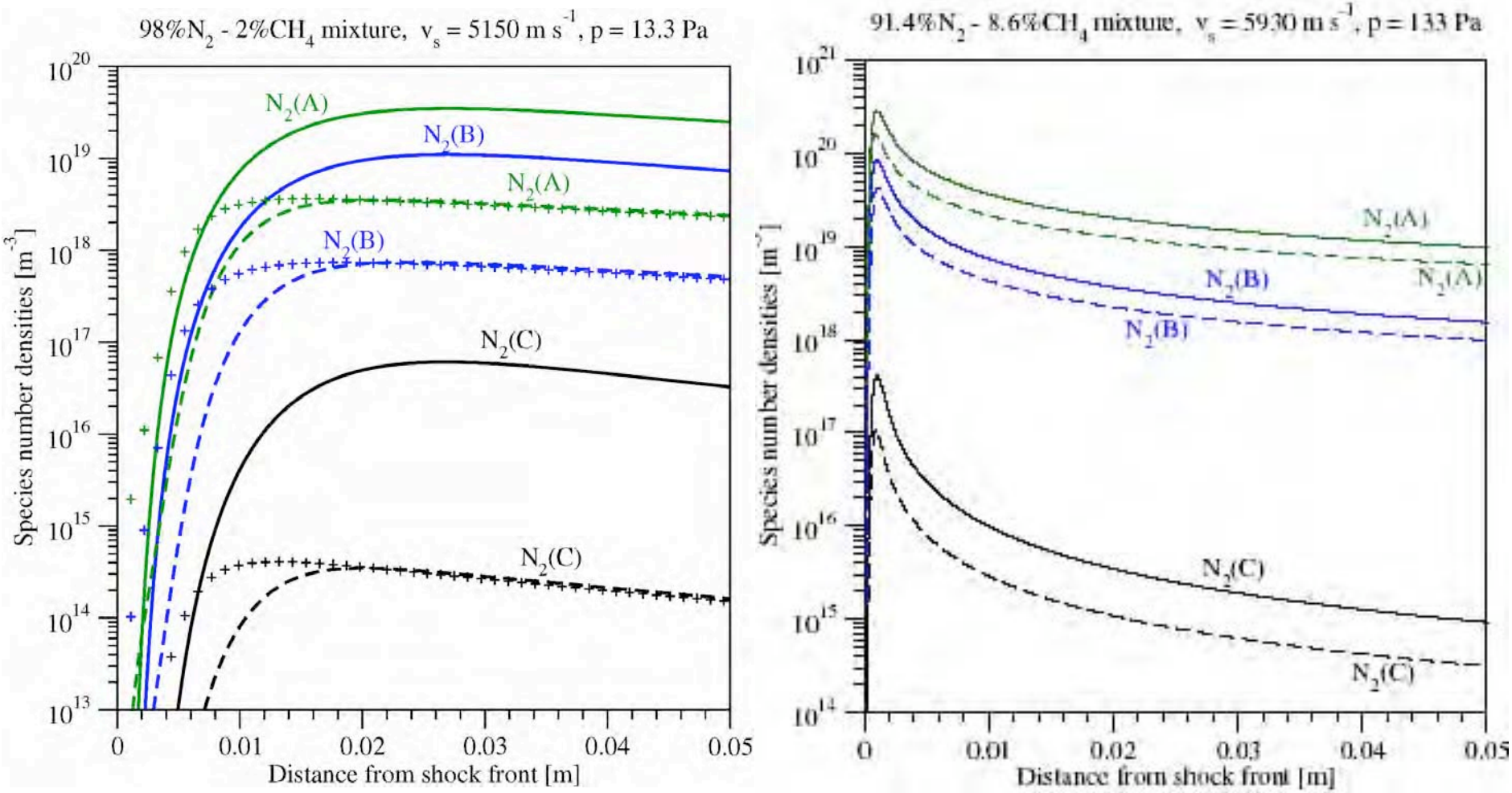


Shock-tube [CN(A,B) populations]



— Boltzmann, --- Lagrangian method, +++QSS approximation

Shock-tube [N_2(A,B,C)]



— Boltzmann, --- Lagrangian method, +++QSS approximation

Huygens entry

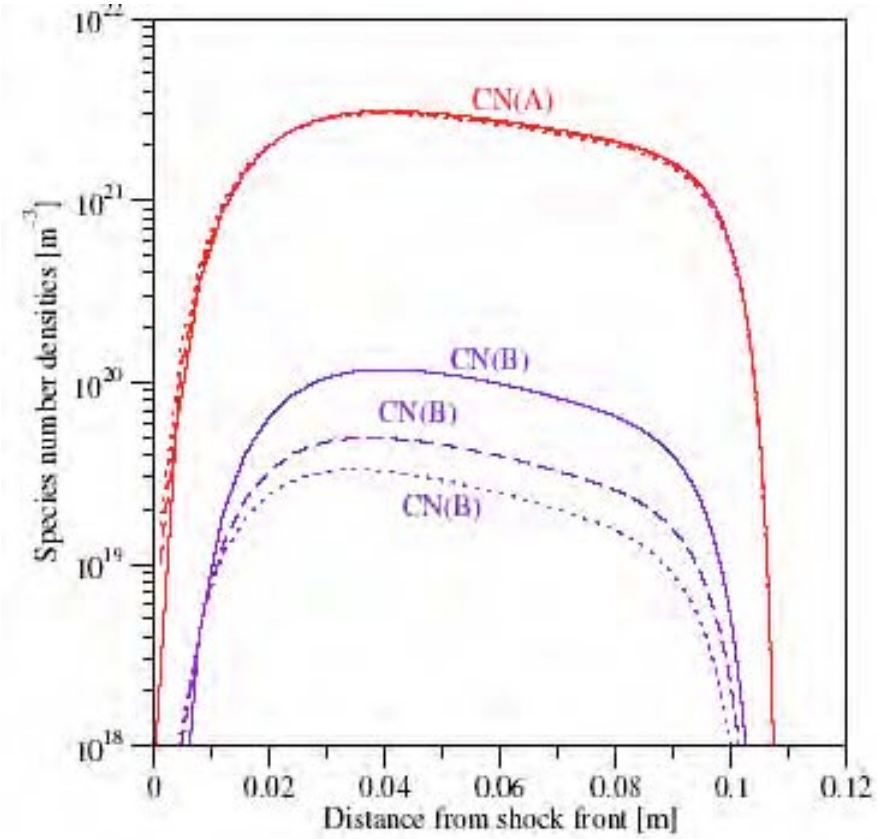
- Yelle nominal trajectory, 95%N_2, 3%CH_4, 2%Ar, -65° path flight angle, no gravity wave.
- Flowfield: LORE code [L. Walpot]

  → t = 165 s, neutral mixture

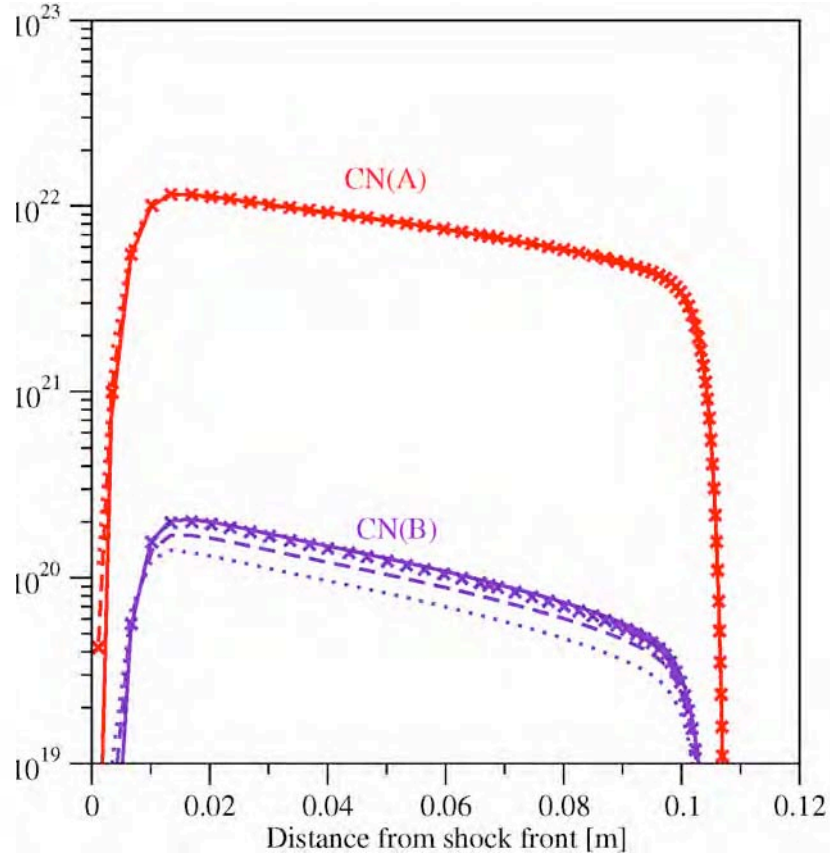
  → t = 187 s, ionized mixture
- CR model: we gradually incorporate the various reactions to assess their relative influence on the nonequilibrium populations.

Huygens entry [CN(A,B)]

t = 165 s

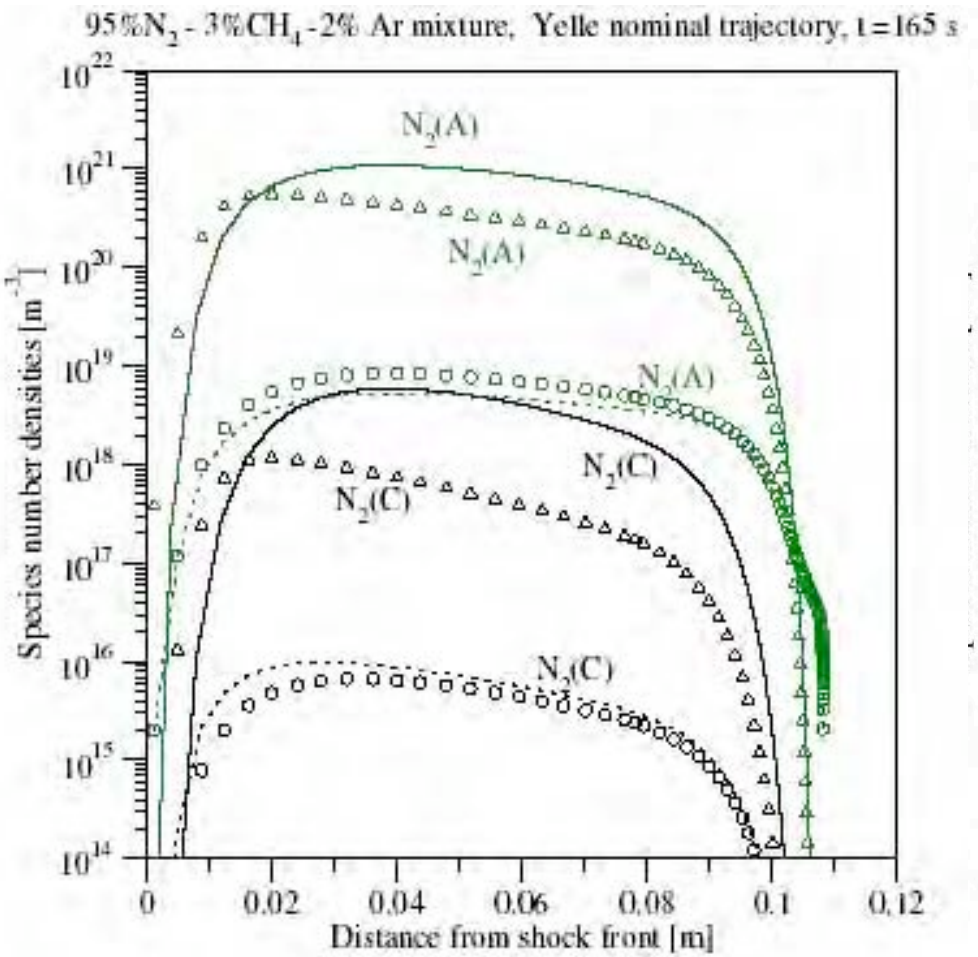


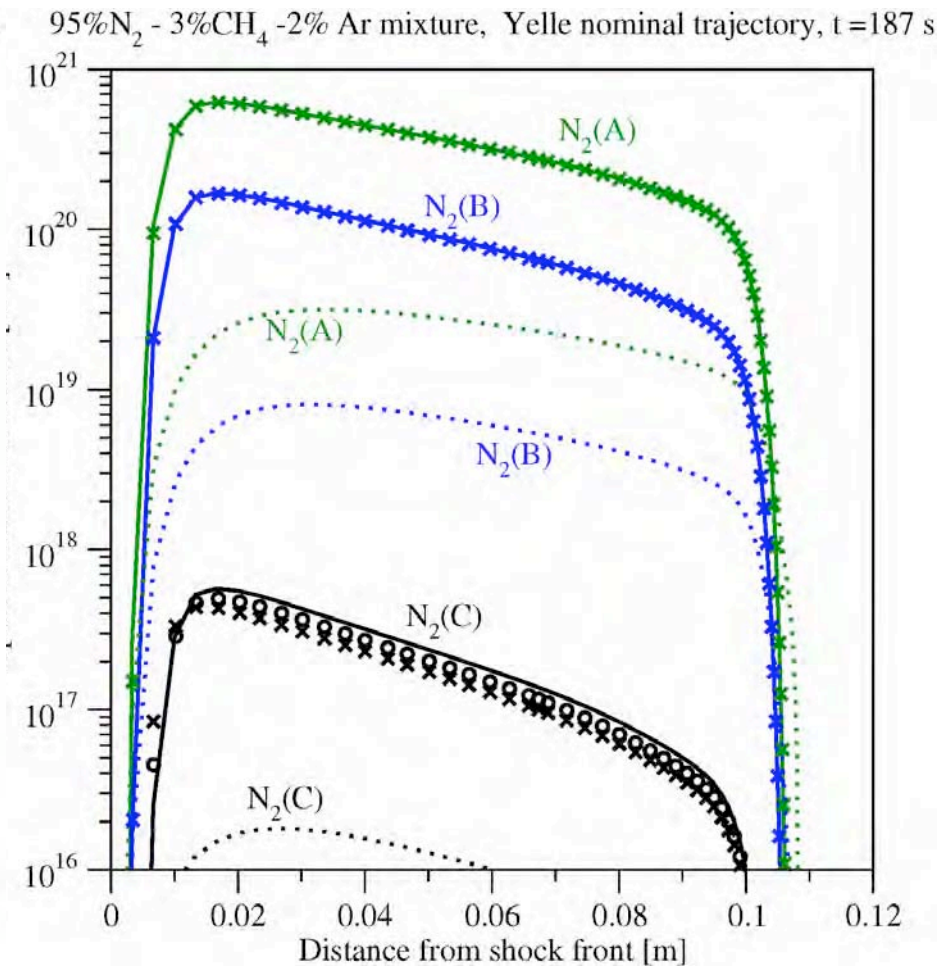
t = 187 s



— Boltzmann, … radiation&molecular impact,---&resonant, ___&electron impact

Huygens entry [N_2(A,B,C)]





— Boltzmann, … radiation&molecular impact,___&electron impact, __ & pooling, ___ & quenching: N_2(A)+CN(X)_N_2(X)+CN(B)

Conclusion

- An electronically specific CR model was proposed to quantify nonequilibrium radiation of CN(A,B) and N2(A,B,C) excited states during Huygens entry on Titan.

- The CR model was solved accurately in time by means of a Lagrangian method.

⇒ The model was applied to the NASA AMES shock-tube experiment. Results agree with those of Bose et al, despite the different approaches.

⇒ The model was applied to Huygens entry simulations obtained by Walpot.

  - The CN(B) population is close to Boltzmann at t = 187 s and about a factor two lower at t = 165 s.

  - The N_2(A,B,C) population is close to Boltzmann for both trajectory points.

Future work

- Improve CR model to better predict rate of radiation decay in shock-tube experiments.
- Implement extension to an electronic and vibrational state-specific CR model because reaction rates depend on the vibrational population distribution (resonant molecular impact, inverse predissociation).
- There is a need for additional experimental validation.

Acknowledgements

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