Improved chemistry and attenuation models for communication black out simulation during Mars 2020 entry

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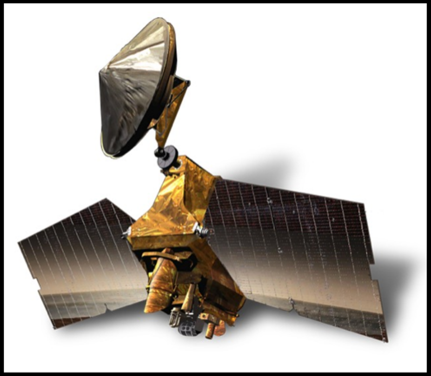
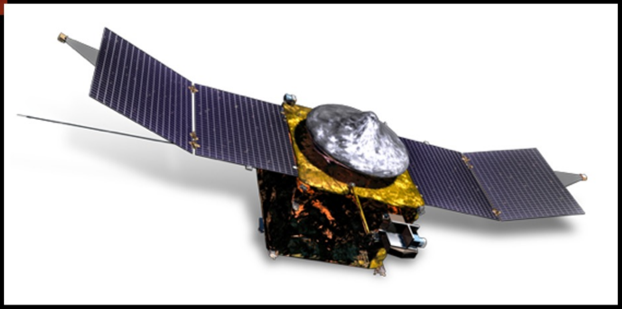
Mars 2020 Entry

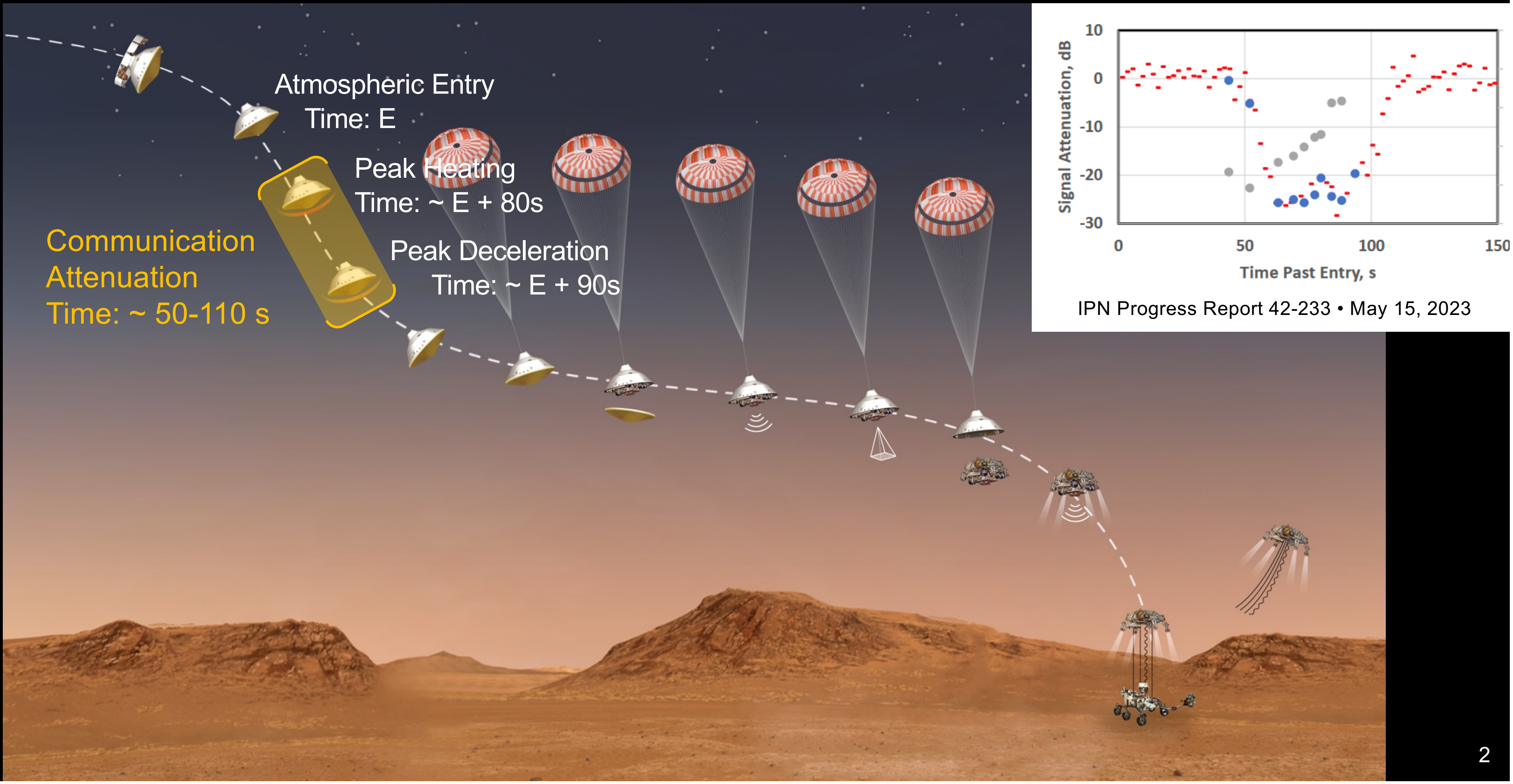


NASA Mars Reconnaissance Orbiter (MRO)



NASA Mars Atmosphere and Volatile Evolution (MAVEN)

Mars 2020 Entry



Atmospheric Entry
Time: E

Peak Heating
Time: ~ E + 80s

Peak Deceleration
Time: ~ E + 90s

Communication
Attenuation
Time: ~ 50-110 s

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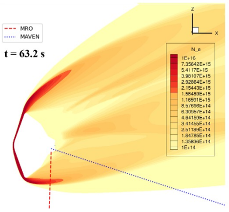
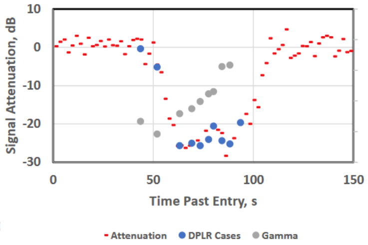
Why model communications attenuation during entry?





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The Mars 2020 Entry, Descent, and Landing Communications Brownout and Blackout at Ultra-High Frequency

Morabito, Papajak, Hedges, Saunders, Ilott, Jin, Fieseler, Kobayashi, Shihabi

- **Ability to predict:** To know when to expect attenuation.
- **Prevention/Mediation:** Must model blackout physics well to find and evaluate ways of mitigating it
- **Model validation:** Accurate attenuation prediction validates the capabilities of our modelling tools
  - Quantify and reduce uncertainties, including for electron density and radiation

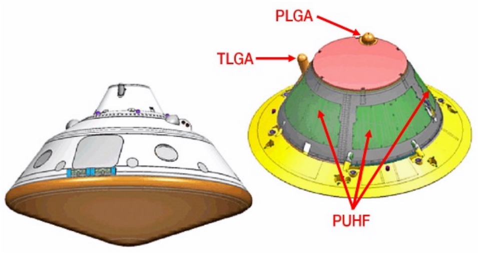
In this study:

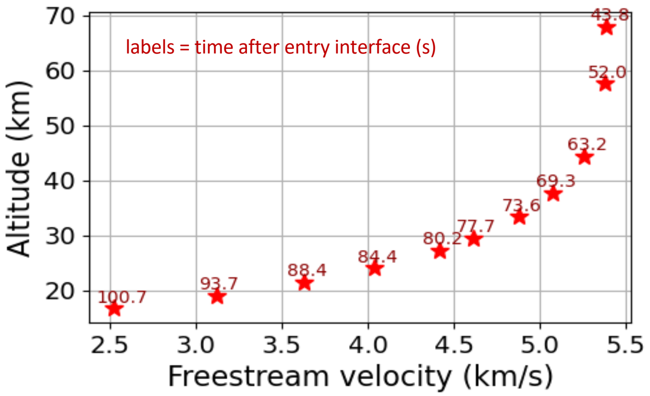
Estimate attenuations for Mars 2020, compare with measurements, and determine electron density sensitivity to
– attenuation formula
– ionization rate coefficients

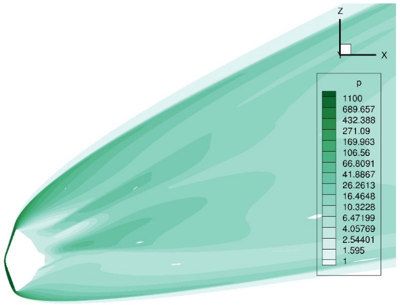
Computational Fluid Dynamics

Trevor Hedges
PhD Candidate at Stanford
Aeronautics and Astronautics
Engineering

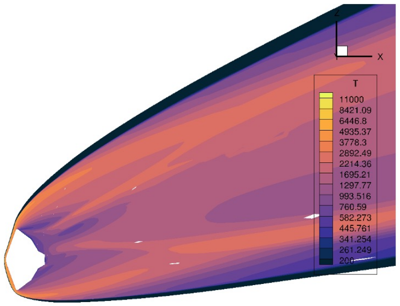
- Ran DPLR along Best Estimated Trajectory (BET) for Mars 2020 (full-body)
- Used chemistry models that include ionization reactions and electrons (17-species for Mars, 11-species for Earth)
- Varied Arrhenius coefficient C_f for ionization reactions to investigate electron density sensitivity





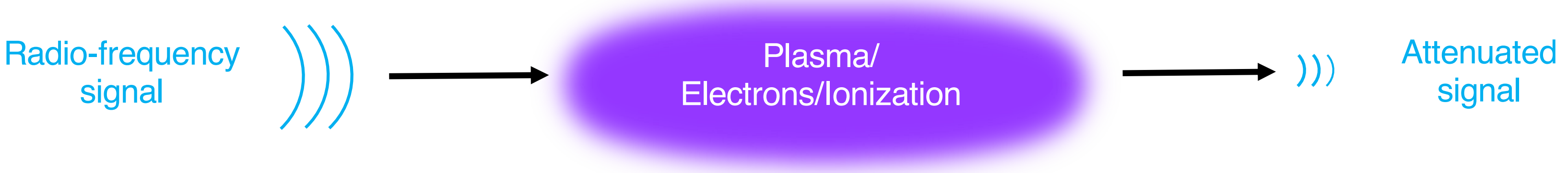


Pressure



Temperature

Physics of radio frequency attenuation



The complex refractive index for radio waves transmitting through a plasma is given by:

$$\tilde{n}^2 = 1 - \frac{\enclose{circle}{\omega_p^2}}{\cancel{\nu^2} + \omega^2} - \cancel{\frac{i(\nu/\omega)\omega_p^2}{\nu^2 + \omega^2}}$$

$\nu = 0$

$$\tilde{n} = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \longrightarrow n_i = Im(\tilde{n}) > 0$$

only if

$$\boxed{\begin{array}{l} \omega_p > \omega \\ n_e > n_{crit} \end{array}}$$

Simple formula, $\nu = 0$

Used by many prior attenuation studies

$\nu \neq 0$

$$\tilde{n} = \sqrt{\frac{1}{2}\left(\left(K_r^2 + K_i^2\right)^{1/2} + K_r\right)} + i\sqrt{\frac{1}{2}\left(\left(K_r^2 + K_i^2\right)^{1/2} - K_r\right)}$$

$$K_r = 1 - \frac{\omega_p^2}{\nu^2 + \omega^2} \qquad K_i = \frac{(\nu/\omega)\,\omega_p^2}{\nu^2 + \omega^2}$$

$$\boxed{\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e} \qquad \omega = 2\pi f}$$

Full formula, $\nu \neq 0$

Dissipation occurs even when $\omega_p < \omega$

Attenuation given by integral along line-of-sight (LOS): $$A_{dB}(z) = \left(\frac{20}{\ln(10)}\frac{\omega}{c}\right)\int_0^z \tilde{n}_i(\omega_p, \nu)\,dz$$

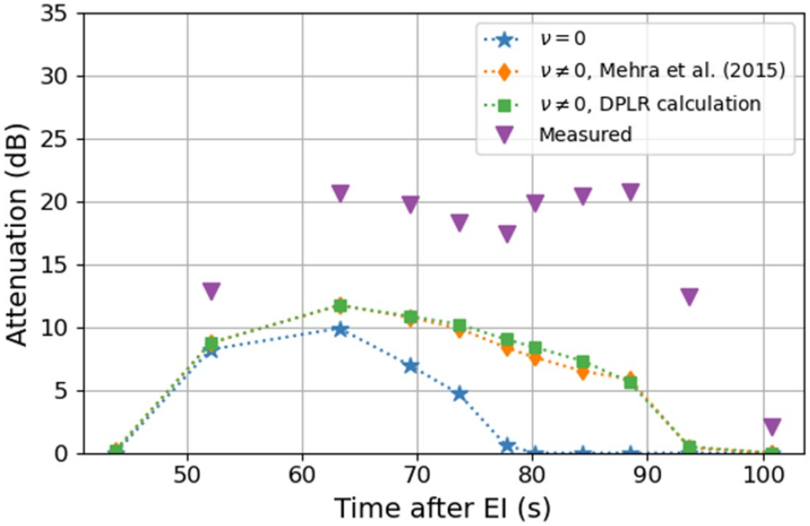
Effect of electron collisions with heavier species

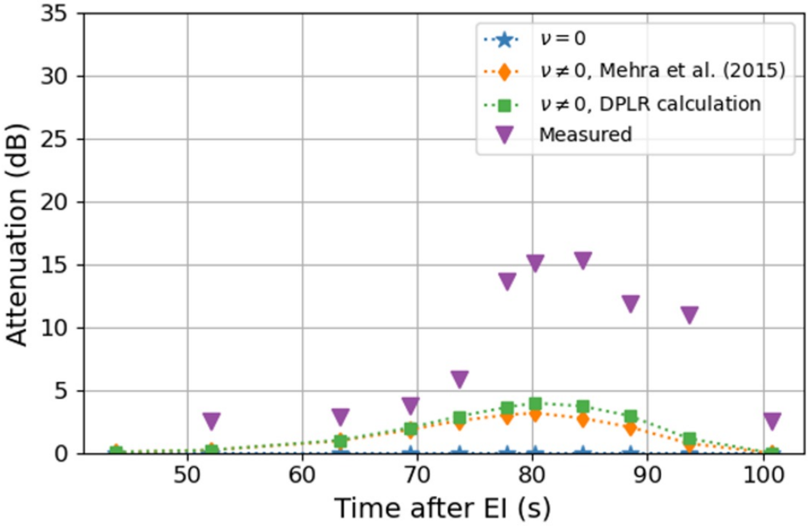
$$\nu = \sum_i n_i \sigma_{ei}(T) \left(\frac{8k_B T}{\pi m_{ei}}\right)^{\frac{1}{2}}$$

where $\sigma_{ei}(T)$ is the temperature-dependent momentum scattering cross section between electrons and heavier species i, and m_{ei} is the reduced mass for the collision

$$\nu = 5.814\times10^{12} \frac{P}{\sqrt{T}}$$

Mehra* expression for Earth entry


Mars Reconnaissance Orbiter (MRO)


Mars Atmospheric and Volatile Evolution (MAVEN)

When the effect of electron collisions with heavier species is included in the attenuation calculations, the duration of predicted attenuation to MRO matches the measured attenuation period more closely.

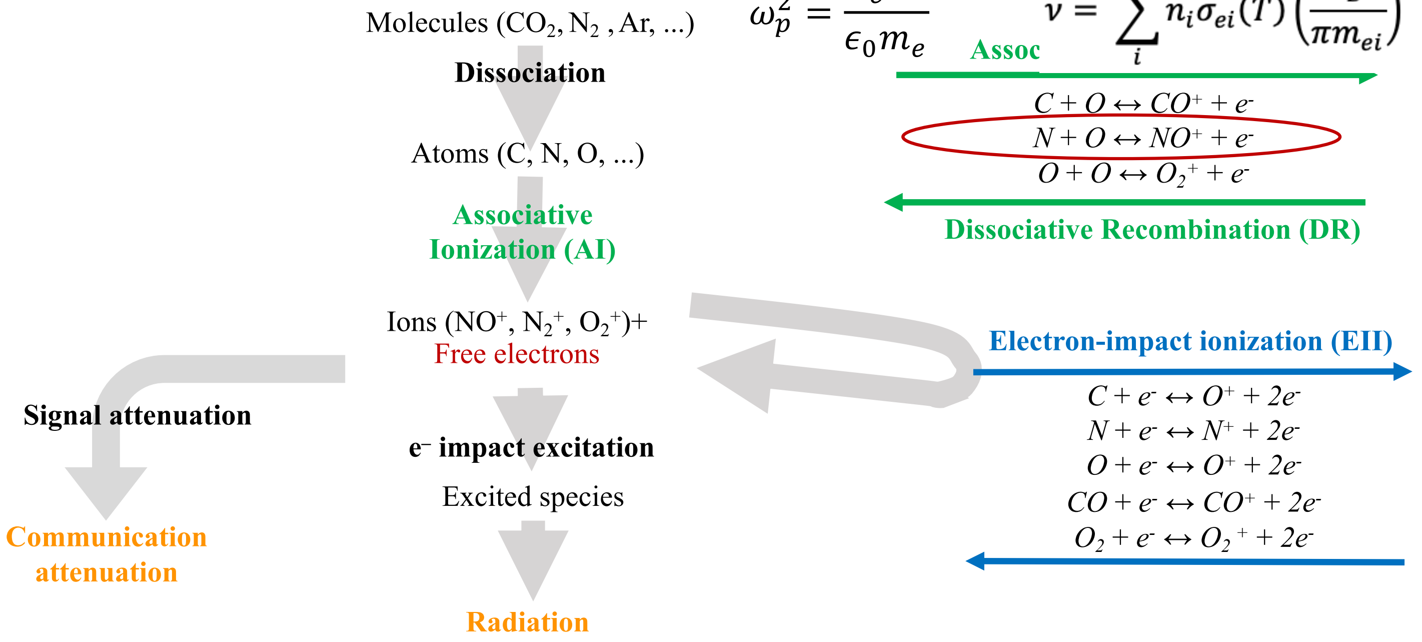
Hypersonic shock layer chemistry at Earth

Attenuation along line-of-sight (LOS):

$$A_{dB}(z) = \left(\frac{20}{\ln(10)}\frac{\omega}{c}\right)\int_0^z \tilde{n}_i(\omega_p, \nu)\,dz$$

$$\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m_e}$$

$$\nu = \sum_i n_i \sigma_{ei}(T)\left(\frac{8 k_B T}{\pi m_{ei}}\right)^{\frac{1}{2}}$$



Molecules (CO_2, N_2 , Ar, ...)

Dissociation

Atoms (C, N, O, ...)

Associative Ionization (AI)

Ions (NO^+, N_2^+, O_2^+)+

Free electrons

e^- impact excitation

Excited species

Radiation

Signal attenuation

Communication attenuation

Assoc

$C + O \leftrightarrow CO^+ + e^-$

$N + O \leftrightarrow NO^+ + e^-$

$O + O \leftrightarrow O_2^+ + e^-$

Dissociative Recombination (DR)

Electron-impact ionization (EII)

$C + e^- \leftrightarrow O^+ + 2e^-$

$N + e^- \leftrightarrow N^+ + 2e^-$

$O + e^- \leftrightarrow O^+ + 2e^-$

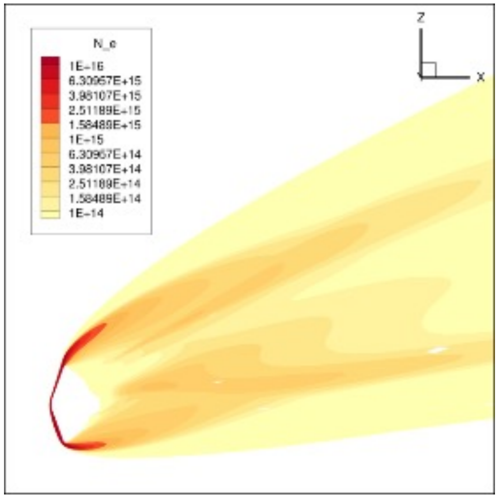
$CO + e^- \leftrightarrow CO^+ + 2e^-$

$O_2 + e^- \leftrightarrow O_2^+ + 2e^-$

Signal attenuation can be measured more easily than radiation, so it helps us validate model for electron density

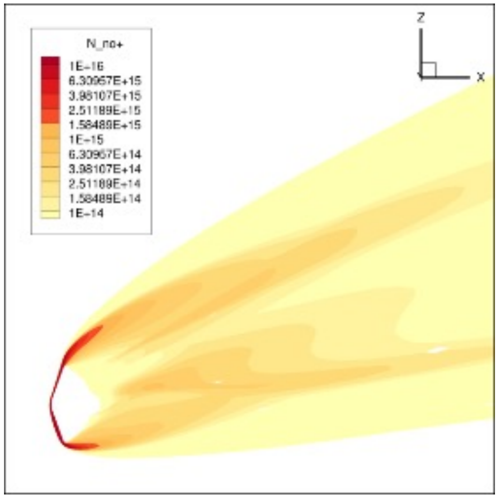
AI rate coefficients' impact on electron density

e^- density



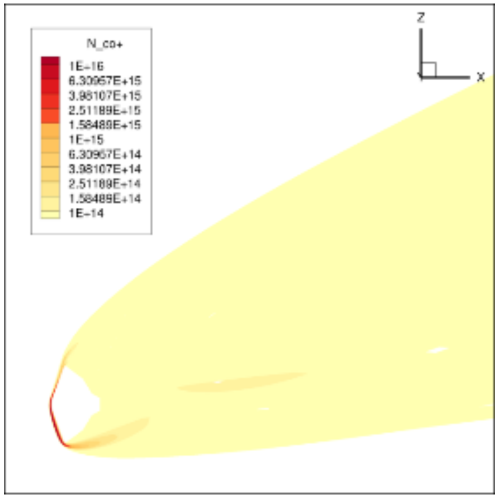
Total ionization

NO^+ density



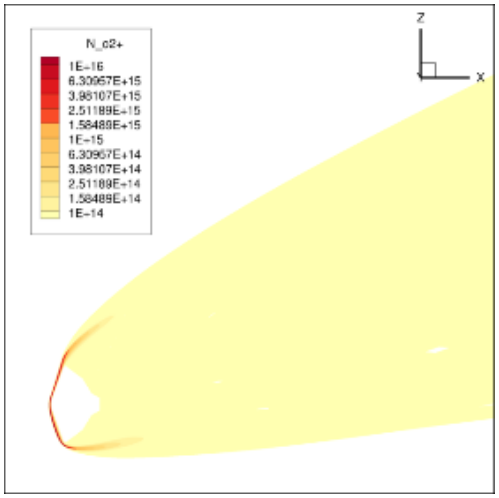
N+O AI

CO^+ density



C+O AI

O_2^+ density

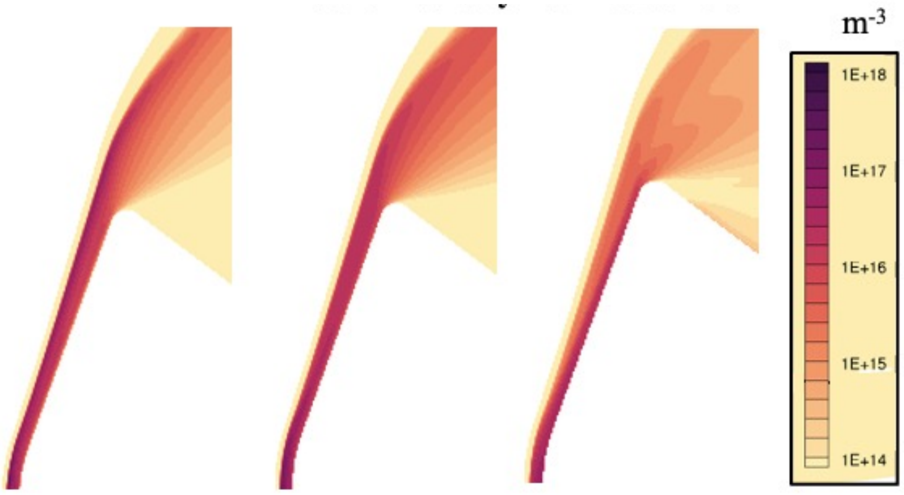


O+O AI

Of all AI reactions included in this model N+O reaction contributes most to ionization

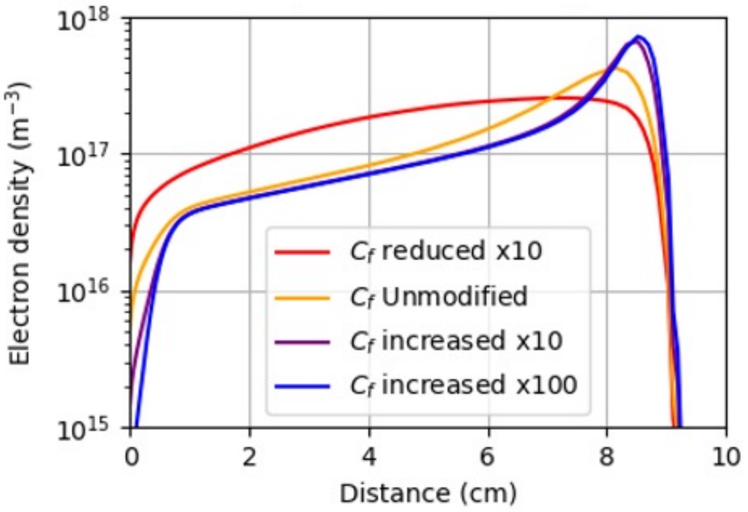
AI rate coefficient impact on electron density in the forebody region

"k_f" is the commonly assumed Mars/Venus rate coefficient citing Park 2001 model. For nitrogen-oxygen associative ionization, k_f is varied by factors of 10^x in these calculations to show its effect on ionization.



10*k$_f$ **k$_f$** **k$_f$/10**

Electron density contour plots at 63.2 seconds after entry interface in the forebody region



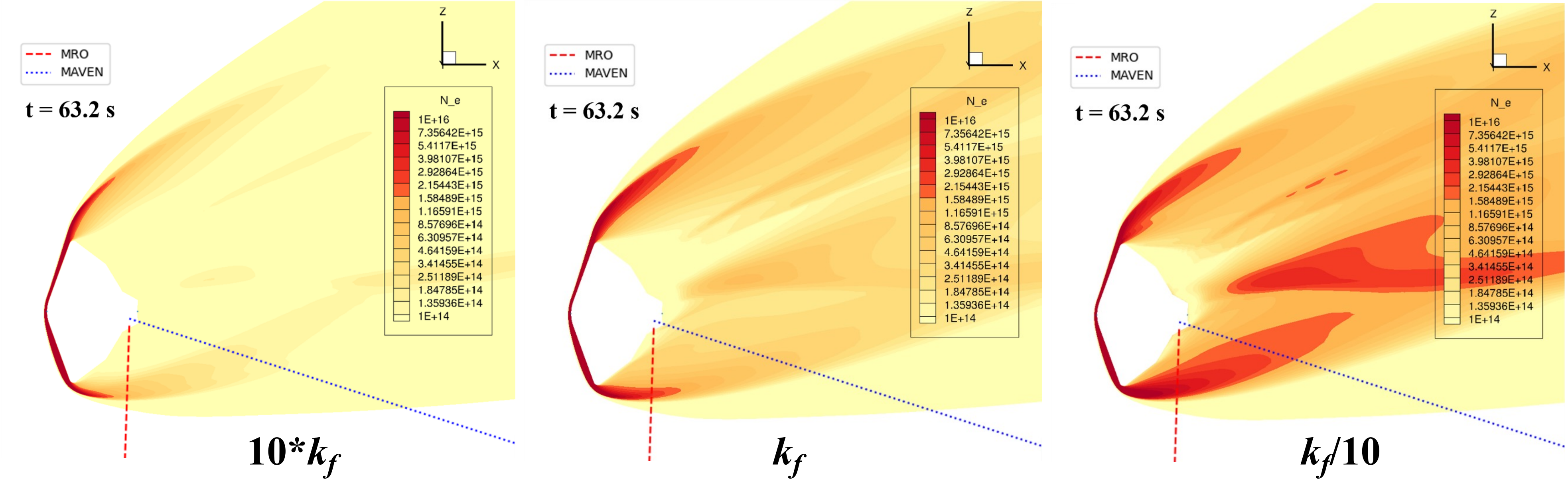
Profiles along a line that points outward from the heatshield nose to the edge of the domain

Increased k_f N+O results in increased peak electron densities in the region immediately behind the shock.

AI rate coefficient impact on electron density in the wake region

- Colorbar turns red where electron density > critical density

f = 400 MHz for Mars 2020
→ Critical density $n_e = 2.0 \times 10^{15}\ m^{-3}$



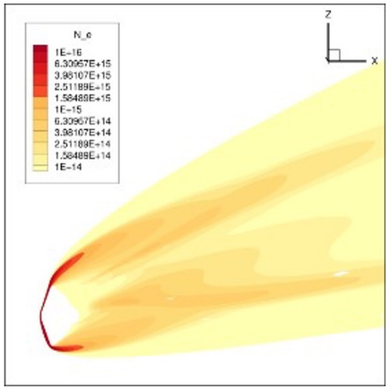
Chemistry overall "faster" with higher forward rate coefficient k_f

- Ionization faster in high temperature forebody region after shock
- Recombination faster in lower temperature aft regions (backward rate is based on forward rate)

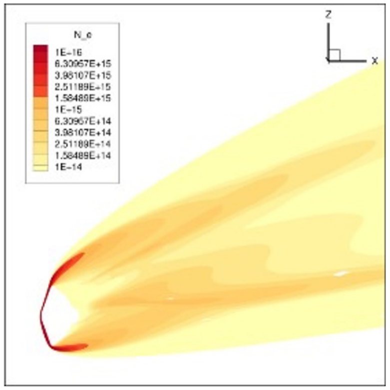
Effect of varying the EII forward rates on the electron density

Electron-impact ionization (EII)

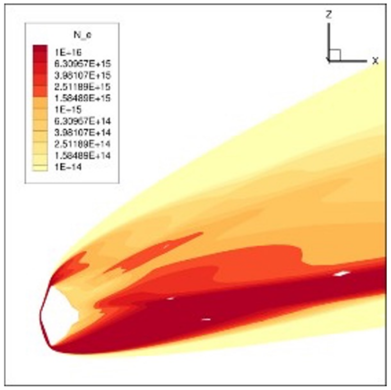
$$C + e^- \leftrightarrow O^+ + 2e^-$$
$$N + e^- \leftrightarrow N^+ + 2e^-$$
$$O + e^- \leftrightarrow O^+ + 2e^-$$
$$CO + e^- \leftrightarrow CO^+ + 2e^-$$
$$O_2 + e^- \leftrightarrow O_2{}^+ + 2e^-$$



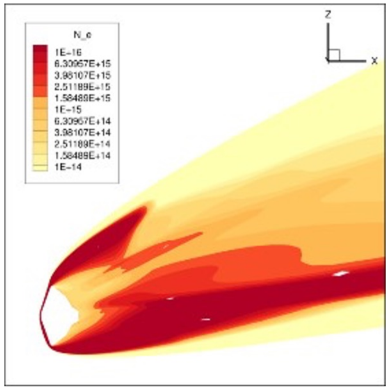
EII coeffs. unchanged



Every EII coeff. × 10^2



Every EII coeff. × 10^3

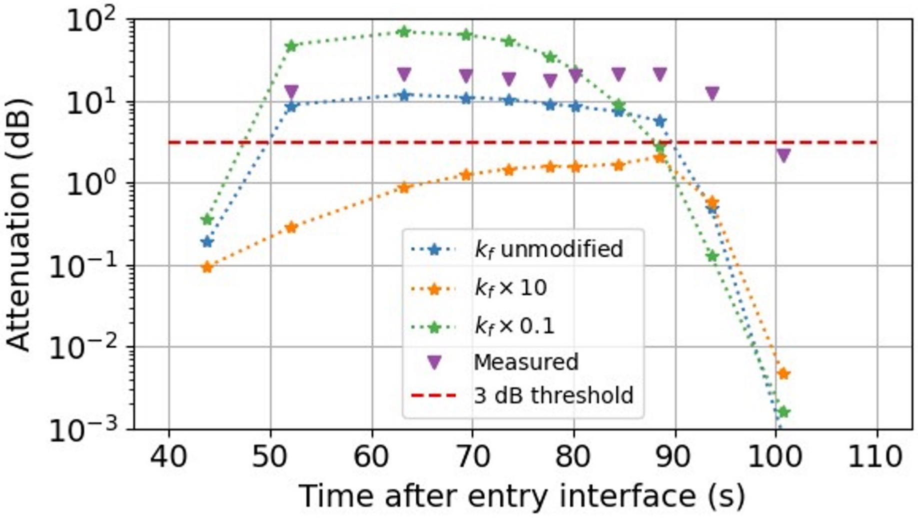


Every EII coeff. × 10^4

Varying k_f for all 5 EII reactions by one or two orders of magnitude did not yield a significant difference in the electron density

Predicted attenuation over time for each variation of k_{fNO}

Mars Reconnaissance Orbiter (MRO)



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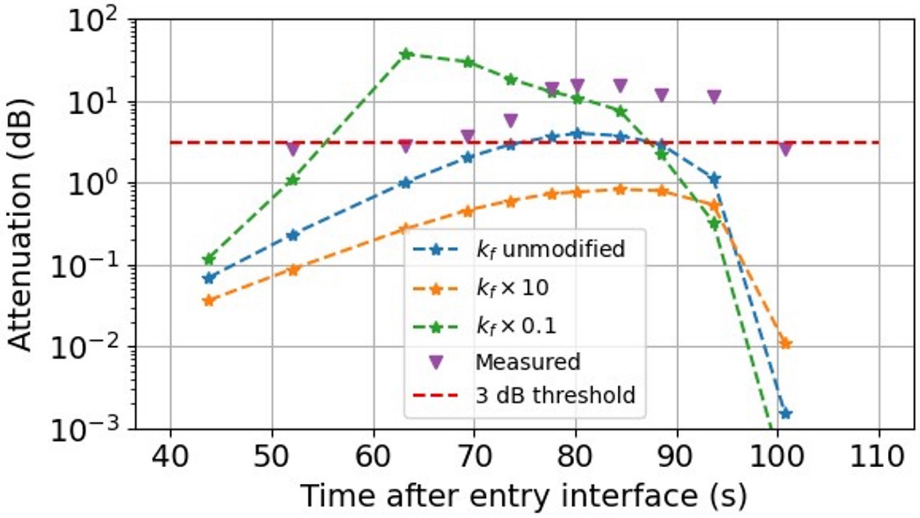
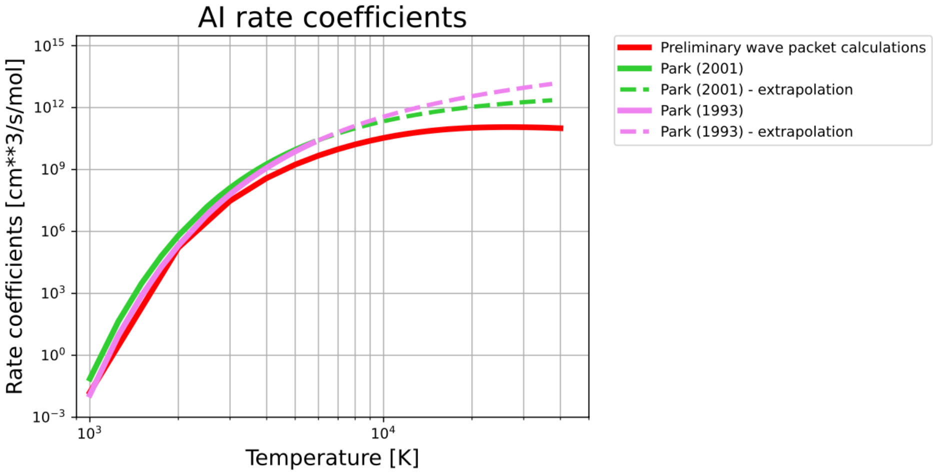


- the rate coefficient k_{fNO} has a clear impact on uncertainty in magnitude of attenuation throughout the trajectory
- appears to have less impact on predicted attenuation start and end times

- likely that other sources of uncertainty besides the nitrogen-oxygen AI rate may influence attenuation

Predicted attenuation over time for each variation of k_{fNO}



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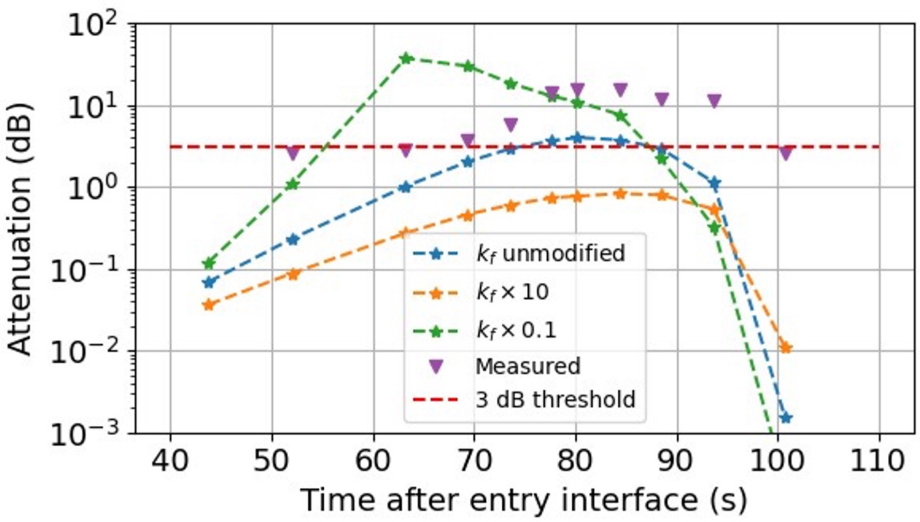

- the rate coefficient k_{fNO} has a clear impact on uncertainty in magnitude of attenuation throughout the trajectory
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Conclusions + Future Work

Future/current work:

- Include first ab initio rates for N+O AI
- Include more complete material response, ablation, and ionization reactions could further extend the predicted blackout window and close the gap between the measurement and the calculation.

Conclusions:

- N+O AI coefficient (k_{fNO}) had the greatest effect among the four AI reactions included in the model (O+O, N+O, and C+O)
- EII coefficient variation is not a major contributor to uncertainty in electron density or attenuation for a Mars entry.
- Derivation of the complex index of refraction with the electron collision frequency, ν, presented here, leads to explicit inclusion of the effect of electron-heavy particle collisions in the attenuation prediction and reduces the difference between calculation and measurement to about 7 seconds (20 seconds improvement!).

Acknowledgments

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  - Rich Jaffe and Dinesh Prabhu for many discussions on chemistry
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  - Brett Cruden
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