Ionization from Solar Pumped Metastable Levels of Atomic Samarium

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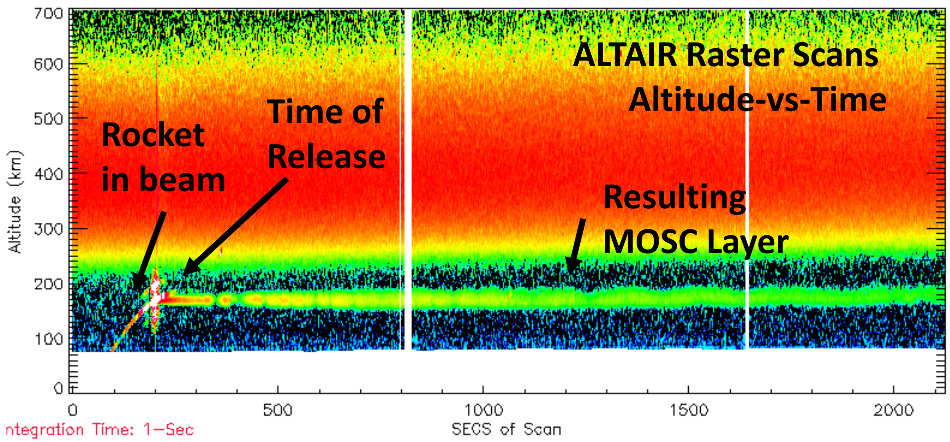
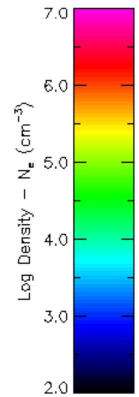
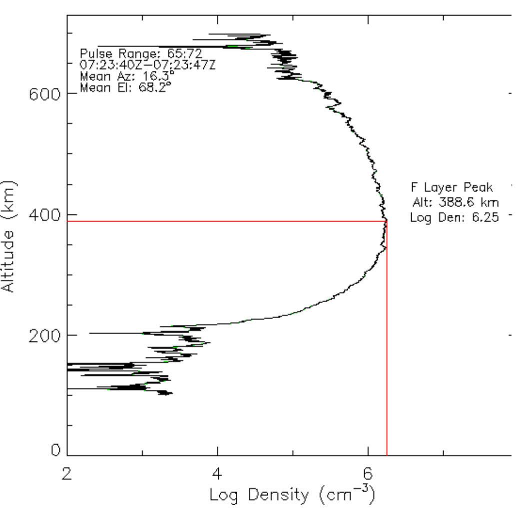
AFRL MOSC Experiment
(Radar Data from ALTAIR)

ALTAIR – Incoherent Scatter Radar

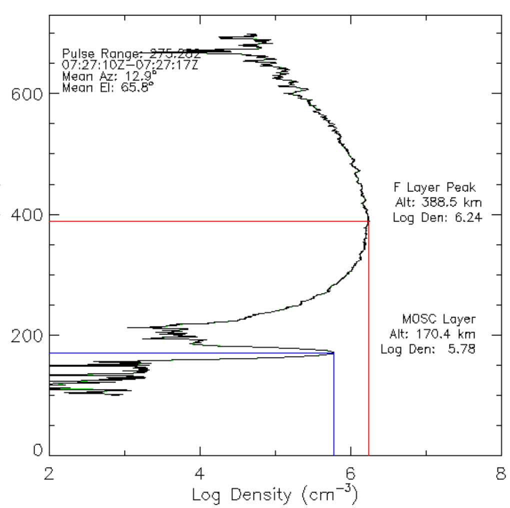




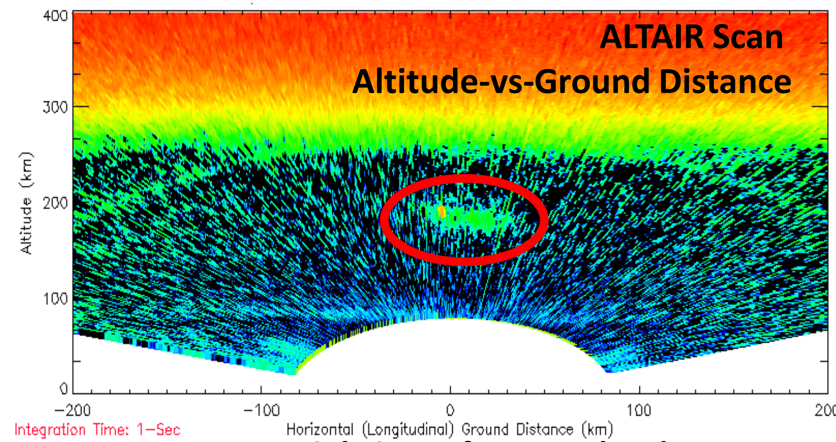
[Click for ALTAIR Pointing Movie]



Ionospheric Density Profile prior to release



Ionospheric Density Profile with MOSC Layer



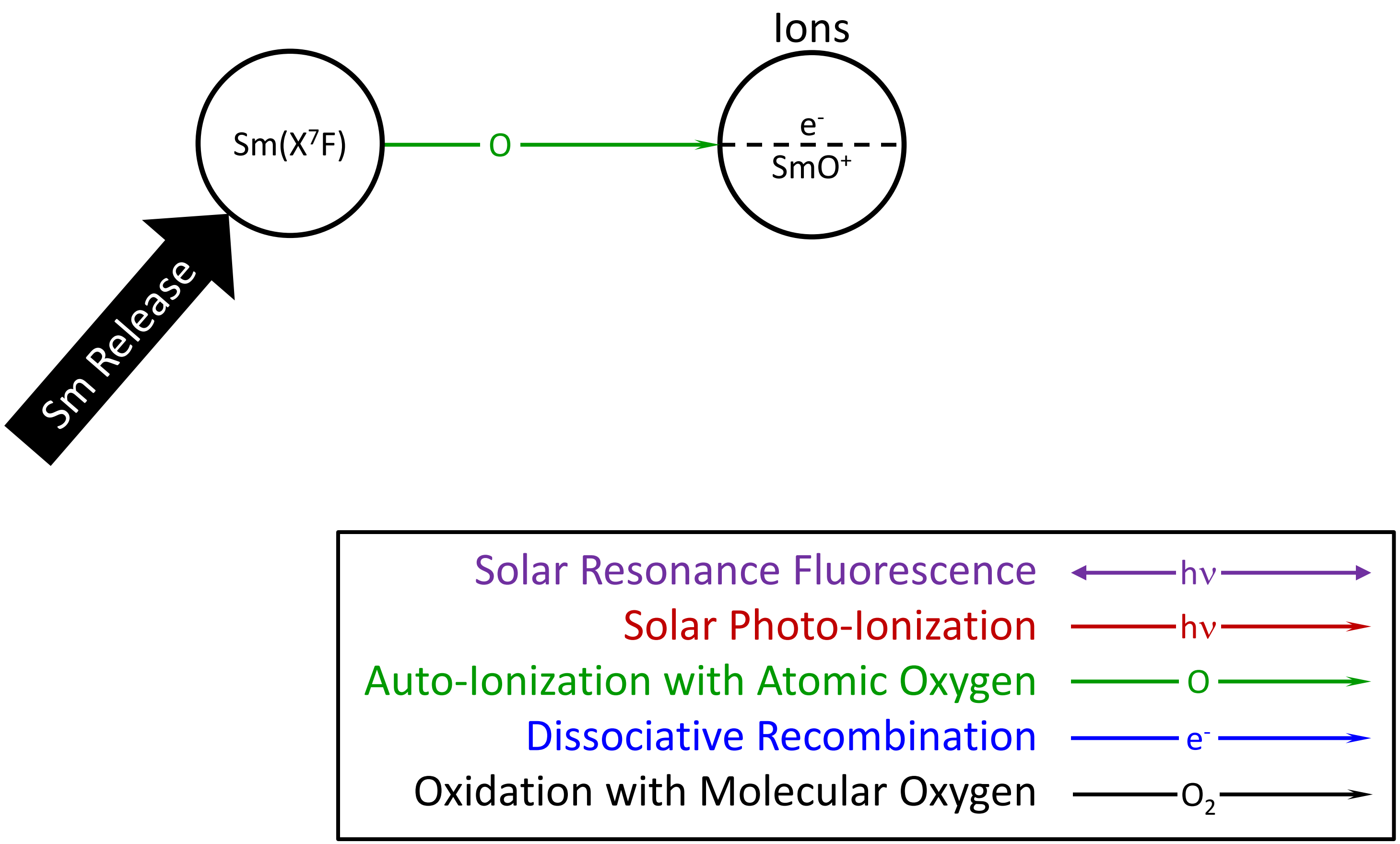
Spatial view of MOSC cloud ~40 minutes after release

CLOUD MUCH LESS DENSE THAN PREDICTED BUT DID HAVE SIGNIFICANT IMPACT ON IONOSPHERE

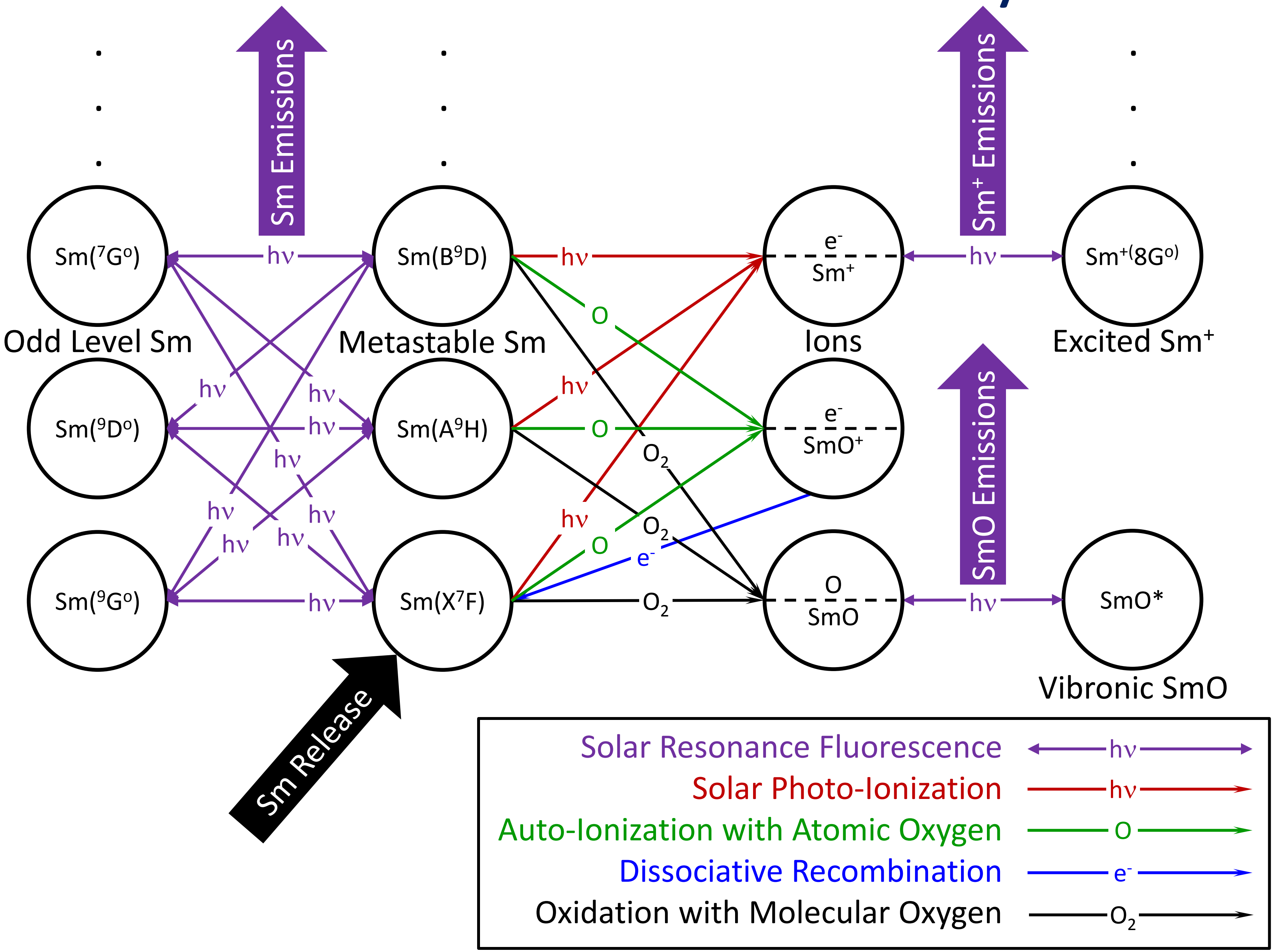
Ionization Processes in Samarium Vapor

- *Why did MOSC Samarium Not Produce Predicted Density Levels?*
- Samarium Atom Photo Chemistry (NRL CRM)
  - Sm Energy Levels
  - Sm Metastable Level Pumping in Sunlight (Important)
  - Samarium Photo-Ionization (Important but Slow)
  - Samarium Associative Ionization with Atomic Oxygen
    - Reaction Energy
      - Weakly Exothermic from Ground State Sm (7F) Metastable Levels
      - Strongly Exothermic from Higher Sm(9H, 7H, …) Metastable States
    - SmO^+ Production (Autoionization) and Loss (Recombination-Important)
  - Samarium Reaction with Diatomic Oxygen (Important)
- 3-D Time Dependent Predictions for MOSC Release
- Data Acquired During AFRL MOSC Experiment for Comparison
  - Initial Electron Production Inventory from NRL CERTO Beacon
  - Altair Radar Map of Electron Density
  - AFRL Spectrogram of Optical Emissions
- Conclusions

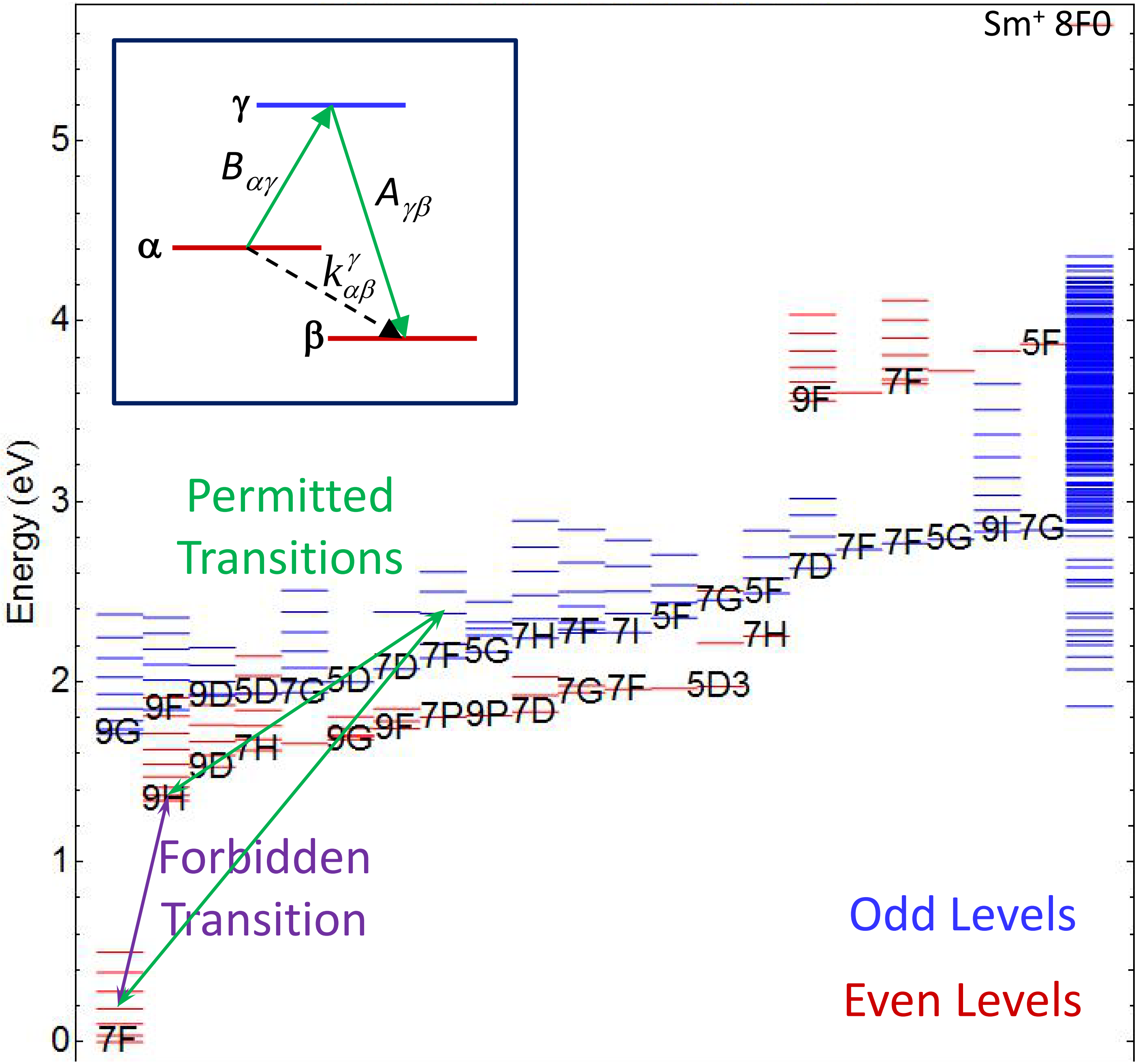
Conceptual Samarium Photo Chemistry



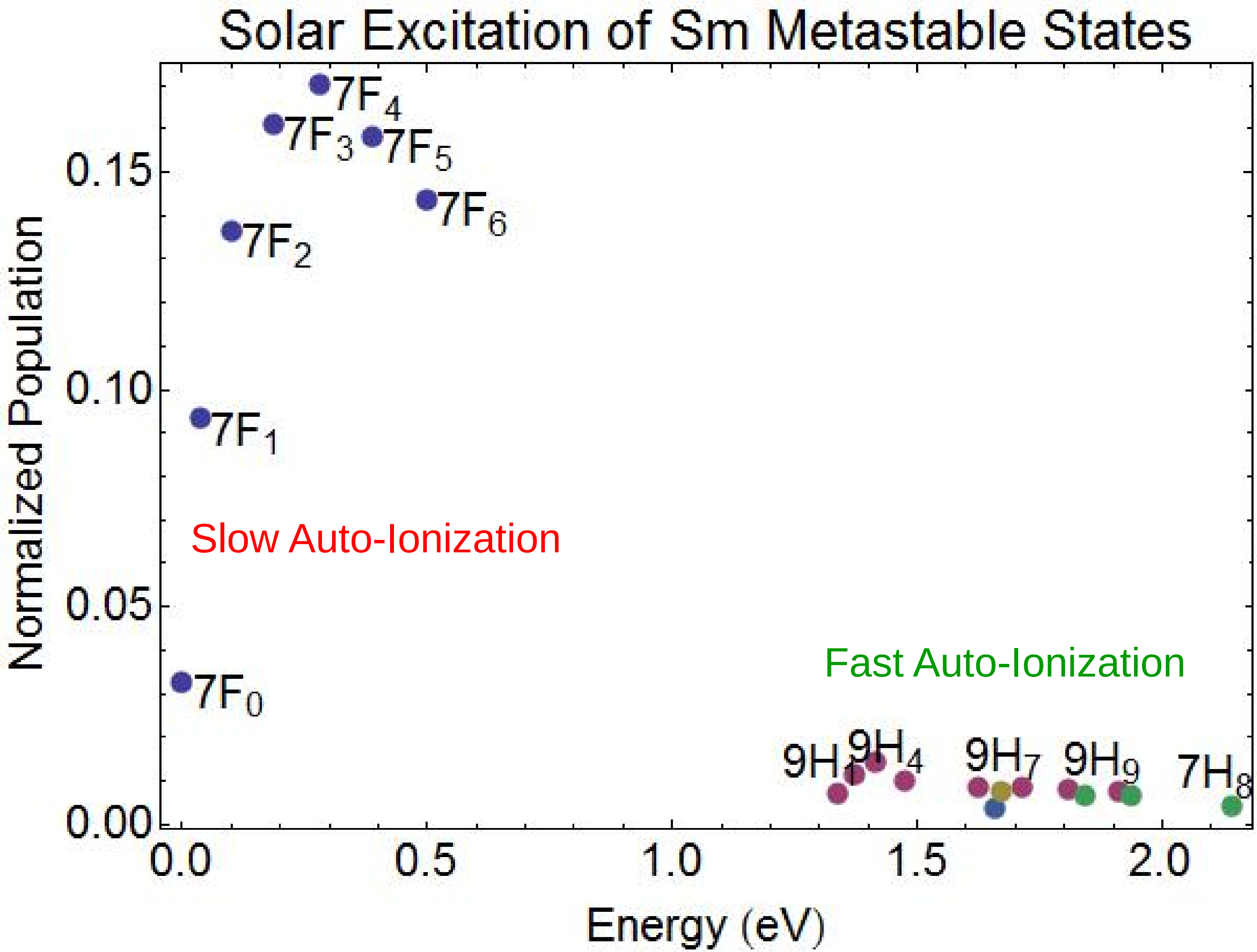
Samarium Photo Chemistry



All Known Samarium Atomic Levels

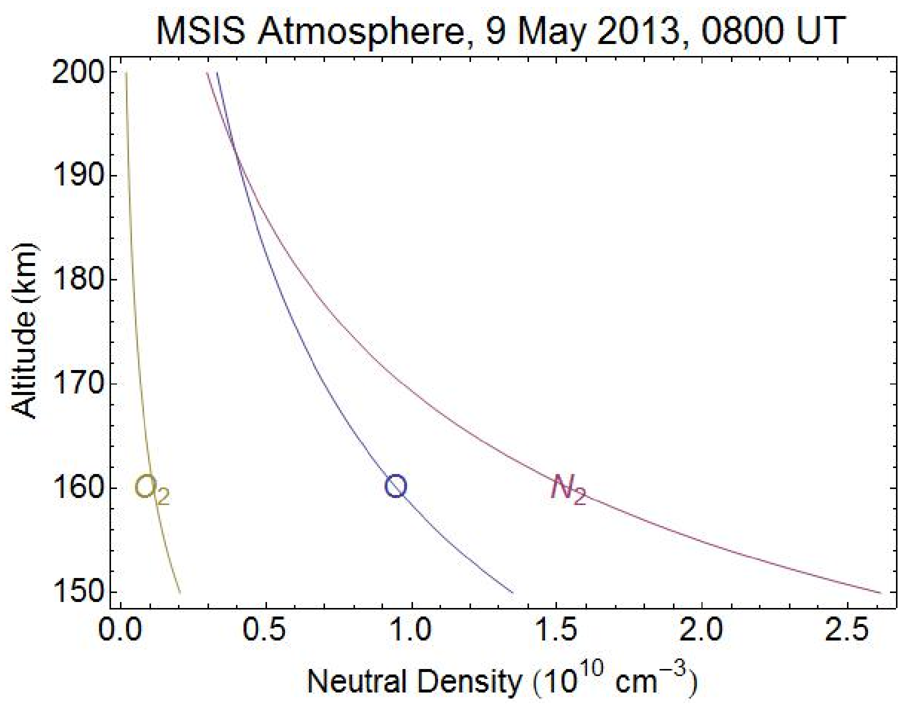


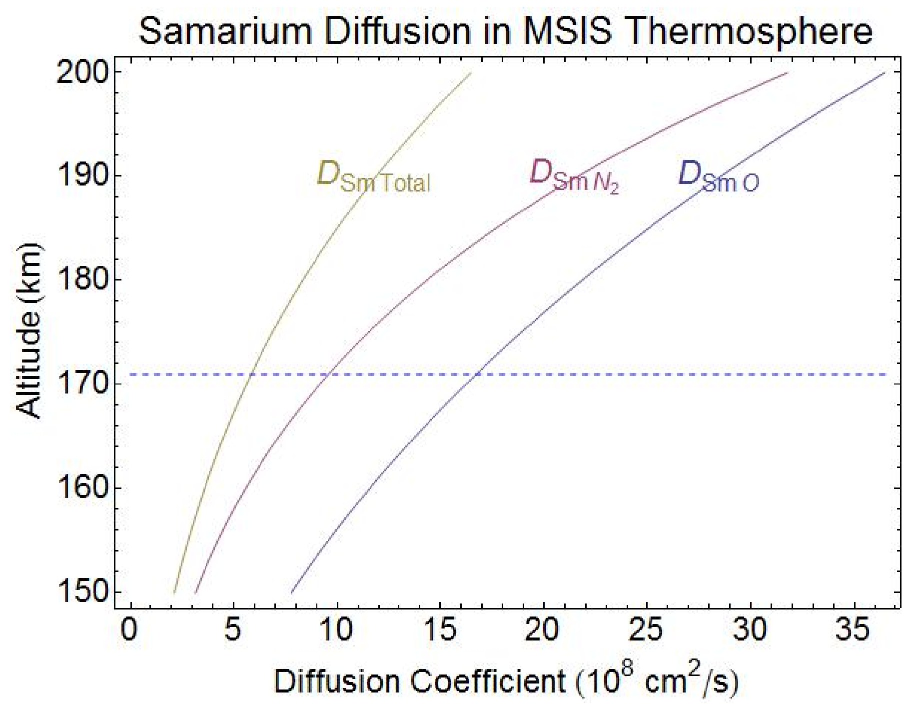
Normalized Equilibrium Populations of the Metastable Levels of Samarium with Direct Solar Illumination with Auto-Ionization Dependence on Energy



Samarium Neutral Diffusion Based on the MSIS Atmosphere for 9 May 2013

$$D_{Sm} = \left(\sum_{j \neq Sm} 1/D_{Smj} \right)^{-1} \text{ where } D_{Smj} = \frac{3}{32\, f r_{Smj}^2 n_j} \left(1 + \frac{m_{Sm}}{m_j} \right)^{1/2} \left(\frac{8kT_{Sm}}{\pi m_{Sm}} \right)^{1/2} \text{ and j = O, } N_2\text{, or } O_2$$





$D_{Sm} = 5.83 \times 10^8\ cm^2/s$ at 171 km Altitude

(Latest) Time Dependent Computation of Sm^+ and SmO^+ Ions for Sm Release in Sunlight and Autoionization Reaction with O

- Solar Photoionization Reaction

$$Sm + h\nu_{Sun} \xrightarrow{\beta_{SmSun}} Sm^+ + e^- \text{ rate: } \beta_{SmSun} = 0.00442\ s^{-1}, \tau_{SmSun} = {k_{SmSun}}^{-1} = 220 \text{ s}$$

- Metastable State Autoionization Reaction for Release at 171 km Altitude

$$Sm^* + O \xrightarrow{k_{Sm+O}} SmO^+ + e^- + \Delta E_\alpha \text{ rate: } k_{Sm+O} = \phi_{SmExo} \overline{\sigma_{Sm+O} \text{v}}$$

$$\phi_{SmExo} = 0.104,\ \sigma_{Sm+O} \approx 5\times10^{-15} cm^2, \text{ v} \approx \sqrt{kT_O / m_O} \approx 718 \text{ m/s for } T_O = 1000K$$

$$k_{Sm+O} \approx 3.73\times10^{-10} \text{ cm}^3\text{/s}, n_O = 6.8\times10^9 \text{cm}^{-3}, \beta_{Sm+O} = k_{Sm+O} n_O = 2.54 \text{ s}^{-1}$$

- Samarium Oxidation* $Sm[\alpha] + O_2 \xrightarrow{k_{Sm+O_2}} SmO + O$

$$k_{Sm+O_2} \approx 5.1\times10^{-10} \text{ cm}^3\text{/s}, n_{O_2} = 6.4\times10^8 \text{cm}^{-3}, \beta_{Sm+O_2} = k_{Sm+O_2} n_{O_2} = 0.32 \text{ s}^{-1}$$

- Dissociative Recombination Reaction

$$SmO^+[^6\Gamma] + e^- \xrightarrow{k_{SmO^+e^-}} Sm[^7F] + O[^3P] \text{ rate: } k_{SmO^+e^-} \approx 10^{-7} \text{ cm}^3 s^{-1}$$

*Note: Sm + O_2 Reaction from M. L. Campbell, Temperature-Dependent Rate Constants for the Reactions of Gas-Phase Lanthanides with O_2, J. Phys. Chem. A, 1999, 103 (36), pp 7274–7279

3D Numerical Model of Sm Release Photochemistry

- Neutral and Ion Equations with Chemical Reactions
  - Neutral Samarium, Samarium Monoxide Ion, Samarium Ion, Samarium Monoxide, Electrons

$$\frac{\partial N_{Sm}}{dt} = \frac{D_1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial N_{Sm}}{\partial R}\right) + D_1\frac{\partial^2 N_{Sm}}{\partial z^2} - \beta_{Sm} N_{Sm} + k_{SmO^+e^-} N_{SmO^+} N_e$$

$$\frac{\partial N_{SmO^+}}{dt} = D_1\frac{\partial^2 N_{SmO^+}}{\partial z^2} + \beta_{Sm+O} N_{Sm} - k_{SmO^+e^-} N_{SmO^+} N_e, \beta_{Sm+O} = k_{Sm+O} n_O$$

$$\frac{\partial N_{Sm^+}}{dt} = D_1\frac{\partial^2 N_{Sm^+}}{\partial z^2} + \beta_{SmSun} N_{Sm}$$

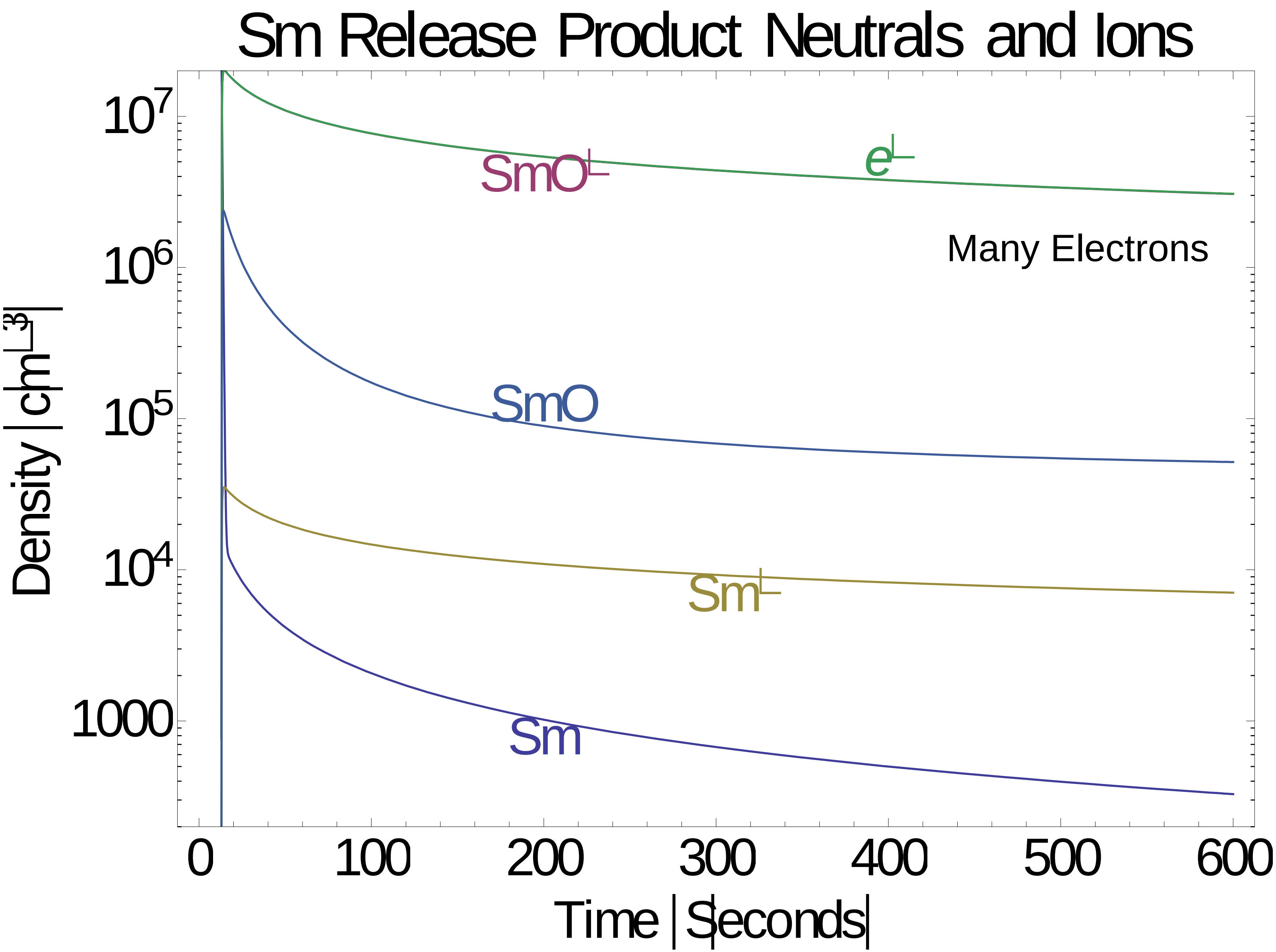
$$\frac{\partial N_{SmO}}{dt} = \frac{D_1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial N_{SmO}}{\partial R}\right) + D_1\frac{\partial^2 N_{SmO}}{\partial z^2} + \beta_{Sm+O_2} N_{Sm}, \beta_{Sm+O_2} = k_{Sm+O_2} n_{O_2}$$

$$N_e = N_{Sm^+} + N_{SmO^+}, \ \beta_{Sm} \equiv \beta_{SmSun} + \beta_{Sm+O} + \beta_{Sm+O_2}$$

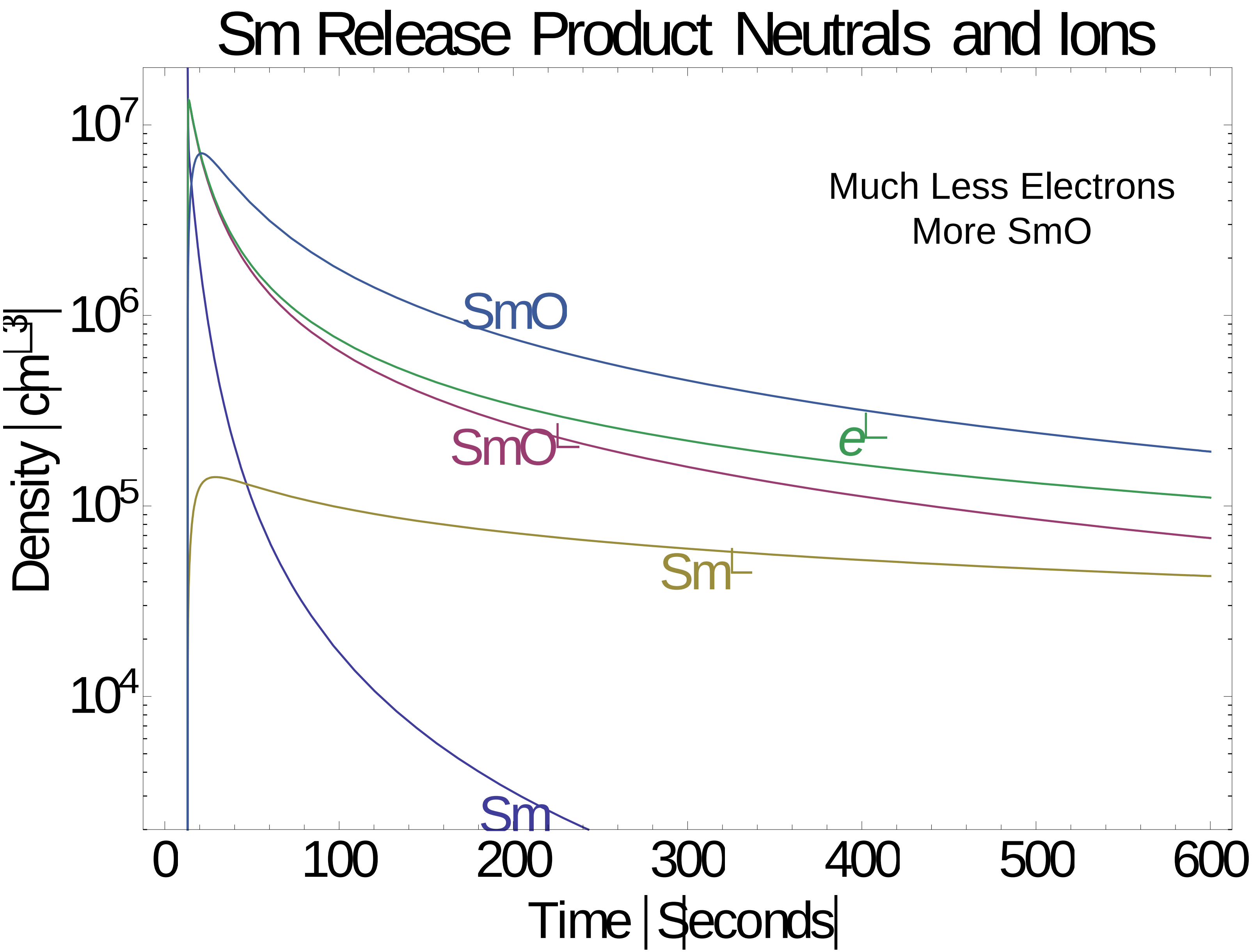
- Cylindrical Coordinates with **z** along **B**
- Numerical Solution by Expanding Boundary Coordinate Transform

Central Cloud Density for

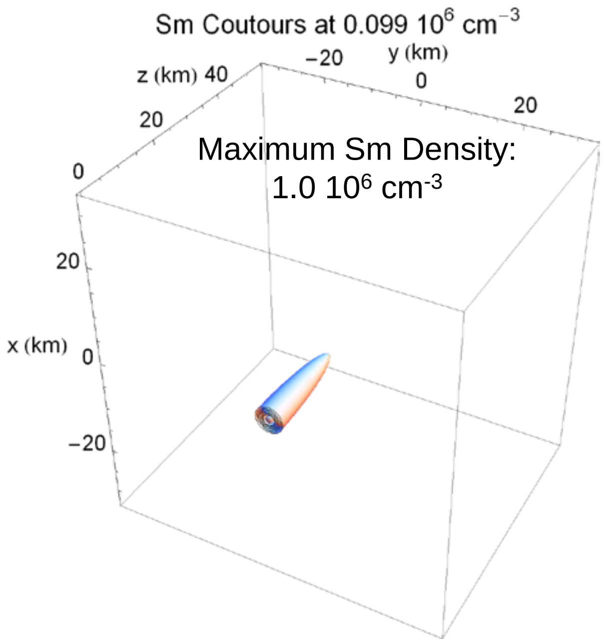
Samarium Release with *No Recombination*

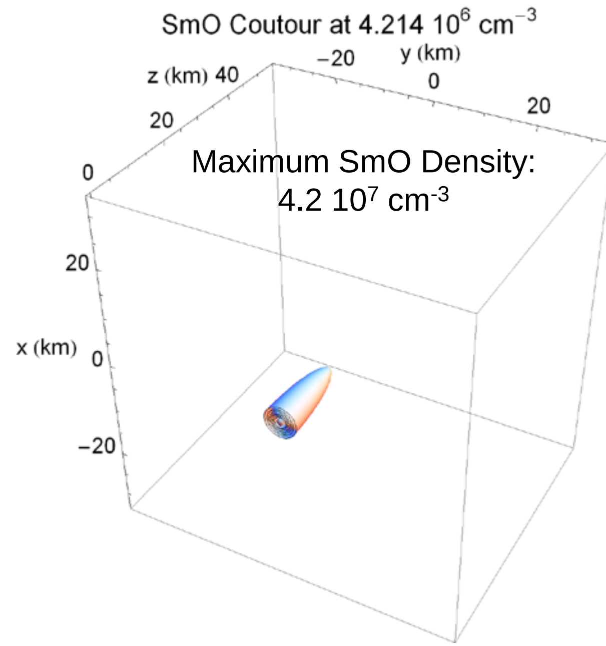


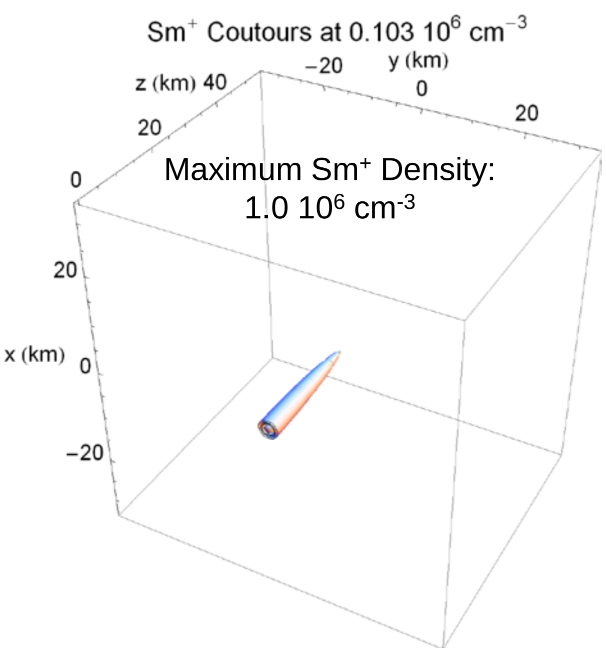
Central Cloud Density for Samarium Release Including *Recombination*

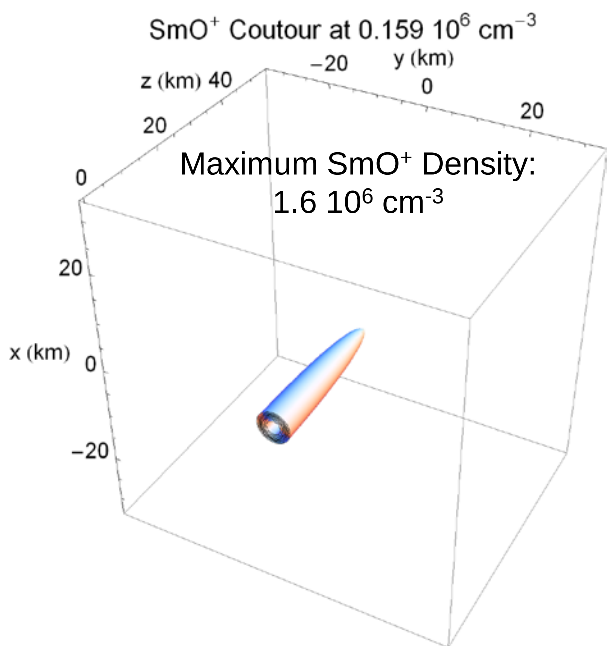


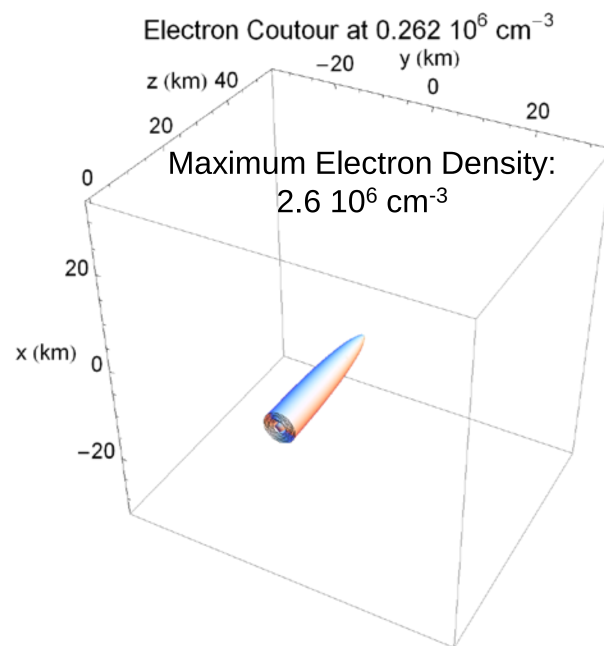
New 3-D Model for Samarium Release at t = 20 s



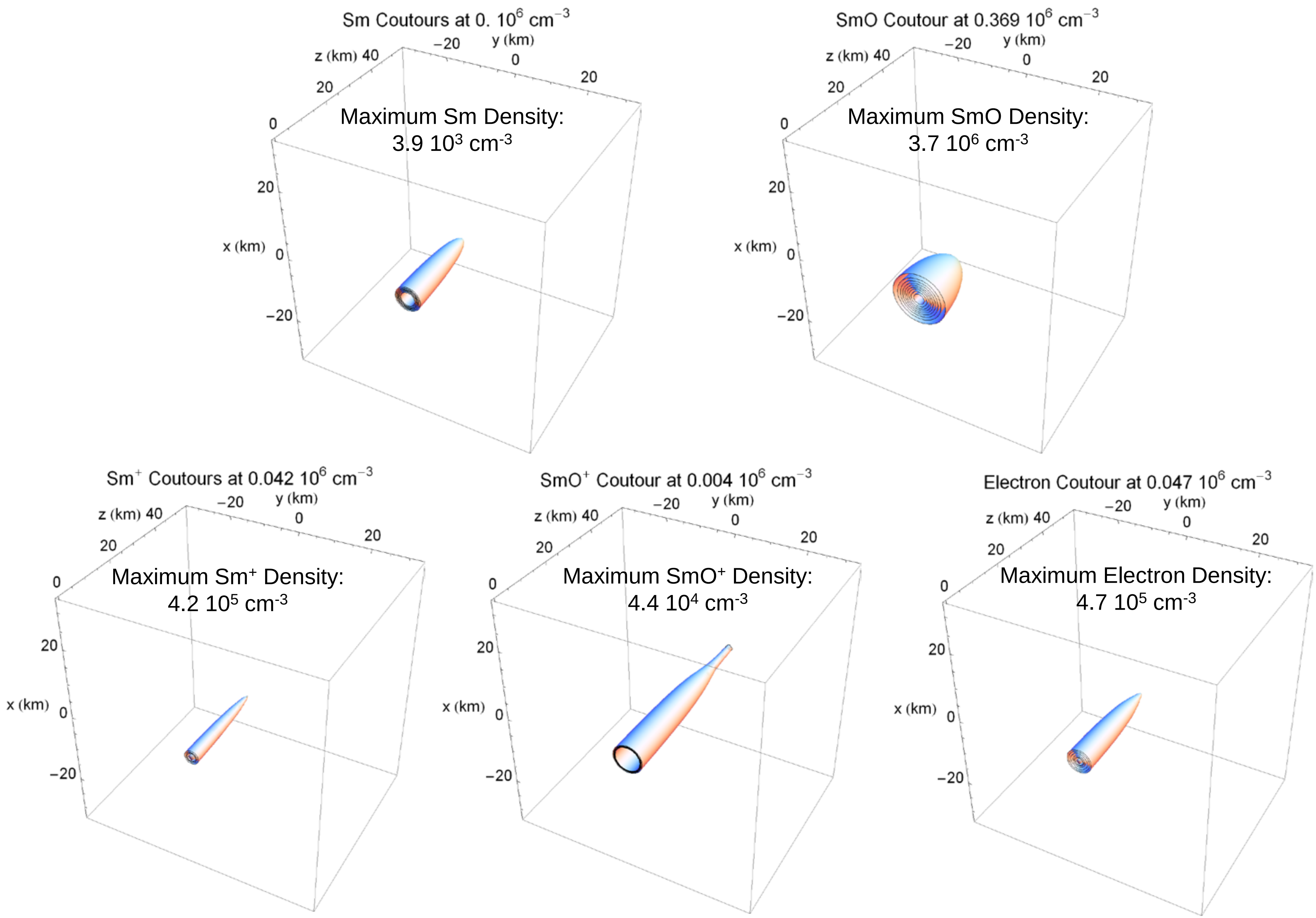




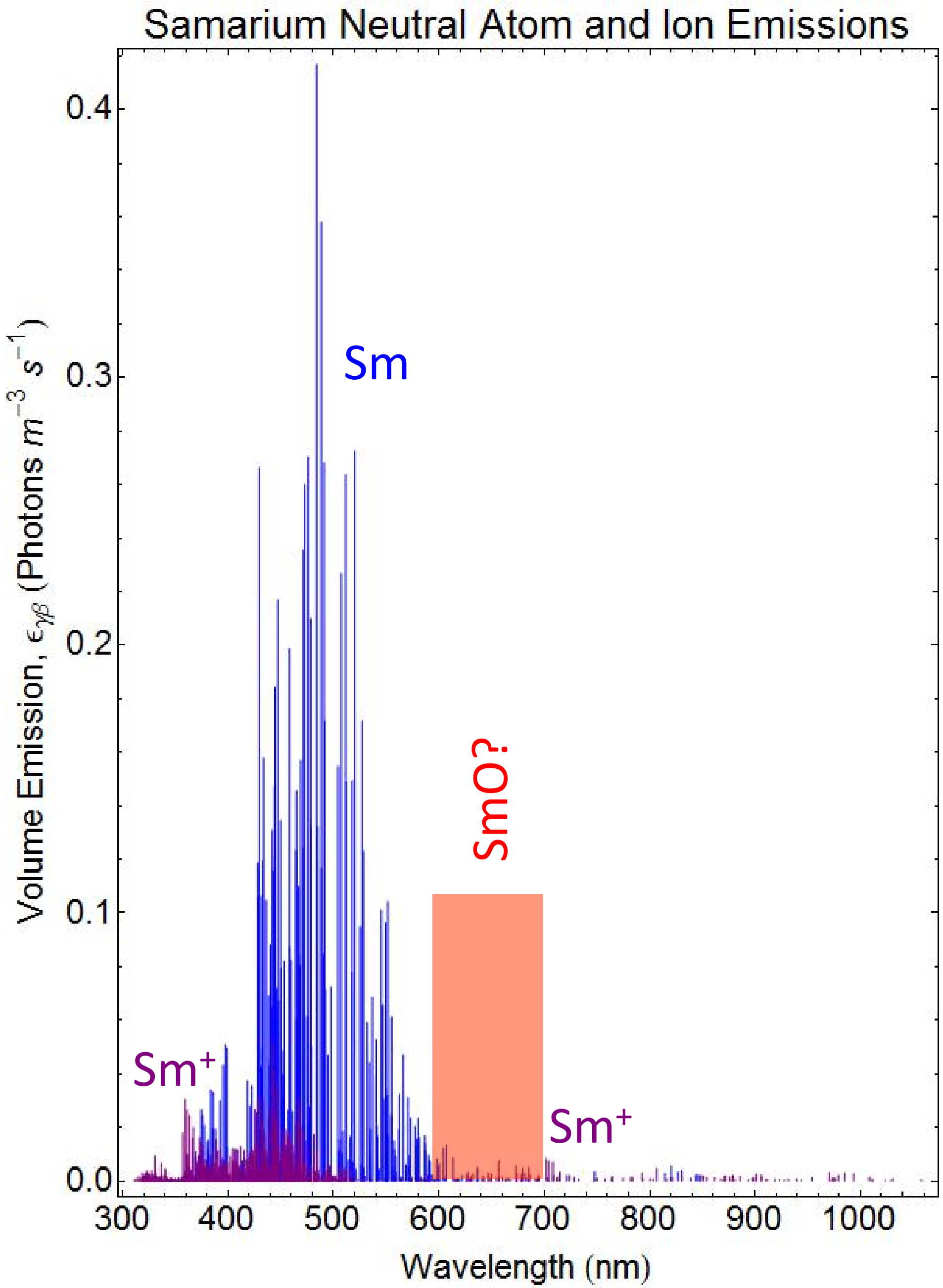


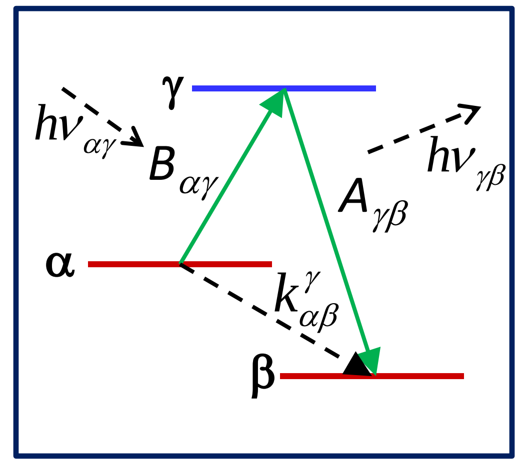


3-D Model for Samarium Release at t = 100 s



Resonance Fluorescence of Samarium Atoms and Atomic Ions

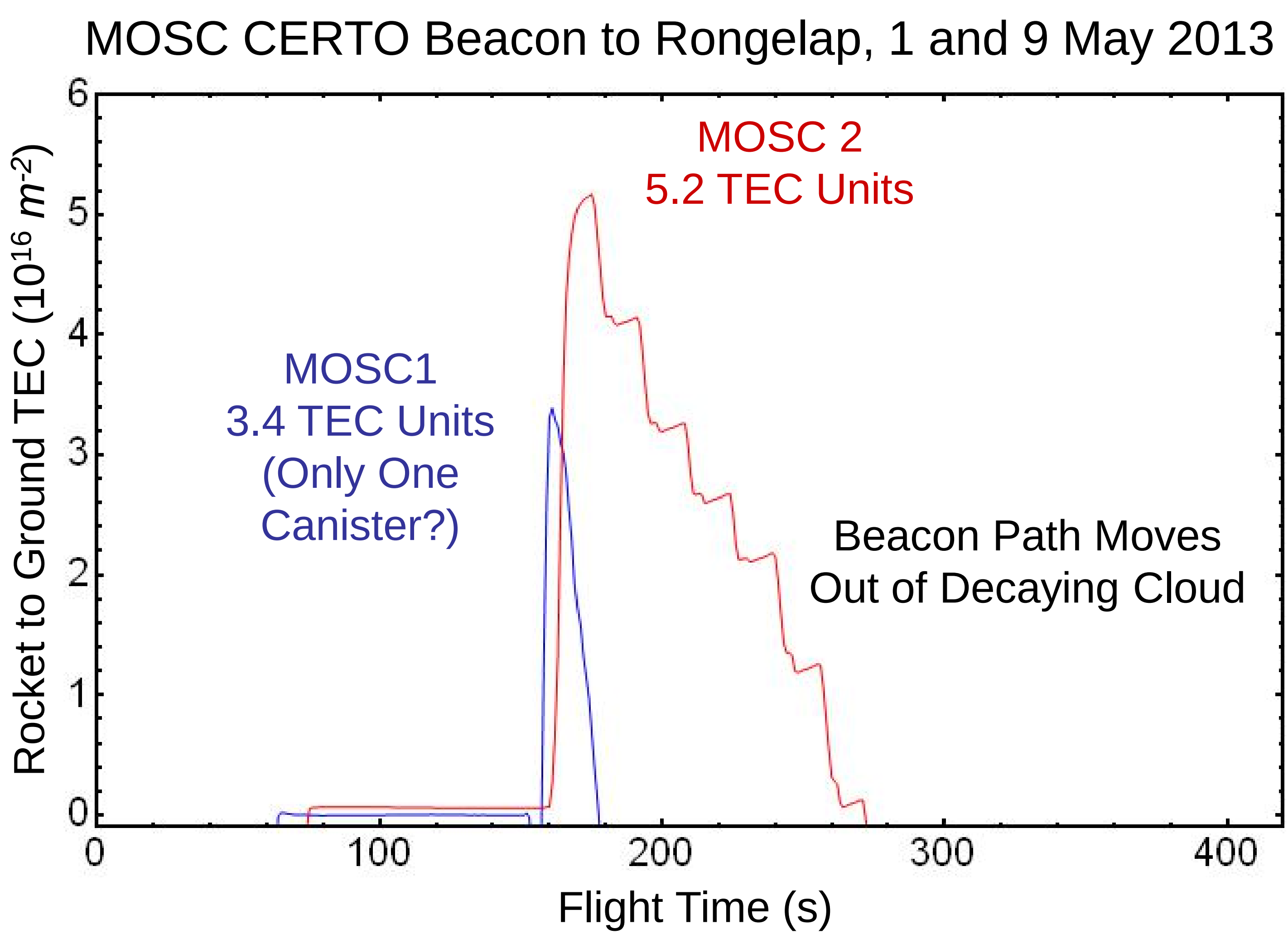




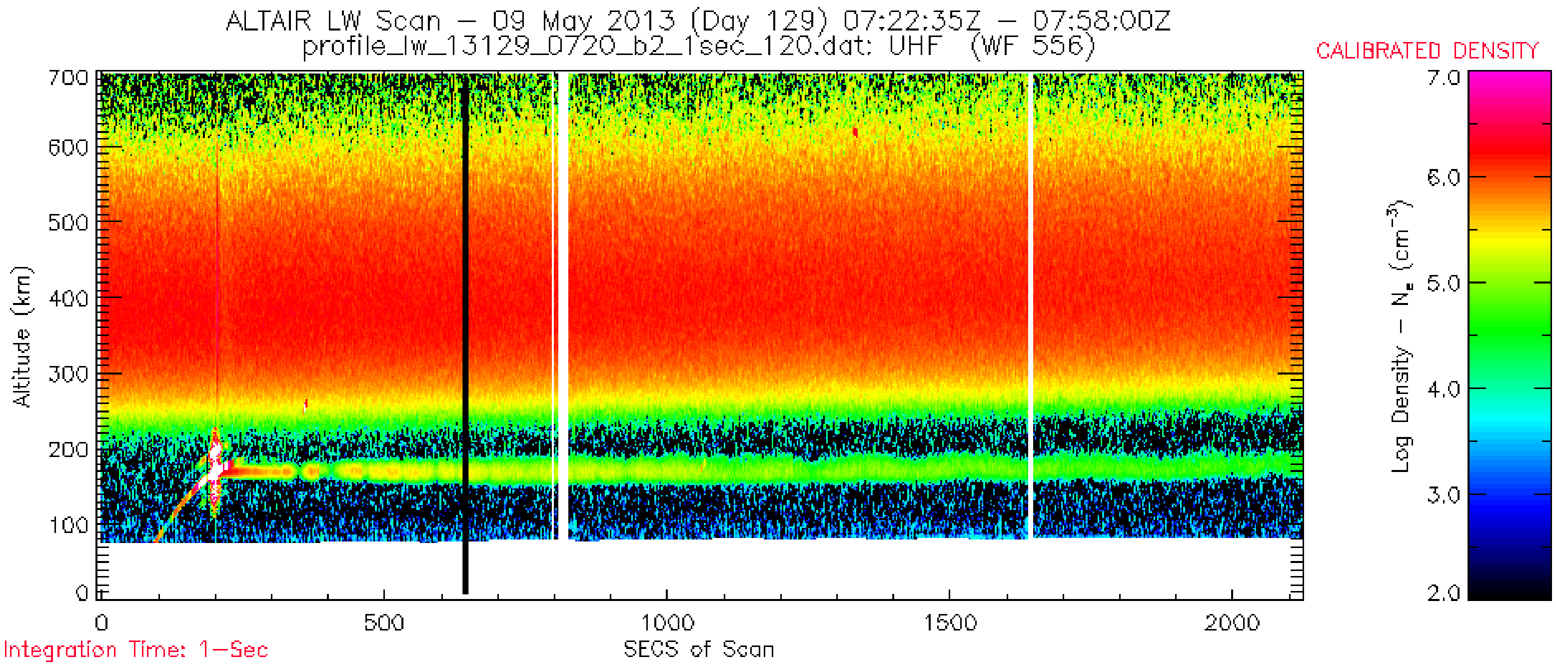
$$4\pi I_{\gamma\beta Sm}(\text{Rayleighs}) = 10^{-10}\int N_{Sm}(s)\varepsilon_{\gamma\beta Sm}ds$$

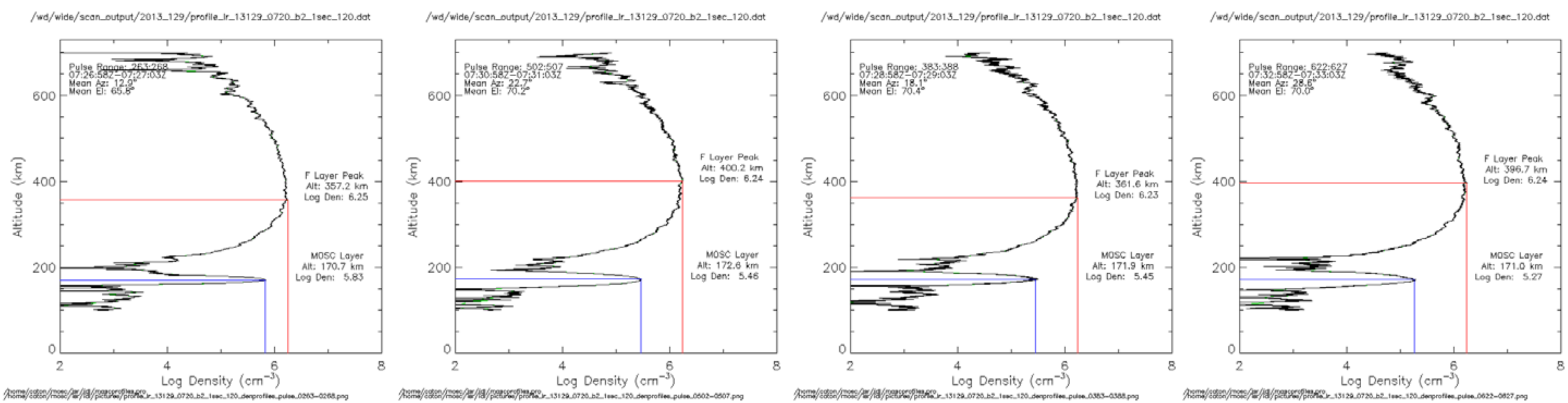
$$4\pi I_{\gamma\beta Sm^+}(Sm^+, \text{Rayleighs}) = 10^{-10}\int N_{Sm^+}(s)\varepsilon_{\gamma\beta Sm^+}ds$$

Estimated Total Electron Content Yield for MOSC Samarium Releases

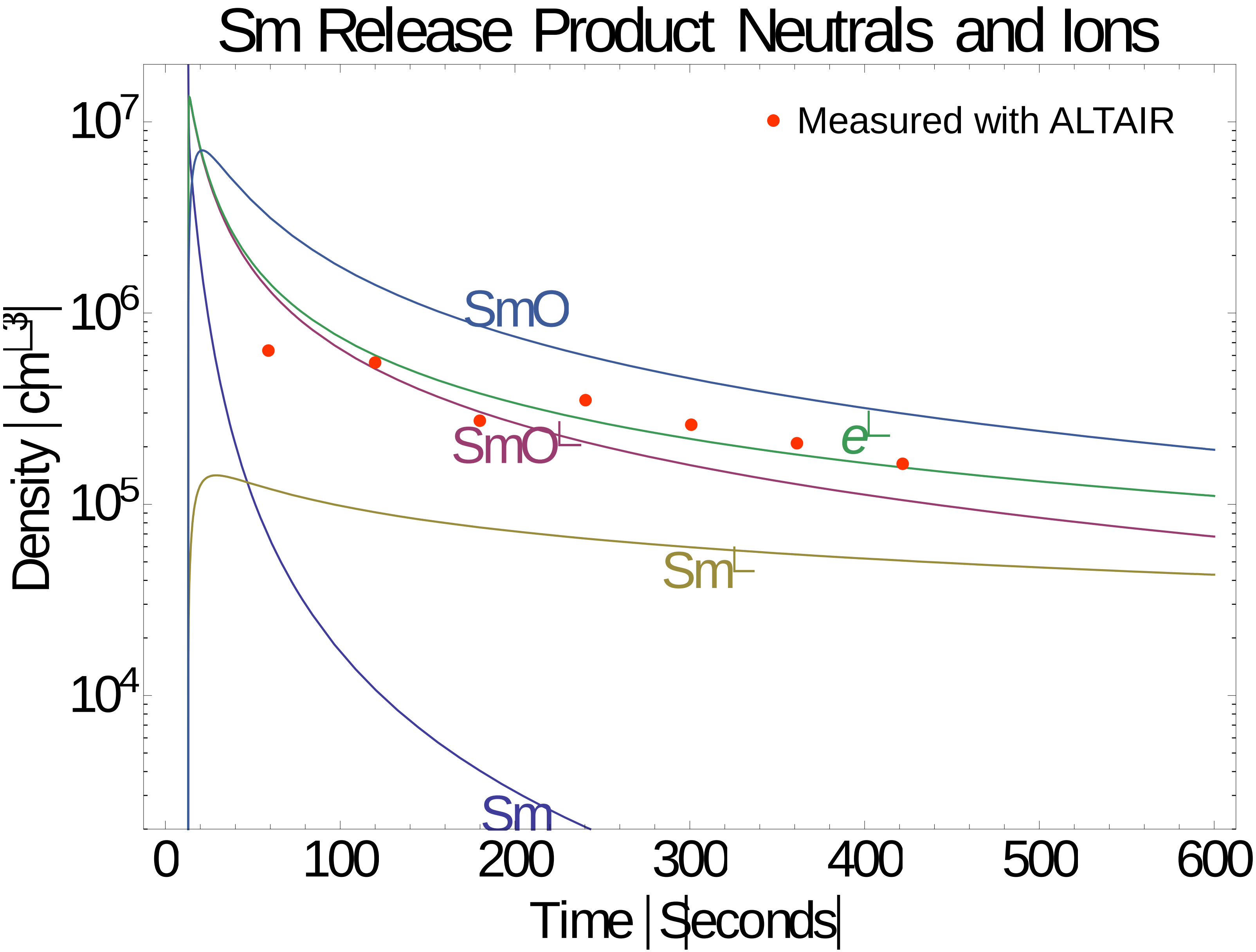


AFRL MOSC Experiment, ALTAIR – Launch 2

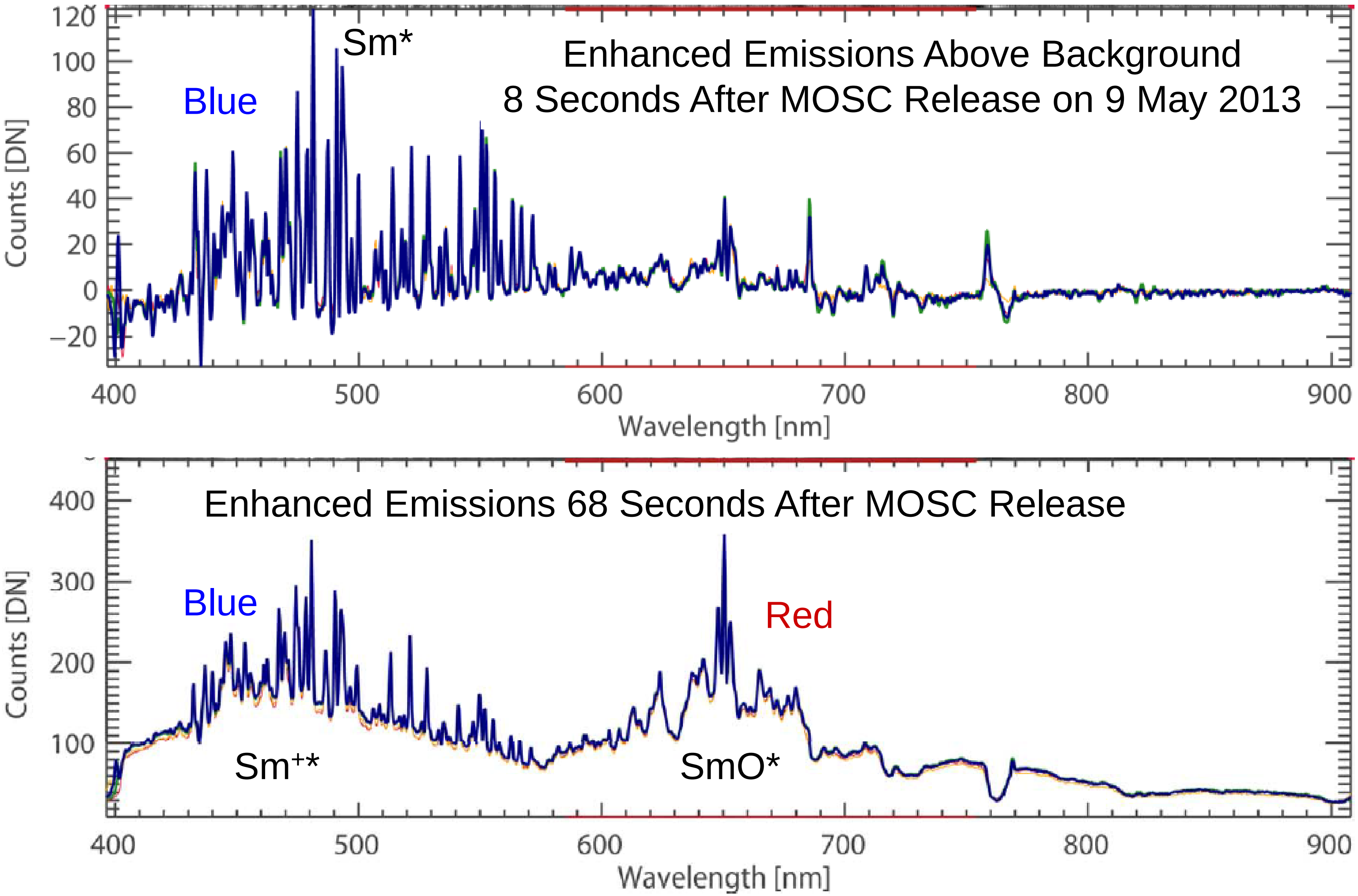




Central Cloud Density for Samarium Release Including *Recombination*



MOSC Optical Spectra
(From Todd Pedersen and Jeff Holmes, AFRL)



Summary on MOSC Samarium Release

- Factors that Control the Ionization from Sm Release in Sunlight
  - Formation Metastable States
    - Photo-ionization
    - Atomic Oxygen Reaction
  - Recombination of Samarium Monoxide Ion (Depletes Electrons)
  - Reaction of Samarium with Diatomic Oxygen (Depletes Samarium)
- Physics Based Modeling of MOSC Sm Release
  - Predictions of Metastable Level Population, (Sm and Sm^+) Optical Spectra
  - Time Dependent Predictions of Ion Compositions and Electron Density
  - Spectral Lines for Sm, Sm+ and SmO
  - Future Work (Model Validation and Prediction for Future Experiments)
    - Compare with Beacon, Radar and Optical Observations
    - Compare with AFRL Empirical Model
    - Compute HF Refraction Off Model Electron Clouds
- Conclusions
  - CRM Model Is Converging on Accurate Solutions
  - MOSC Used Critical Diagnostics
    - Visible Spectrograph Yields Neutral and Ion Composition
    - Incoherent Scatter Radar Yields Long Term Electron Production
    - Radio Beacon Instrument Yields Initial Electron Production
  - $SmO^+ + e^-$ Recombination is Exothermic and Very Reactive
  - Sm + O Reaction is Slightly Exothermic and Very Reactive
  - Sm Release Probably Will Produce Few Ions Without Sunlight