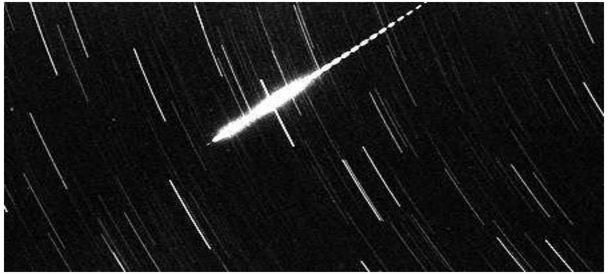
Theory and simulations of meteor head echo

Y. Dimant, M. Oppenheim, G. Sugar, and S. Close (Elshot)
Collaborators: R. Marshall, L. Tarnecki, et al.

BOSTON UNIVERSITY
APL
Stanford University

Jicamarca 60th Anniversary Workshop
Monday, 25 July 2022, 14:00 - 14:15
Lima, Peru



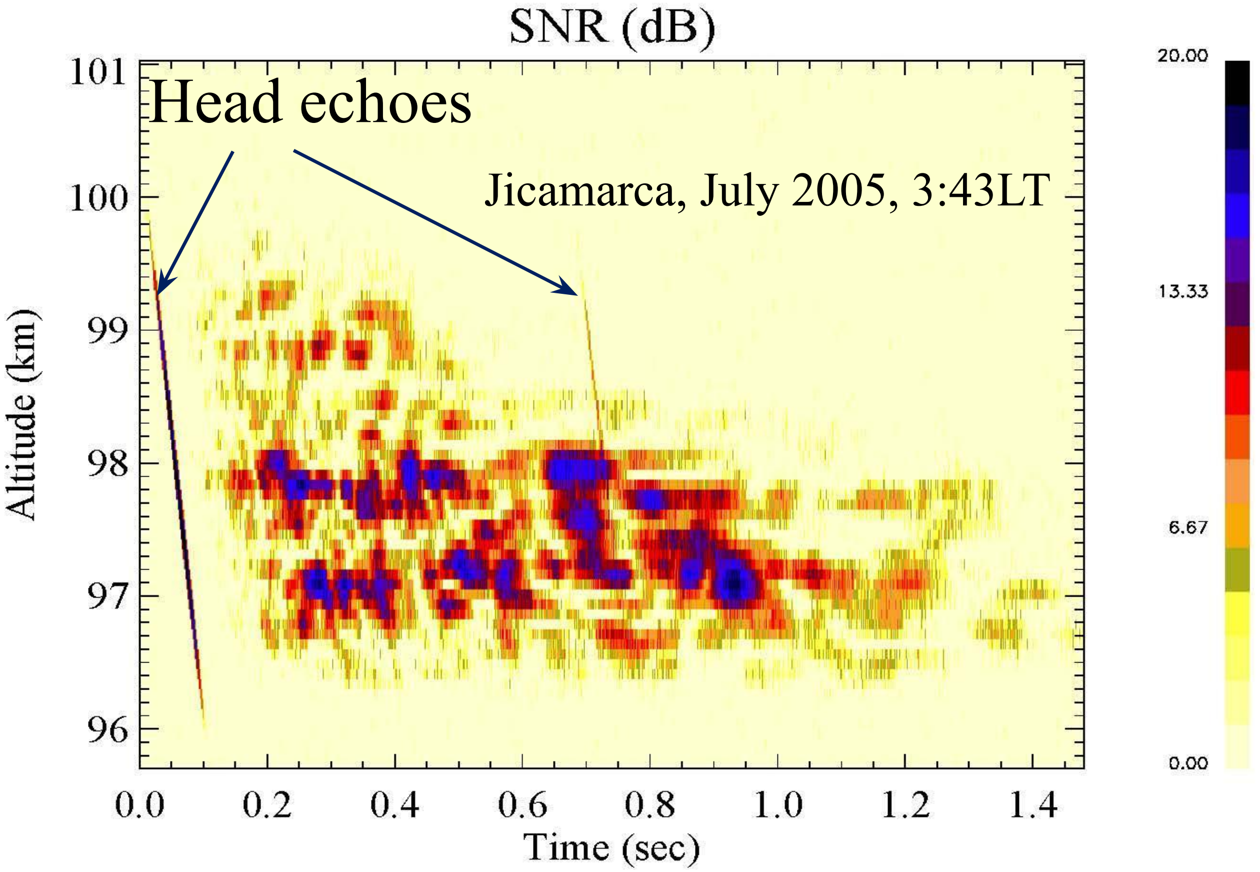
Small-Meteor Trivia

- *Stream* (predictable) and *sporadic* (unpredictable) meteors.
- Meteoroids enter the Earth's atmosphere at *hypersonic speed* (11-73 km/s), burning up below 100 km altitude.
- The origin, mass distribution, composition, and total annual input of meteoroids still remain unknown.
- The majority of small meteoroids cannot be optically detected (if $< 10^{-4}$ g), but sensitive radars may detect them (if $> 10^{-10}$ g).
  - *Due to the meteor plasma formed around and behind the fast-descending meteoroid*

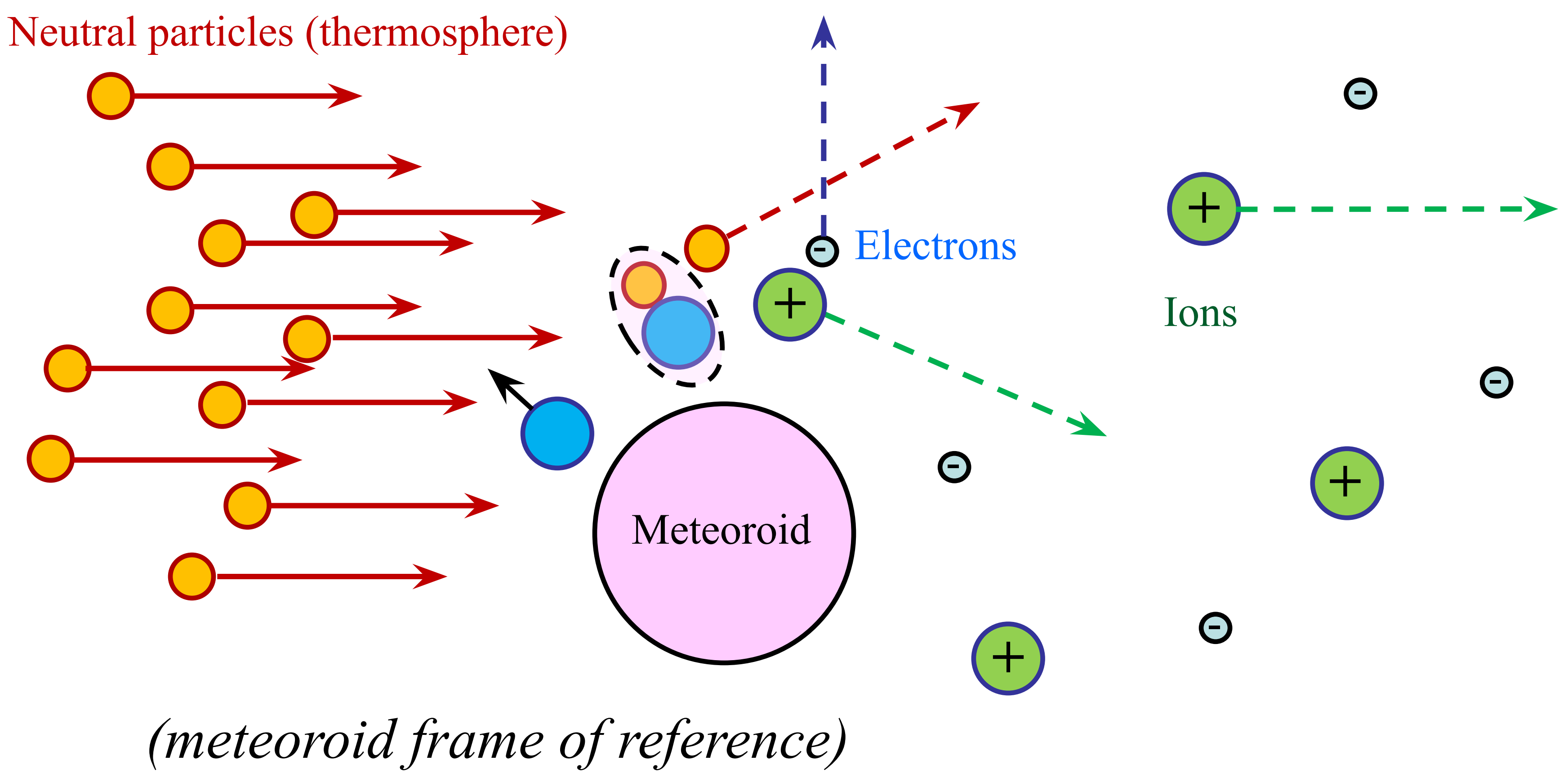
Background

- ***What?*** Dense plasma near fast-descending ablating meteoroids.
- ***Where?*** In the *E*-region ionosphere (90-120 km of altitude: *magnetized electrons + unmagnetized ions*).
- ***Radar observations:*** Head echoes, specular, and non-specular trails.
- ***Questions?*** How is the meteor plasma formed? What are its characteristics?
- ***Why do we care?*** Need to properly interpret radar measurements in order to obtain useful information about meteoroid masses and composition.

Typical Plasma Trail and Head Echoes



Formation of Meteor Plasma



Theory: Goal and Justification

- Spatial structure of near-meteoroid plasma:
    - To model radar head echo

- Need collisional ***kinetic*** theory – for two reasons:
    - Length-scale: ~ one ion-neutral collision mean free path
    - Non-Maxwellian ion velocity distribution.

- Analytical theory of meteor head plasmas provides:
    - Quantitative parameter dependence, scaling
    - The spatial structure for FDTD wave propagation simulations

Scaling: Length and Energy

$$\lambda_{\text{coll}}(h) = \frac{1}{n_{\text{A}}(h)\sigma} = \left(\frac{10^{-15}\,\text{cm}^2}{\sigma}\right)\left(\frac{10^{13}\,\text{cm}^2}{n_{\text{A}}(h)}\right), \text{m}$$

h	80km	90km	100km	110km	120km
	4.3 cm	32 cm	1.3 m	7.1 m	17.2 m

$$r_{\text{met}} \approx 60\mu\text{m}\left(\frac{\text{M}_{\text{met}},\mu\text{g}}{\rho_{\text{met}},\text{g/cm}^{-3}}\right)^{\frac{1}{3}} \qquad r_{\text{met}} \lll \lambda_{\text{coll}}(h) \ll H \sim 10\text{ km},$$

$$\frac{mU^2}{2} \approx 140\text{eV}\left(\frac{m}{30\,\text{amu}}\right)\left(\frac{U}{30\,\text{km/s}}\right)^2, \qquad T_A \approx 0.03\text{eV} \ll T_M \le 1\text{eV} \ll \frac{m_{\text{A}}U^2}{2}$$

Plasma Density Spatial Distribution

$$n = \frac{8\pi n_0 n_{\text{Atm}}}{\sqrt{3}} \frac{R_M^2}{R}\left(1+\frac{m}{m_{\text{Atm}}}\right)\left[\frac{d\sigma}{d\Omega}(U)\right]_{\text{ion}} Q, \qquad Q = f\left|\cos\theta\right| + l\cos\theta + I_1 + I_2,$$

$$f = \frac{1}{R}\sqrt{\frac{2\pi}{3}}\,\text{erf}\left(\sqrt{\frac{3}{2}}\,R^{\frac{1}{3}}\left|\cos\theta\right|^{\frac{1}{3}}\right) - \left[\frac{(4-\pi)\left|\cos\theta\right|}{2\sqrt{1+(4-\pi)^2 R^{2/3}\left|\cos\theta\right|^{2/3}/2\pi}} + \frac{2\left|\cos\theta\right|^{1/3}}{R^{2/3}}\right]\exp\left(-\frac{3R^{2/3}\left|\cos\theta\right|^{2/3}}{2}\right)$$

$$l = \frac{1}{R}\sqrt{\frac{2\pi}{3}}\,\text{erf}\left(\sqrt{\frac{3}{2}}\,R^{\frac{1}{3}}\right) - \left(1+\frac{2}{R^{2/3}}\right)\exp\left(-\frac{3R^{2/3}}{2}\right)$$

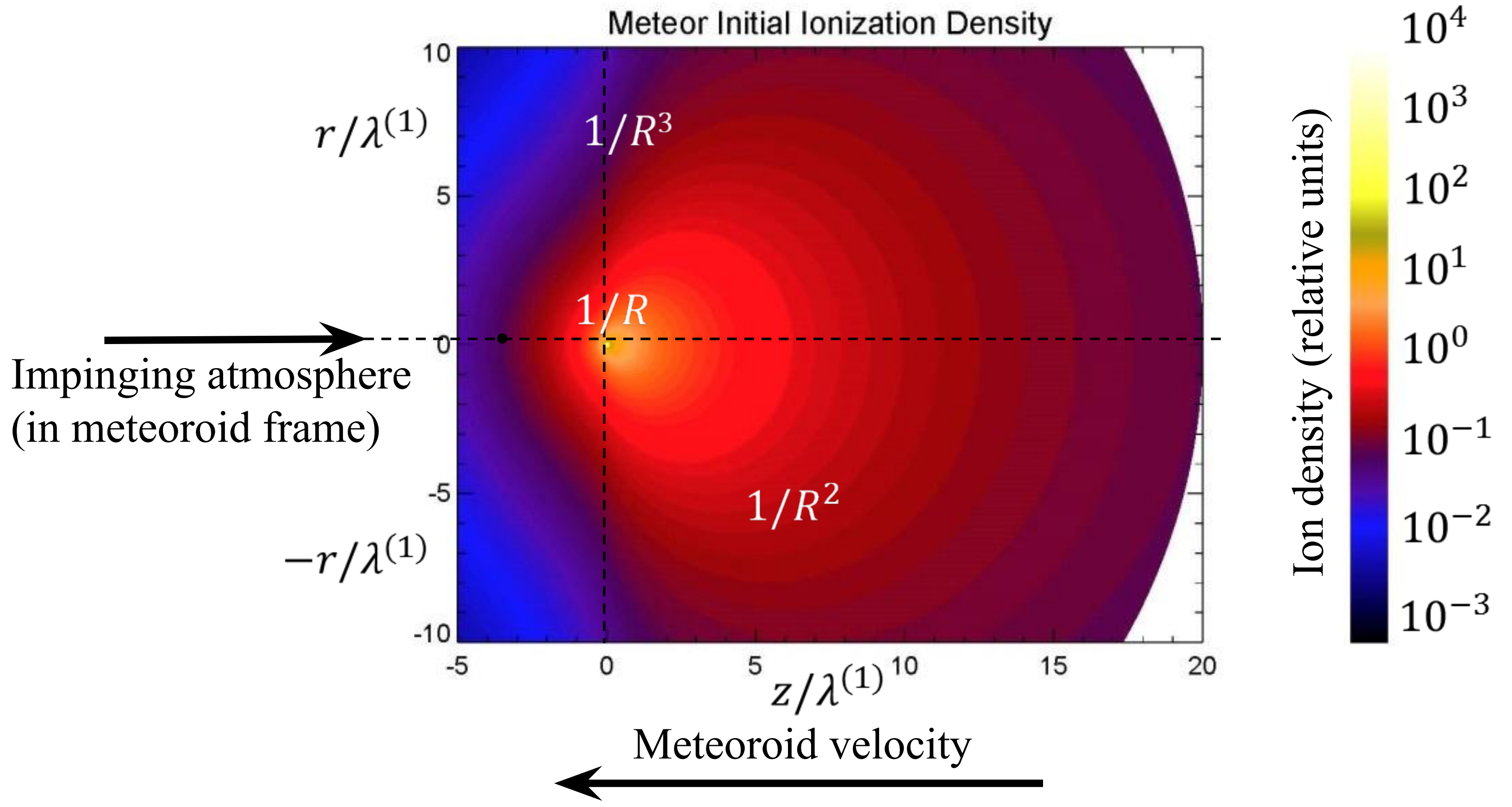
(R is normalized to $\lambda^{(1)}$)

$$I_1 = \int_{\left|\cos\theta\right|}^{1}\sqrt{1+\frac{2R^{2/3}x^{2/3}}{\pi}}\,\exp\left(-\frac{3R^{2/3}x^{2/3}}{2}\right)\sqrt{\frac{x^2-\cos^2\theta}{1-x^2}}\,dx$$

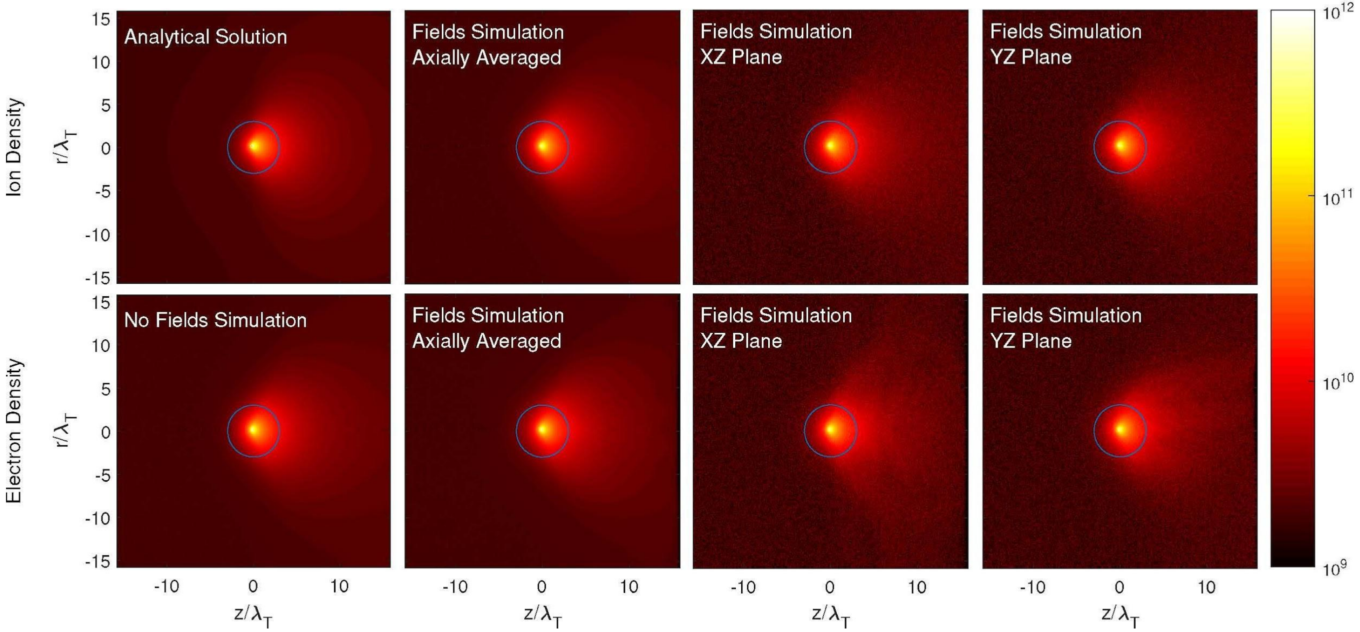
$$\lambda_{\text{coll}} = \frac{1}{n_A\sigma} >> \lambda^{(1)} = \frac{\langle V\rangle}{n_A\sigma U}$$

$$I_2 = \left|\cos\theta\right|\int_{\left|\cos\theta\right|}^{1}\sqrt{1+\frac{2R^{2/3}x^{2/3}}{\pi}}\,\exp\left(-\frac{3R^{2/3}x^{2/3}}{2}\right)\arcsin\frac{\sqrt{1-x^2}\left|\cos\theta\right|}{x\sin\theta}\,dx$$

Ion Density Distribution (Analytic Theory)

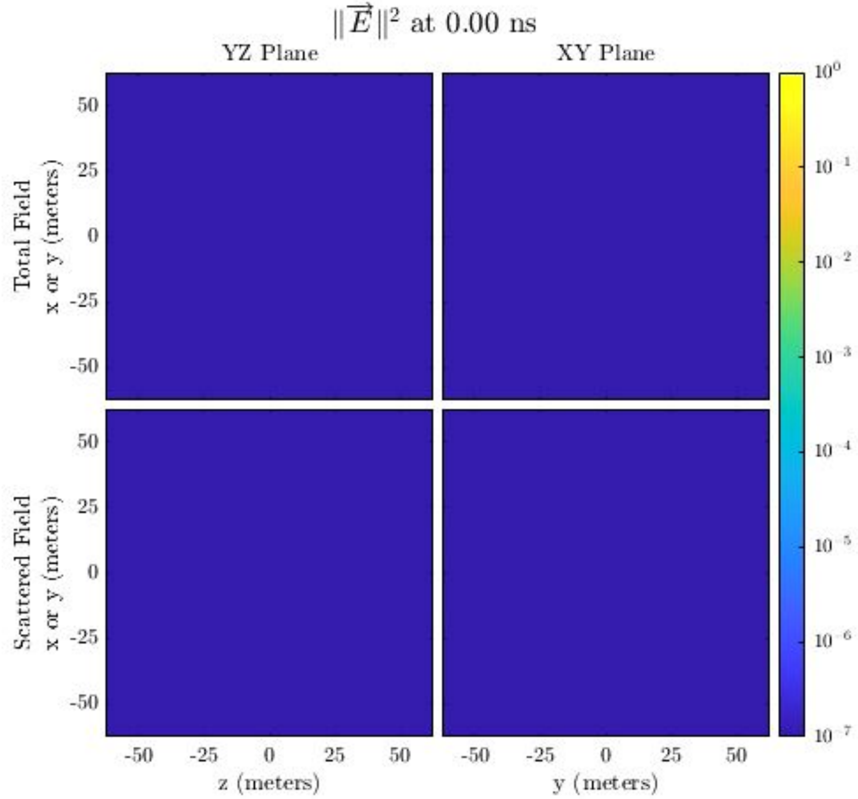


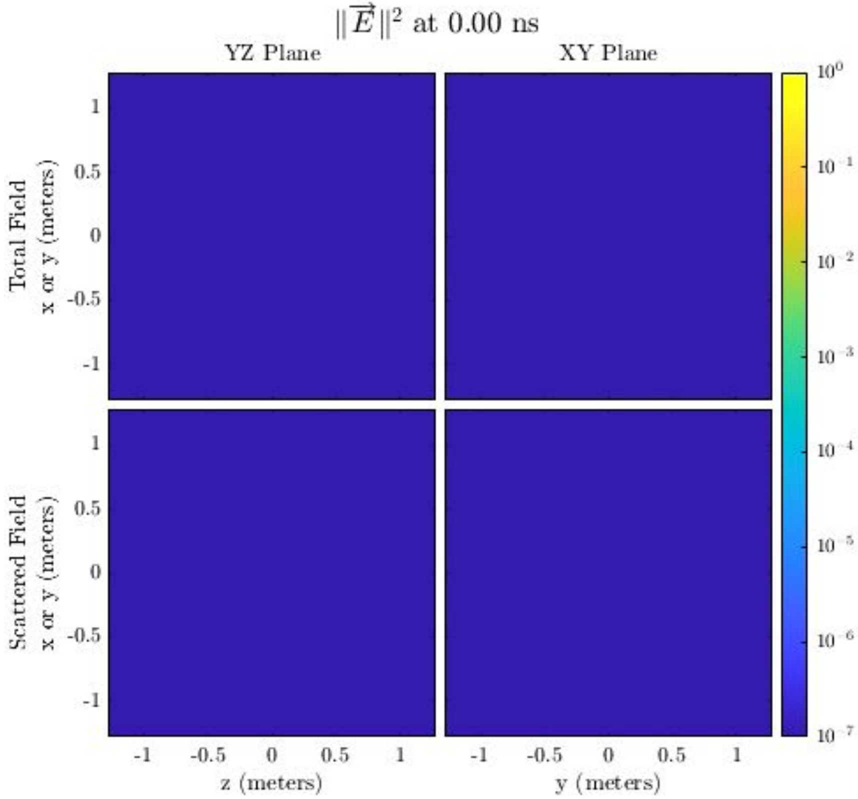
Comparison of Theory and PIC Simulations



(x – along the magnetic field; z – along the meteor path)

FDTD simulations





Recent Publications

Y. Dimant and M. Oppenheim, JGR, **122**, DOI: 10.1002/2017JA023960 (2017)

Y. Dimant and M. Oppenheim, JGR, **122**, DOI: 10.1002/2017JA023963 (2017)

G. Sugar, M. Oppenheim, Y. Dimant, and S. Close, JGR, **123**, DOI: 10.1002/2018JA025265 (2018)

G. Sugar, M. Oppenheim, Y. Dimant, and S. Close, JGR, **124**, DOI: 10.1029/2018JA026434 (2019)

G. Sugar, R. Marshall, M. Oppenheim, Y. Dimant, and S. Close, JGR, **126**, DOI: 10.1029/2021JA029171 (2021)

L. Tarnecki, R. Marshall, G. Stober, and J. Kero, JGR, **126**, DOI: 10.1029/2021JA029525 (2021)

Conclusions

- A first-principle kinetic theory of the dense plasma formed around a fast-descending meteoroid produces an explicit universal analytic expression for the spatial distribution of the plasma density.
- This axially-symmetric distribution changes from $n \sim 1/R$ at short distances mostly to $n \sim 1/R^2$ at longer distances from the meteoroid center, with varying anisotropy.
- EPPIC simulations of the head-echo plasma support the analytic theory.
- Recent simulations of the radar cross sections suggest the $n \sim 1/R^2$ distribution as the closest one to CMOR radar (Canada) observations.
- FDTD simulations based on plasma structure from theory and PIC simulations have already been started; first results have been published. To be continued!

Analytic theory

- First-principle physics based on collisional kinetic theory:
  - Quasi-stationary plasma velocity distribution in the meteoroid frame
  - Local atmospheric background and given meteoroid ablation
- Major assumptions (based on the actual physical conditions):
  - Collisions of the ablated particles and meteor plasma only with the undisturbed distribution of atmospheric molecules (N_2, O_2)
  - Large Knudsen number: $\lambda_{\text{coll}} \gg r_M$
  - Electrons are magnetized, ions are unmagnetized; quasi-neutrality
  - Electric and magnetic fields only weakly affect the ion motion
  - The hypersonic meteoroid speed $U \gg V_{\text{abl}} \sim (T_{\text{abl}}/m_{\text{abl}})^{1/2}$
  - Meteor head plasma is formed by particles ionized after a first collision
  - Inelastic losses are small compared to the particle kinetic energies
- Major result: universal spatial distribution of the meteor head plasma scaled to the local collisional mean free path