Interfacing Cloud and Plume Models with the **Fra**ctal **M**odel of **E**lectrical **D**ischarges (FraMED)

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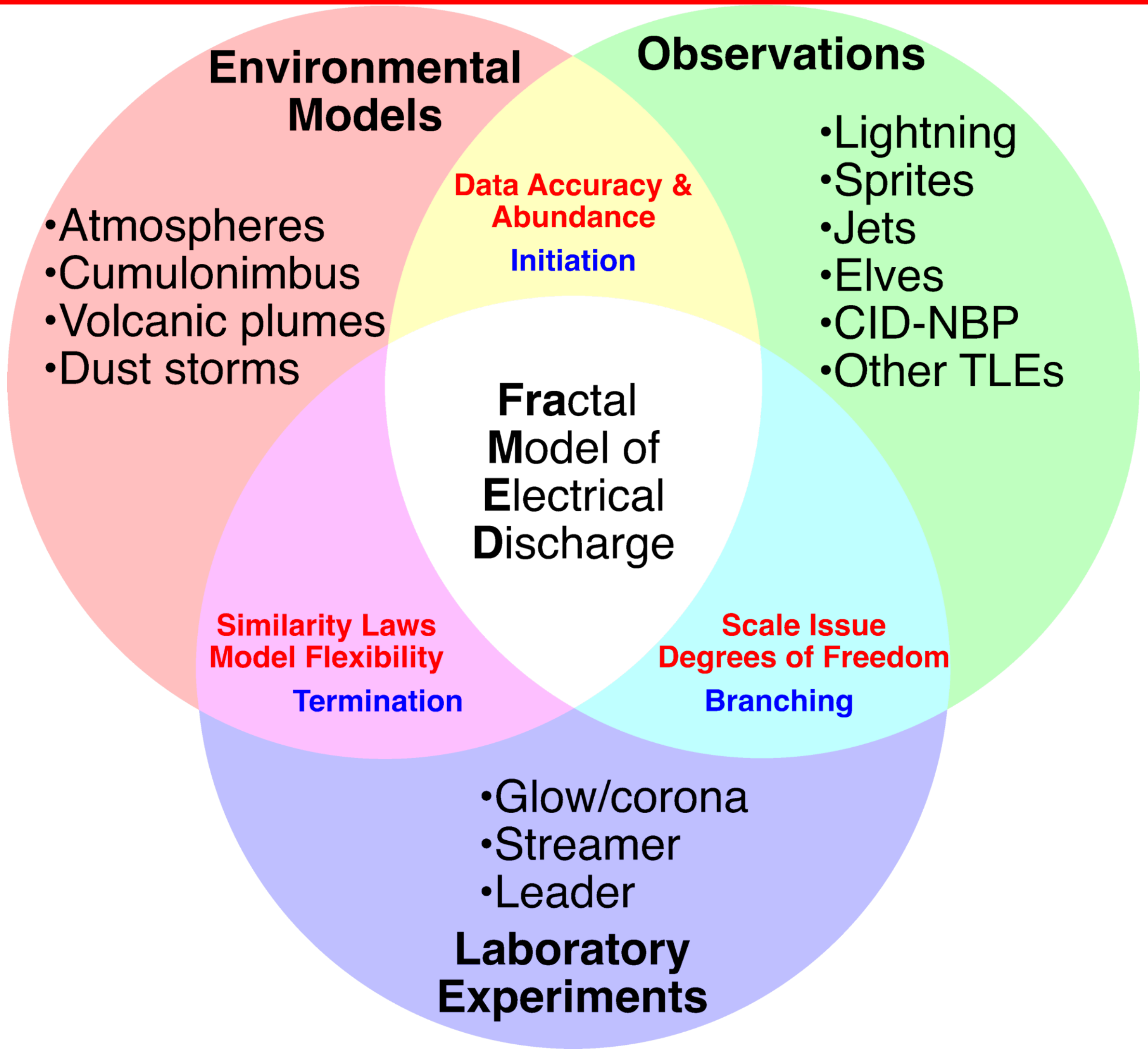
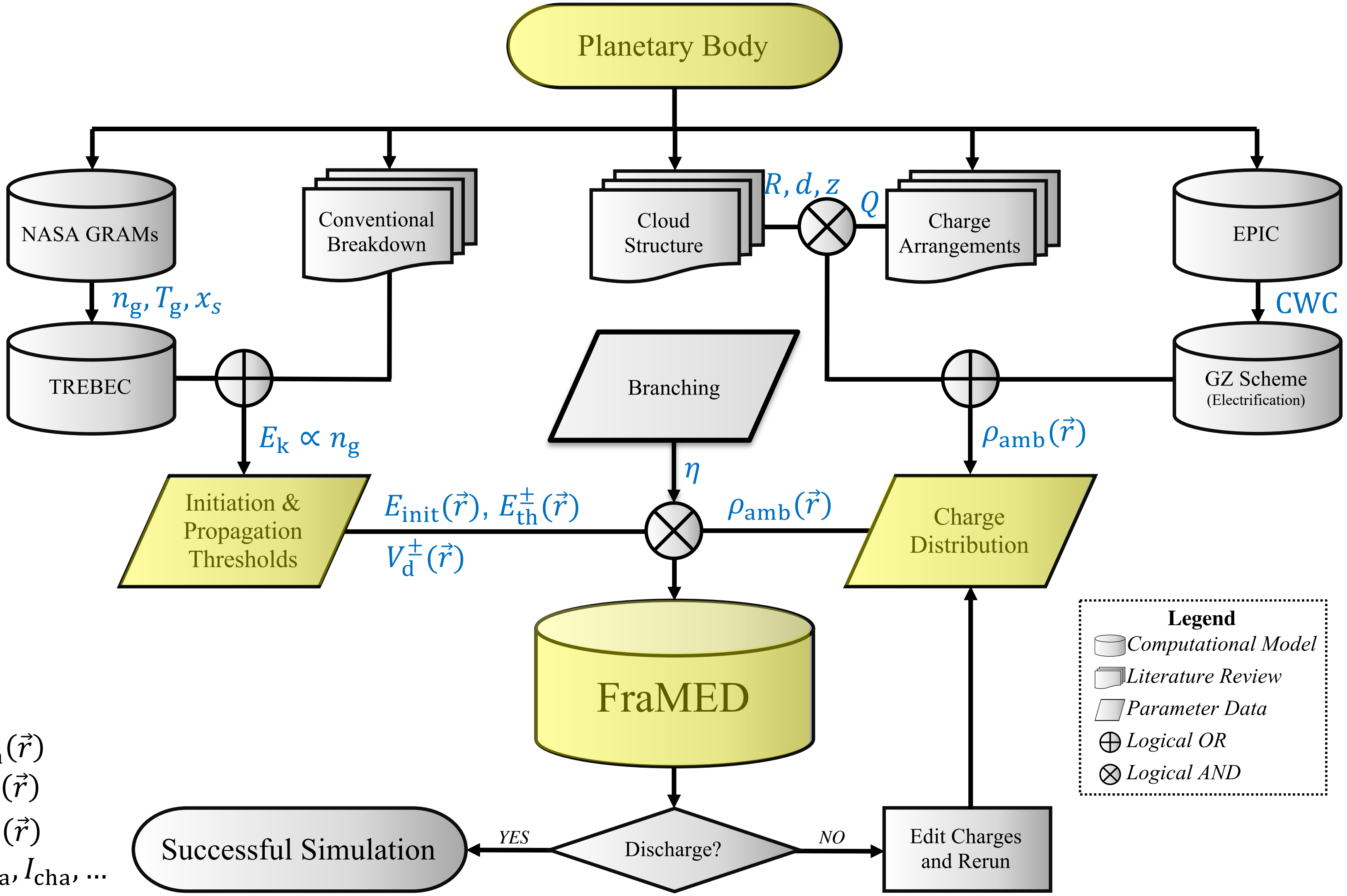
Venn View



Environmental Models
•Atmospheres
•Cumulonimbus
•Volcanic plumes
•Dust storms
Observations
•Lightning
•Sprites
•Jets
•Elves
•CID-NBP
•Other TLEs
Data Accuracy & Abundance
Initiation
Fractal Model of Electrical Discharge
Similarity Laws
Model Flexibility
Termination
Scale Issue
Degrees of Freedom
Branching
•Glow/corona
•Streamer
•Leader
Laboratory Experiments

Model Interoperability: Inputs



Output

- $\varphi_{amb,cha}(\vec{r})$
- $\rho_{amb,cha}(\vec{r})$
- $\vec{E}_{amb,cha}(\vec{r})$
- $Q_{cha}, l_{cha}, I_{cha}, \ldots$

Physical Approach: FraMED

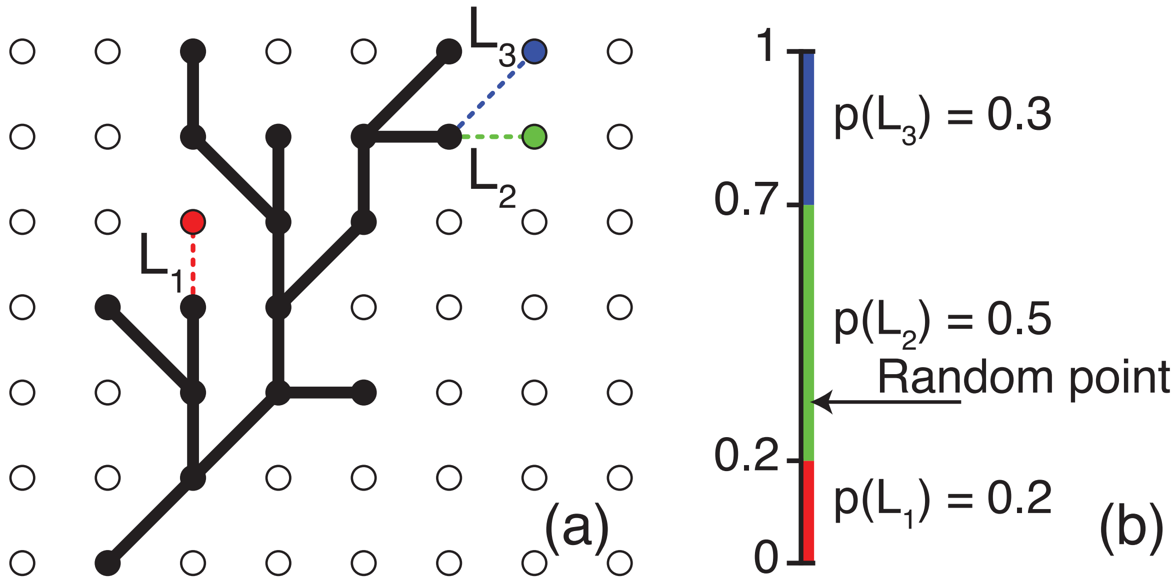
- What physics are implemented in this model component?

Hypothesis	Advantage	Outstanding questions/Limitations	Community Interface
Stochasticity	• Macroscale/Speed • CG/IC/Jet behavior	• No microphysics • Fractal dimension	• LMA/optical data • Chemical models
Electric neutrality	• Physically sound	• Ground connection • Computationally expensive	• Similarity laws • Propagation thresholds
Equipotentiality + Voltage drop	• Flexibility • Lightning/Sprite/TLE	• Streamer-leader transition	• Streamer zone model • Jet "jump" model
A posteriori time-estimate	• Max/min duration • Currents	• "Causality" interpretation • Radiation pattern	• Spherics data/model • E-M spectrum

Methods: **Fr**actal **M**odel of **E**lectrostatic **D**ischarges

Link depiction: [20] Riousset (2010); *More info on FraMED:* [19] Riousset et al. (2007), [21] Esparza (2022); *Table data:* [26] Janalizadeh & Pasko (2023)

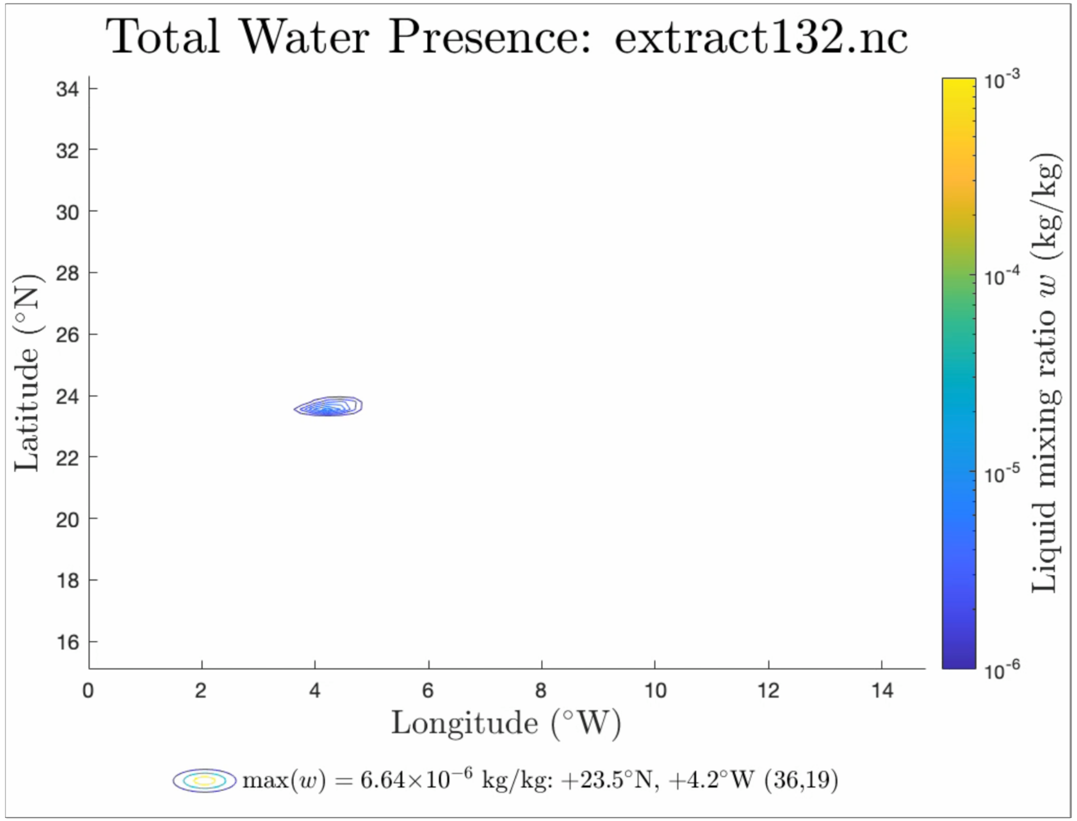
$$p(L_i) = \frac{\left|E_i - E_{\mathrm{th}}^{\pm}\right|^{\eta}}{\sum_j \left|E_j - E_{\mathrm{th}}^{\pm}\right|^{\eta}}$$



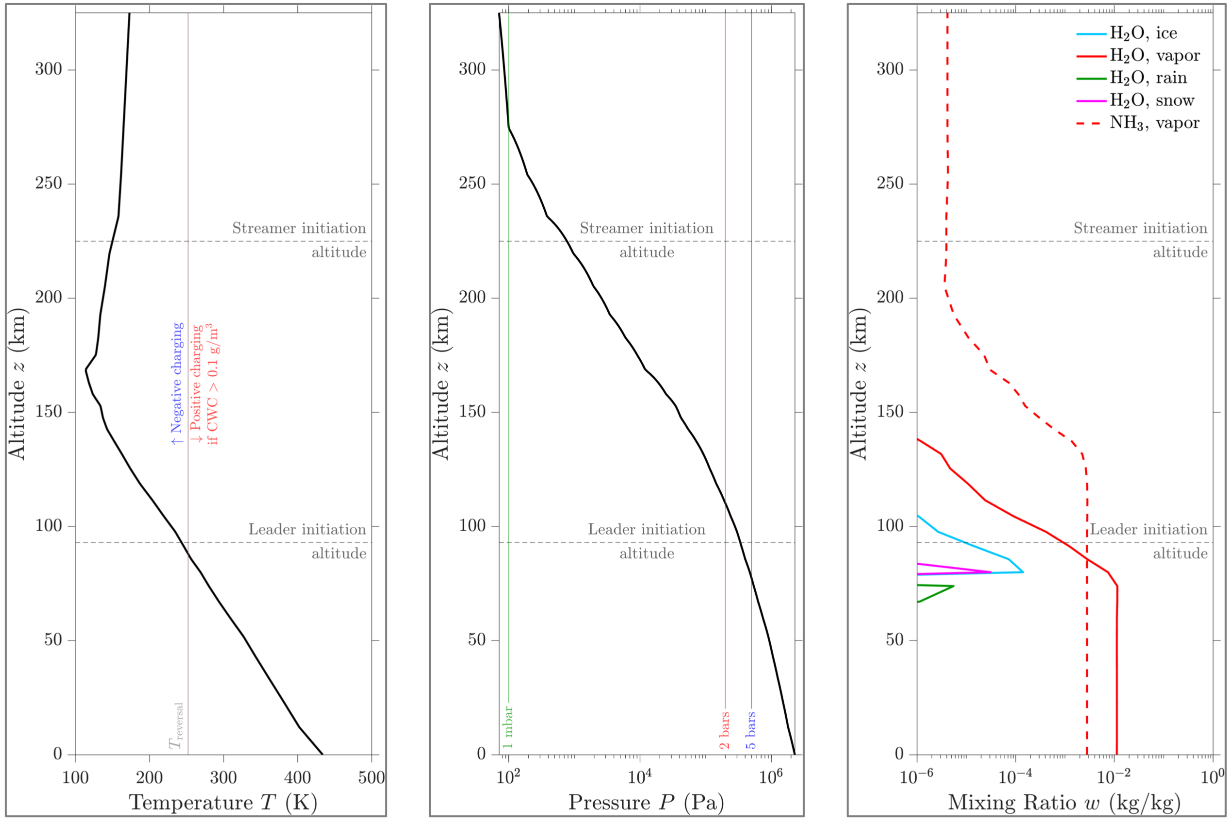
	Leader	Streamer
$\boldsymbol{E}_{\mathbf{k}}$	Literature + TREBEC	
$\boldsymbol{E}_{\mathbf{init}}$	$\pm\frac{1}{10}E_{\mathrm{k}}$	$\pm 1.5E_{\mathrm{k}}$
$\boldsymbol{E}_{\mathbf{prop}}$	$\pm\frac{1}{20}E_{\mathrm{k}}$	$-\frac{1}{3}E_{\mathrm{k}}$ or $+\frac{1}{6}E_{\mathrm{k}}$
$\boldsymbol{V}_{\mathbf{d}}$	0	E_{prop}
$\boldsymbol{\rho}_{\mathbf{amb}}$	Literature + EPIC & GZ Scheme	

Methods: Explicit Planetary Isentropic-Coordinate

Visualize atmospheric water content



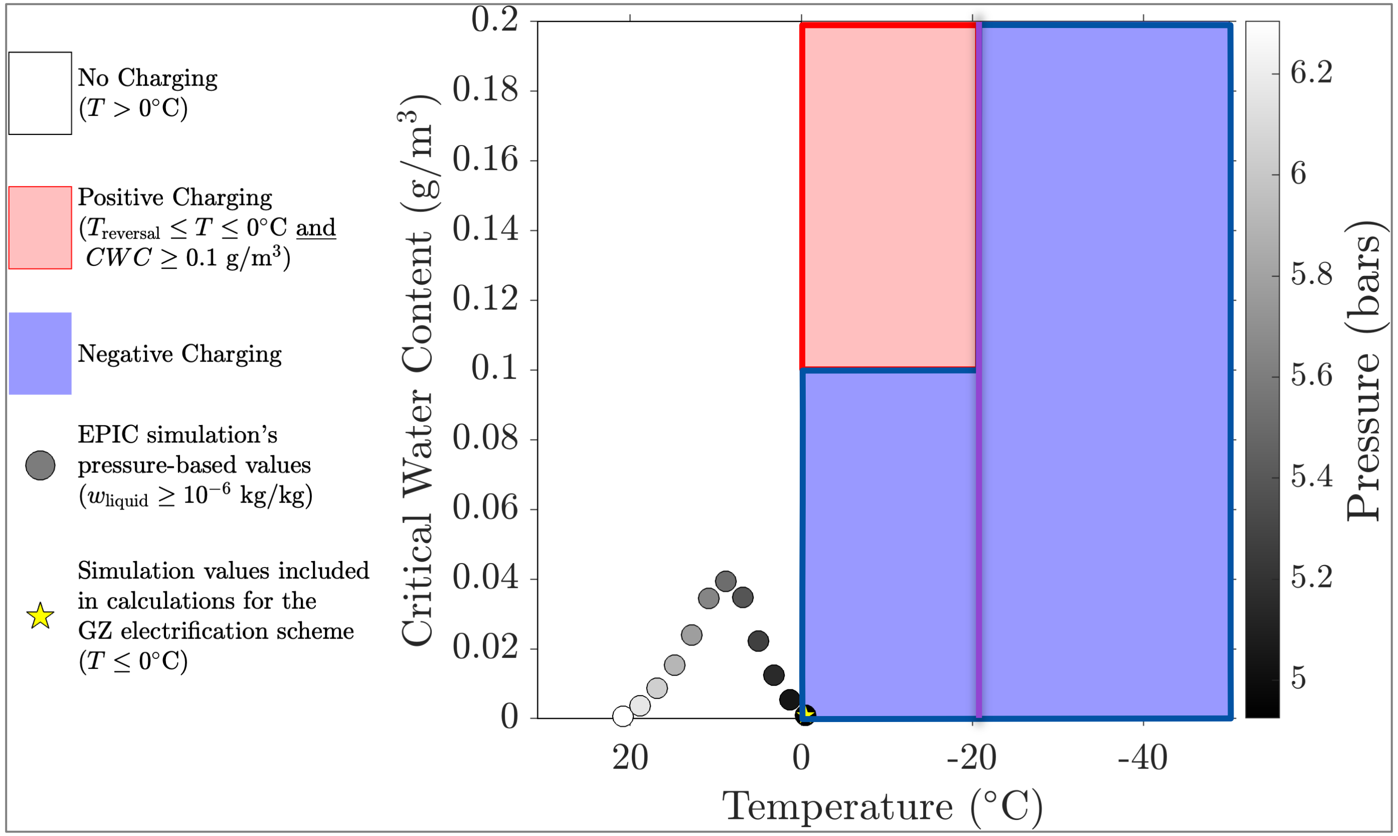
Isolate suitable region's
temperature, pressure, and mixing ratios



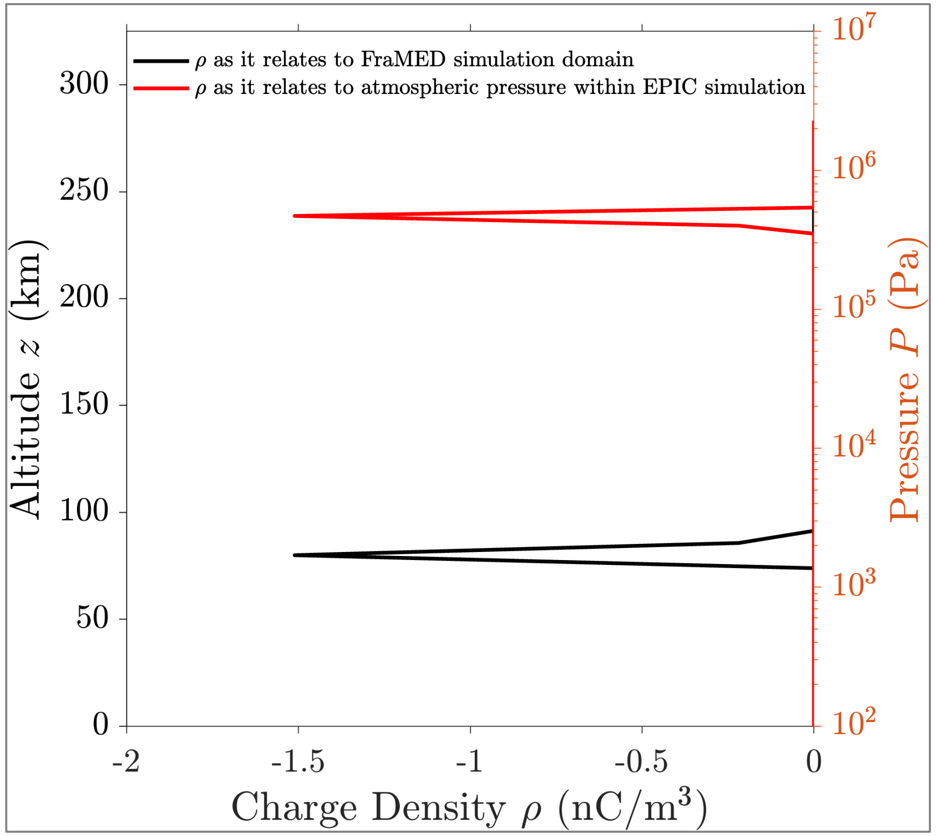
More info on EPIC: [12] Dowling et al. (1998), [13] Palotai & Dowling (2008)

Methods: Gardiner-Ziegler Electrification Scheme

Categorize temperature-dependent charge polarity

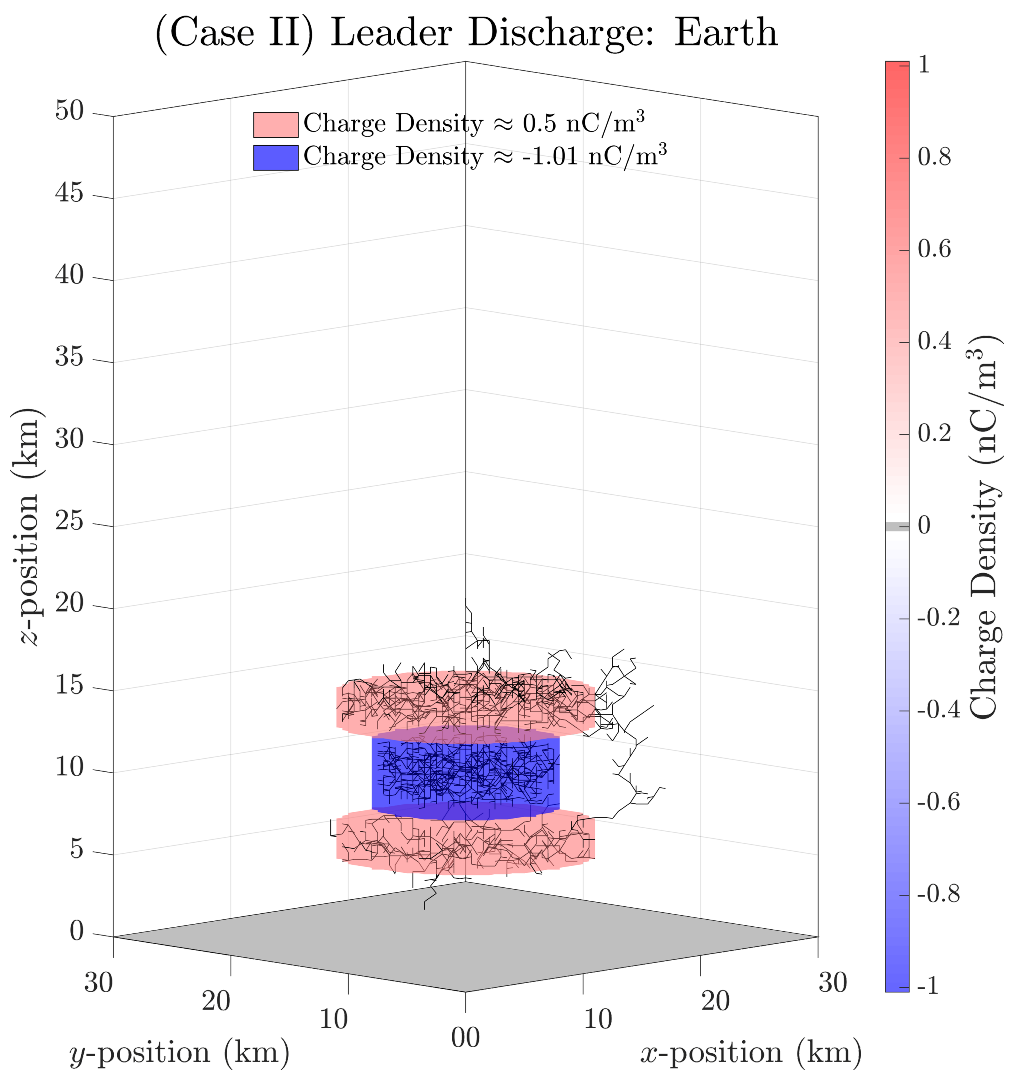


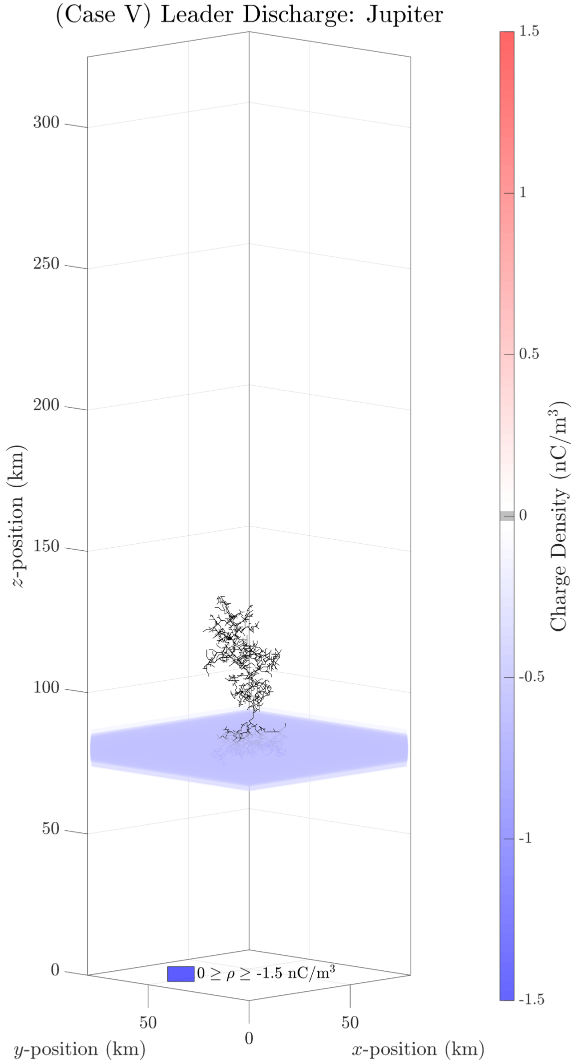
Determine charge density

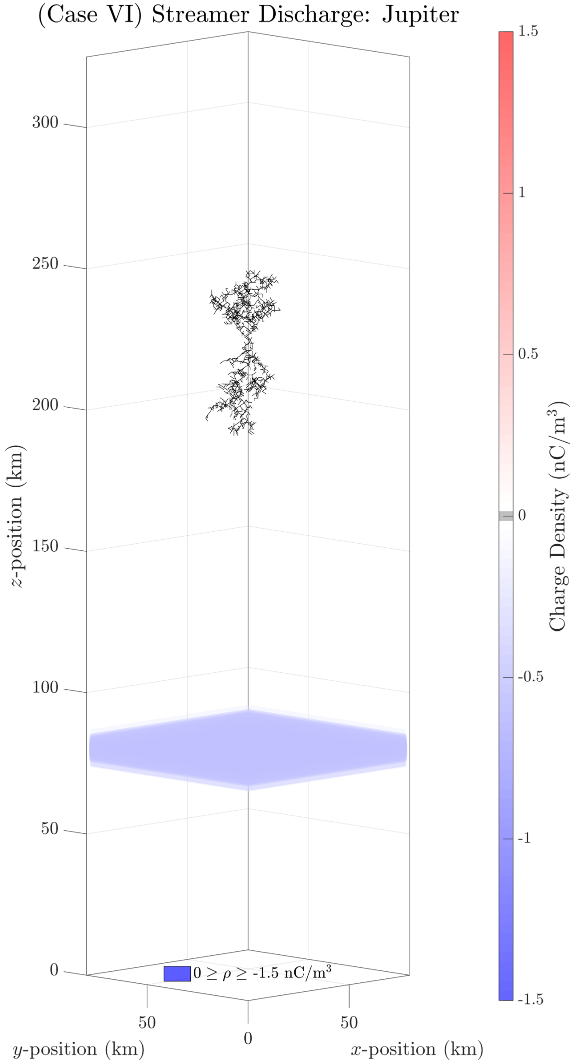


More info on GZ scheme: [14] Jayarante et al. (1983), [15] Gardiner et al. (1985), [16] Ziegler et al. (1991), [17] Mansell et al. (2005), [18] Straka (2009)

Results: Atmospheric Streamer/Leader Discharges







Model Interoperability: Model Sharing

Road blocks	Possible solution(s)
Domain compatibility	• Standardized interpolation tools b/w 3-D grid
Two-way coupling	• Compatibility: Standardized data format (FITS, NetCDF, HDF5) • Performance: HPC
Usability	• GUI • Tutorial • Open source • Open access
Validation	• Centralized repository for LMA, spherics, etc. • Resource à la PDS

Physical Approach: Current gaps

Complete theory for… to explain…

Initiation	Propagation/branching	Termination
Why leader initiation is ”easier” than streamer’s.	Why Streamer propagation is ”harder” than leader’s.	Why upward/jet behavior is “easier” than CG[1].
The role of secondary electron emission in surface discharges.	Resolve fractal dimension.	How multiple RS can be modeled stochastically.
Optimal lightning rod.	How to implement explicit time in a probabilistic scheme.	How upward leader connects to CG.

[1]and how similarity laws hold near the ground

Physical Approach: Current gaps

3-5 yrs	5+ yrs
One-way coupling at input: • Cloud models (WRF) • Atmospheric models (GRAMS, MSIS, EPIC, etc.) • Volcanic plume models	Two-way coupling with: • Chemical models • Streamer models • Upward leader connection (ground connection) • Cloud models
One-way coupling during propagation: • Leader's streamer zone (à la Agoris et al., 2004) • Chemistry (à la Riousset et al., 2010) • Leader-streamer transition (jet-like)	• Explicit time scheme. • Multiple return-stroke model. • Lightning rod optimal design.
One-way coupling at output: • Jet "jump" model • E-M spherics	• Multiscale model of leader/streamer systems.

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- C.3: Solar System Workings
- F.7: Support for Open-Source Tools, Frameworks, and Libraries

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NSF

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- GEO EMpowering BRoader Academic Capacity and Education (GEO-EMBRACE)
- ECosystem for Leading Innovation in Plasma Science and Engineering (ECLIPSE)
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FSGC

- Dissertation and Thesis Improvement Fellowship
- Masters Fellowship Program
- Student Club Projects

Model Interoperability (Details)

- What are the model outputs?

Current outputs	Internal diagnostics	Roadblocks/Opportunities
3-D grid	Max/min discharge duration: $\Delta t_{\mathrm{max}}, \Delta t_{\mathrm{min}}$	A posteriori $\longrightarrow$ a priori time estimates
Charge density distribution: $\rho_{\mathrm{amb}}(\vec{r}), \rho_{\mathrm{cha}}(\vec{r}), \rho_{\mathrm{tot}}(\vec{r})$	Potential at initiation: $\varphi_0(t)$	Standardized interpolation tools
Electric potential: $\varphi_{\mathrm{amb}}(\vec{r}), \varphi_{\mathrm{cha}}(\vec{r}), \varphi_{\mathrm{tot}}(\vec{r})$	Likelihood of branch selection	Standardized data format (FITS, NetCDF, HDF5)
Electric field: $\vec{E}_{\mathrm{amb}}(\vec{r}), \vec{E}_{\mathrm{cha}}(\vec{r}), \vec{E}_{\mathrm{tot}}(\vec{r})$	Sequence of production of the branches	Data compression/HPC
Charge transfer: Q_{cha}	Voltage drop along the channel: V_d	One-way $\longrightarrow$ Two-way coupling
Electric dipole moment: $\vec{p}$	Longest branch length: $l_{\mathrm{cha}}(t)$	Initiation theory: $E_{\mathrm{init}} \stackrel{?}{=} E_{\mathrm{k}}$
Discharge length: l_{cha}	Charge distribution: $q(t, \vec{r})$	Branching theory/fractal dimension: $E_{\mathrm{th}}^{\pm}, \eta$
Discharge current: i_{cha}	Current distribution: $i(t, \vec{r})$	Return stroke/ground connection: $\rho_{\mathrm{amb}}(z \approx 0)$
		Radiation waveform: $(\vec{E}, \vec{B}), \vec{S}$
		Similarity laws: Why do we ever go to the ground?
		Jump to jet/transition streamer/leader Multiscale physics

Model Use and Validation (Details)

How is this model component validated?	What observations are necessary for validation?	Notes
Charge transfer: Q_{cha}	Cloud charge before/after flash	Available
Charge density: ρ_{amb}	Storm sounding	Temporal/spatial accuracy issues
Resistivity/voltage drop: V_{d}	Streamer/leader resistivity	Estimates
Electric dipole moment: $\vec{p}$	Charge transfer/average altitude	Large uncertainties
Overall length: $\mathcal{L}$	LMA/optical	Branching uncertainties
Remnant E-field after discharge: $\vec{E}_{\mathrm{tot}}$	Initiation, propagation thresholds: $E_{\mathrm{init}}, E_{th}^{\pm}$ Ambient (cloud) electric field: $\vec{E}_{\mathrm{amb}}$	Poorly constrained Currently limited to localized data
Remnant screening charge: ρ_{amb}	Ambient (cloud) electric charge: ρ_{amb} Cloud electric conductivity: σ	Inaccurate Unknown
Average current: $i(t)$	Current measurements	Available
Max/min duration: Δt	LMA, antennae	Available
E-M radiation	E-M spectrum	Feature not implemented
Channel behavior	Branching, discharge type (IC/CG)	Scale issues in lab & +CG/IC uncertainties

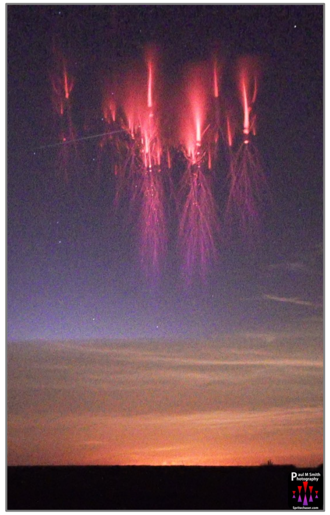
Physical Approach (Details)

- What are the current gaps?

Initiation	Propagation	Termination
• **Full theory of lightning initiation.** • $E_{\text{init}} \overset{?}{\propto} E_{\text{k}}$ • $E_{\text{k}} \gg E_{\text{amb}}$	• **Full theory of propagation/branching.** • $E_{\text{th}}^{\pm} \overset{?}{\propto} E_{\text{k}}$	• **Full theory of ground connection.** • $E_{\text{th}}^{\pm} \overset{?}{\propto} n_{\text{g}}$ @ $z \approx z_{gnd}$ • $\rho_{\text{amb}} \overset{?}{\approx} 0$ @ $z \approx z_{gnd}$
• Leader initiation ”easier” than streamer’s: $E_{\text{init,l}} \ll E_{\text{init,s}}$ • Adequate understanding of the role of secondary electron emission: $\gamma \approx 10^2 - 10^4$	• Streamer initiation ”harder” than leader’s: $E_{\text{th,s}}^{\pm} \gg E_{\text{th,l}}^{\pm}$ • Fractal dimension: $\eta \overset{?}{\approx} 1$ • Streamer-leader transition. • Revised probability with explicit time.	• Upward connecting leader model. • Multiple return-stroke model. • Lightning rod theory. • Similarity laws exceptions?

Methods: Breakdown Observations

CC lightning: [6] RMS (2007); *CG lightning:* [7] RMS (2007); *Jellyfish sprite:* [8] Smith (2019); *Table data:* [9] Pasko & George (2002), [10] Bazelyan & Raizer (1998), [11] Fu et al. (2020)



	Streamers		Leaders	
	Earth	**Generalization**	**Earth**	**Generalization**
Initiation $\boldsymbol{E_{\mathrm{init}}^{\pm}}$	$\approx 32\ \mathrm{kV/cm} \approx E_{\mathrm{k}}$[9]	$E_{\mathrm{init}}^{\pm} = E_{\mathrm{k}}$	$\approx 2\ \mathrm{kV/cm}$[9] $\approx 0.06E_{\mathrm{k}}$	$E_{\mathrm{init}}^{\pm} = \frac{1}{10}E_{\mathrm{k}}$
Negative Propagation $\boldsymbol{E_{\mathrm{prop}}^{-}}$	$\approx -12.5\ \mathrm{kV/cm} \approx -0.39E_{\mathrm{k}}$[9]	$E_{\mathrm{prop}}^{-} = -\frac{1}{3}E_{\mathrm{k}}$	$\approx -1\ \mathrm{kV/cm}$[9] $\approx -0.03E_{\mathrm{k}}$	$E_{\mathrm{prop}}^{-} = -\frac{1}{20}E_{\mathrm{k}}$
Positive Propagation $\boldsymbol{E_{\mathrm{prop}}^{+}}$	$\approx 4.4\ \mathrm{kV/cm} \approx 0.14E_{\mathrm{k}}$[9]	$E_{\mathrm{prop}}^{+} = \frac{1}{6}E_{\mathrm{k}}$	$\approx 1\ \mathrm{kV/cm}$[9] $\approx 0.03E_{\mathrm{k}}$	$E_{\mathrm{prop}}^{+} = \frac{1}{20}E_{\mathrm{k}}$
Resistance / Voltage drop	$\approx 5\ \mathrm{kV/cm} \approx 0.16E_{\mathrm{k}}$[10] $\approx -10\ \mathrm{kV/cm} \approx 0.31E_{\mathrm{k}}$[10]	$V_{\mathrm{d}}^{\pm} = E_{\mathrm{prop}}^{\pm}$	$\approx 0\ \mathrm{kV/cm}$[11]	$V_{\mathrm{d}} = 0$

Avenues for Collaborations (non-exhaustive!)

- Across national organizations or agencies (public and private)
  - NASA/NSF/AFSOR: Science
  - NASA: Open Source support
  - Oregon University (volcanology)
  - Portland State University (tribocharging)
- International partnerships (TBD)
  - Large-scale discharge experiments:
    - Ecole Centrale de Lyon: LMFA
  - Satellite observation:
    - Université d'Orléans
    - CNRS/CNES/IRAP
- What is the balance of student, postdoc, and career-expert work?
  - Experiments: UG, G students
  - Computation:
    - Post-processing: MSc. Ph.D. students
    - C/C++ module: Ph.D./Postdocs
    - HPC: Postdocs, research scientits
- Citizen Science
  - TBD