



A charge-conserving gap-ionization discharge scheme for particle models of thundercloud electrification: a case study with Thunder v1.0

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Abstract

Discharge schemes in particle models of thunderclouds remove charge from a stochastically grown channel, which does not conserve charge and imposes the channel geometry rather than deriving it. This paper replaces the scheme with a plasma process: when the field in the gap between two oppositely signed charge layers reaches the ionization level the gap is filled with neutral air at the simulation's own initial density, molecules above threshold separate into a positive ion and an electron, and everything after that follows from the force law that moves every other particle. Charge is conserved at every reaction. Two quantities such schemes leave free are derived rather than chosen: the separation at which a new pair is unbound, from the ambient field, and the timestep, from the electron drift velocity at the reduced field the model itself produces, $E/N = 27$ Td. In a column whose charge layers are prescribed rather than generated, the same charge spread smoothly through each layer gives 19 kV m^{-1} and never fires; gathered into local concentrations it gives up to 196 kV m^{-1} and does. The requirement is a layered and locally concentrated charge structure. Rotation is how this model produces one, but the discharge acts identically on prescribed layers that no vortex has shaped. Against matched controls the field in the firing gap falls 55.8 ± 6.5 per cent over eleven seeds, with relief of neighbouring gaps attenuating to zero by 2.16 km. Without an electron attachment loss the discharge never terminates; with attachment on oxygen all ten discharges self-terminate, at a median 190 ms and $1.44 \times 10^4 \text{ m s}^{-1}$ against 192 ms and $1.69 \times 10^4 \text{ m s}^{-1}$ for flashes measured in a mapped storm using the model's own definitions. The reach is a factor of four short, which bounds the result to initiation and local field relief rather than to flash extent. Two predictions follow that observation can test: initiation should track the concentration of charge within a layer rather than the layer-averaged field, and flash duration should scale with the oxygen number density that sets the attachment length.

1. Introduction

Balloon soundings through convective regions do not find a simple dipole. They find several thin layers of alternating polarity, four inside updrafts and at least six outside them, individual layers often a few hundred metres thick (Williams, 1989; Stolzenburg et al., 1998). That fine structure, rather than any storm-scale potential difference, is what a discharge encounters: it is the local field between adjacent layers that first exceeds breakdown. How a discharge behaves in such a structure is a question about the gaps between layers, and it is the question this paper addresses.

Particle models of electrified clouds generally discharge by the stochastic dielectric-breakdown scheme of Niemeyer et al. (1984), developed for thunderclouds by Mansell et al. (2002): a channel is grown cell by cell through a solved field, and the charge inside it is then set to zero. That scheme has a defect. It destroys charge. A carrier inside the channel has its charge removed irrespective of sign and with no counterpart anywhere in the domain, so the net charge of the column changes by whatever the channel



41 happened to contain. Real lightning conserves charge: a bidirectional leader is a conductor that moves
42 negative charge one way and positive the other and deposits it at the channel ends (Kasemir, 1960). The
43 consequence is not cosmetic. Because deletion lowers the field everywhere, a discharge in such a scheme
44 can never raise the field anywhere, and the refractory timing reported in the first paper is therefore partly
45 a property of the scheme rather than a discovery about the storm.

46 This paper replaces that scheme rather than patching it. The replacement is a plasma process with no
47 channel in it. When the axial field between two oppositely signed layers reaches the ionization level, the
48 space between them is filled with neutral air, molecules sitting where the local field is strong enough are
49 separated into an ion and an electron, and from that point everything is the same force law that moves
50 every other particle in the model. There is no propagation rule, no branching exponent, no neutralisation
51 fraction and no Poisson grid. The discharge is whatever the ionized air does.

52 Three consequences follow, and they organise the paper. Charge is conserved exactly, so the objection
53 above is answered. Two quantities that look like free parameters turn out to be derivable, which removes
54 them from the list of things a reader must take on trust. And because the model now contains electrons
55 with a physical mass ratio moving under a clock that can be anchored to laboratory swarm data, the speed
56 at which the ionization front advances becomes an output rather than an input – a quantity the model
57 predicts and observation can refute.

58 The mechanism under examination was proposed as a physical chain: rotation sorts charge into layers; the
59 field between layers grows; that field ionizes the air between them; the electrons released near a negative
60 layer accelerate toward the positive one; some survive the crossing, are re-accelerated on the far side, and
61 ionize further. Each link is examined here in turn, and the last two – the crossing and the subsequent
62 ionization – are measured per particle rather than inferred.

63 The contribution is fourfold. First, a discharge scheme for particle models of electrified clouds that
64 conserves charge exactly, imposes no channel and requires no propagation rule, no Poisson grid and no
65 breakdown lattice: the entire discharge follows from the same force law that moves every other particle in
66 the domain. Second, the removal of two quantities that such schemes normally leave free. The separation
67 at which a newly created pair is unbound is derived here from the ambient field rather than chosen, and
68 the timestep is anchored on the electron drift velocity at the reduced field the model itself produces, which
69 converts the propagation speed from a tuned quantity into a falsifiable output. Third, a statement of what
70 the mechanism actually requires of a charge structure, established by building the structure by hand rather
71 than inferring it from the model that generated it: layering alone is not sufficient, and local concentration
72 within the layers is necessary. Fourth, a quantitative test against mapped flashes in which the observations
73 are reduced with the model's own definitions rather than taken from published summary statistics,
74 reporting both the two quantities that agree without having been fitted and the one that does not.

75 What the paper does not claim should be stated with the same precision. It does not claim that this
76 mechanism produces lightning, and it does not exclude that it does. What is demonstrated is narrower
77 than the first and stronger than nothing. It demonstrates that a mechanism assembled from the rules above
78 produces localised, subcritical, charge-transferring discharges whose duration, propagation speed and
79 charge moment fall within observed ranges, and it identifies precisely where the resemblance fails. The
80 distinction matters because the charging model beneath the discharge has documented deficiencies, set
81 out in Sect. 10, that no discharge treatment can repair.



One objection to that model is answered here rather than conceded, and it is worth flagging at the outset because it determines how much of the paper survives the objection. If the layered charge structure the discharge acts on were an artefact of vortex sorting – of a charging model with no gravity, no size spectrum and no fall speeds – then nothing measured downstream of it would mean anything. Section 4 removes the question by building the layers by hand, in a column no vortex has ever acted on, and running the identical discharge on them. The discharge does not care how the layers arrived. What it requires of them is stated there and is narrower and more useful than a rotating column: layering together with local concentration within the layers.

2. The model

The model described here is Thunder v1.0. It comprises a charging component, which produces a layered charge structure in a rotating particle column, and the discharge component that is the subject of this paper. The two are separable: Sect. 4 shows that the discharge acts on any layered and locally concentrated charge structure, including one assembled by hand, and does not depend on how the charging component produced it. Both components, together with every script used below, are archived as described in the code and data availability section.

2.1 The charging model

The column is a minimal particle model, specified here in full. Carriers of unit mass move under a prescribed Rankine vortex with a conical envelope and a Gaussian axial weighting, feel a pairwise Coulomb and Biot–Savart force within a cutoff, and exchange charge on contact: two neutrals in contact separate as a positive and a negative, and two opposite charges in contact neutralise, each with a refractory period afterwards. There is no microphysics, no size spectrum and no sedimentation. Table 1 lists every constant.

Table 1 *The charging model in full. Lengths are in model units of 40 m and the timestep is the product of dt and the speed multiplier. Nothing else is required to reproduce the column.*

Quantity	Value	Note
Carriers	30,000	sensitivity in Sect. 8.2
Domain	$400 \times 400 \times 260$ u	$16 \times 16 \times 10.4$ km
Metres per unit	40	length anchor
Timestep	$dt \ 0.05 \times \text{speed}$ 20	one host iteration ≈ 24 s
Column base, top	150, 270 u	6.0, 10.8 km
Core radius, base to top	5 to 25 u	concavity exponent 0.7
Circulation	spin 2.4	Rankine, constant circulation
Updraft	4 u/s	Gaussian about the core wall
Radial inflow strength	55	pressure-driven term
Gravity	0	see Sect. 8
Coulomb constant	12	model units

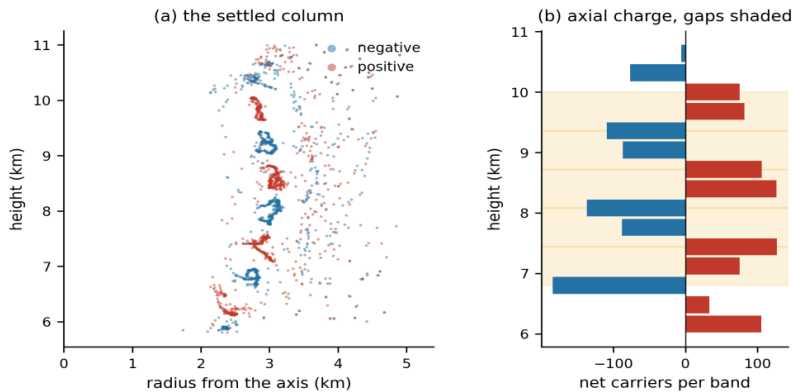


Quantity	Value	Note
Biot–Savart constant	0.35	small correction at these speeds
Interaction cutoff	15 u	600 m
Force softening	6 u	240 m, Sect. 2.7
Contact radius	2 u	80 m
Refractory period	60 steps	after a charge exchange
Charge anchor	1 nC m ⁻³	gives 0.349 C per carrier

106

107 **2.2 What the discharge acts on**

108 Left to run, the column organises into an annulus with an evacuated core, and within that annulus the
109 charge separates into axial layers of alternating sign. Figure 1 shows the state to which the discharge
110 scheme is applied. Two features of it matter, and they are separable.



111

112 **Fig. 1.** The input state, 30,000 carriers after 110 iterations. (a) Charged carriers in a radial-axial section. The charge
113 occupies an annulus between about 2 and 4 km radius and is gathered into dense filaments rather than spread smoothly. (b)
114 Net charge per axial band, with the gaps between consecutive layers of opposite sign shaded; those gaps are what the
115 discharge scheme acts on.

116 The first feature is the layering, visible in panel (b) as alternating bands. The second is the fine structure
117 within each layer, visible in panel (a): the carriers are not spread smoothly but gathered into dense
118 filaments a few hundred metres across. Section 4 shows that the second, not the first, is what produces a
119 field able to ionize anything.

120 **2.3 The column**

121 Three quantities fix the column in physical units. One model unit is 40 m. The column occupies 6 to 10.8
122 km in height and an annulus of roughly 2 to 4.5 km radius. Charge is anchored by matching the densest
123 axial layer to an observed convective layer density of 1 nC m⁻³, which fixes the carrier charge at 0.349 C
124 for the 30,000-carrier configuration used throughout.



125 A settled column develops alternating axial layers. The gaps between consecutive layers of opposite sign
 126 are what the discharge scheme acts on, and they are located from the axial net-charge profile rather than
 127 specified: a layer is a local extremum reaching 30 per cent of the largest excursion, and a gap is the span
 128 between two consecutive extrema of opposite sign.

129 **2.4 Species and masses**

130 Three populations are present. The hydrometeor carriers are those of the charging model. When a
 131 discharge begins, two further species appear: neutral air molecules, and the ions and electrons they
 132 produce. The two kinds of particle are never interchanged. A carrier acquires charge only by contact with
 133 another carrier and is never ionized; an air molecule is never charged by contact and enters only through
 134 ionization. The threshold of Sect. 2.9 is accordingly the field at which air ionizes, not a field at which a
 135 hydrometeor loses an electron.

136 Carrying only hydrometeors until that threshold is reached is a physical statement rather than a
 137 simplification of convenience. The charge that builds the layered structure resides on hydrometeors,
 138 deposited by rebounding graupel–crystal collisions in the mixed-phase region (Takahashi, 1978; Saunders
 139 et al., 2006). Air is present throughout, but while that structure forms it is electrically close to passive:
 140 background conductivity inside a thundercloud is of order $10^{-14} \text{ S m}^{-1}$ or less, below that of clear air at the
 141 same altitude because small ions attach to hydrometeors and the charge they carry is immobilised
 142 (MacGorman and Rust, 1998; Iudin et al., 2019). The Maxwell relaxation time ϵ_0/σ that follows from that
 143 conductivity is of order 10^3 s , long compared with the interval over which the layers assemble, so
 144 conduction through the air does not materially relax the structure while it is being built. Air becomes
 145 electrically active in one circumstance, when the field between two layers reaches the ionization level,
 146 and the model introduces it at exactly that point. What this leaves out is the weak conduction current itself
 147 and the screening layers it forms at cloud boundaries, both of which act on the large-scale charge
 148 distribution rather than on the gap between two adjacent layers.

149 Air at 77 per cent N_2 and 23 per cent O_2 has a mean molar mass of $0.77 \times 28.013 + 0.23 \times 31.998 = 28.93$
 150 g mol^{-1} , within 0.1 per cent of the 28.96 g mol^{-1} of real dry air. An electron is $5.486 \times 10^{-4} \text{ g mol}^{-1}$, so

$$151 \quad m_e / m_{\text{atom}} = 1.897 \times 10^{-5},$$

152 and that ratio is used exactly. It is not a mobility parameter. The transport asymmetry reported in Sect.
 153 6.3, in which electrons travel some 200 times further than ions over the same interval in the same field,
 154 follows from it rather than being imposed alongside it.

155 The mass of an air particle relative to a hydrometeor is not a physical constant, because both are coarse-
 156 grained parcels rather than single objects, and it is therefore exposed as a parameter. Its value is examined
 157 in Sect. 8.

158 **Table 3** *Species and their masses. Only the electron-to-atom ratio is a physical constant; the atom-to-*
 159 *hydrometeor ratio is a coarse-graining choice, because both are parcels rather than single objects.*

Species	Mass	Basis
Hydrometeor carrier	1 (reference)	Charging model of Paper I
Air molecule	0.05	Parameter; swept in Sect. 7



Species	Mass	Basis
Positive ion	0.05	Same as the parent molecule
Electron	9.48×10^{-7}	1.897×10^{-5} of the molecule, exact

160

161 2.5 Reactions

162 Five reactions are implemented. Every one of them conserves charge, and this is asserted in code at each
 163 event rather than assumed.

164 **Table 4** The reaction set. The particle counts on the right are what distinguishes this scheme from one
 165 that deletes charge: nothing is removed except in pairs, and impact ionization produces three particles
 166 from two while leaving the incident electron's identity intact.

Reaction	Products	Count
Field ionization	$\text{atom} \rightarrow \text{ion}^+ + \text{e}^-$	2 from 1
Impact ionization	$\text{e}^- + \text{atom} \rightarrow \text{ion}^+ + 2 \text{e}^-$	3 from 2
Recombination	$\text{e}^- + \text{ion}^+ \rightarrow \text{atom}$	1 from 2
Hydrometeor capture	$\text{e}^- + \text{hydrometeor}^+ \rightarrow \text{hydrometeor}^0$	1 from 2
Elastic reflection	$\text{e}^- + \text{hydrometeor}^- \rightarrow \text{reflected}$	no change

167

168 Impact ionization costs the incident electron the ionization energy, applied as a kinetic-energy subtraction
 169 $v' = \sqrt{v^2 - v_{\text{ion}}^2}$. An electron slower than v_{ion} cannot ionize. This is the Townsend threshold
 170 expressed as an energy condition rather than as a probability, and it is what stops an avalanche when the
 171 field can no longer re-accelerate electrons between collisions.

172 Electron–neutral scattering is treated as a continuum rather than against the sampled molecules, and the
 173 split is deliberate. Real air holds of order 10^{25} molecules per cubic metre; the molecules tracked here are a
 174 sparse sample of it, so the true elastic and excitation collision rates have nothing to do with how many
 175 sample molecules happen to be nearby. Ionization is tracked discretely because it changes the charge state
 176 of a tracked particle; scattering does not. Elastic collisions cost an electron only $2m_{\text{e}}/M \approx 3.8 \times 10^{-5}$ of
 177 its energy and therefore randomise direction; inelastic excitation of N_2 removes energy and is where most
 178 of an electron's energy goes in air, fixing the drift velocity and with it the effective ionization coefficient.

179 The approximation this makes should be stated rather than left implicit: the electron energy distribution is
 180 governed by the real gas density, while the events that change a particle's charge state are sampled from
 181 the tracked subset. The two are consistent so long as the tracked molecules are sparse relative to the real
 182 gas, which is the regime the model occupies by construction and by four orders of magnitude at the fills
 183 used here. It would break down in the opposite limit, where the tracked sample approached the real
 184 density and the same collision would be counted twice – once in the continuum rate and once discretely.
 185 Nothing in the runs reported here comes near that limit.

186 Attachment is on oxygen and not on nitrogen, for a reason worth stating because it is the same asymmetry
 187 that governs the positive ions. O_2 has a positive electron affinity of 0.45 eV, so O_2^- is bound; N_2 has a
 188 negative affinity near -1.9 eV and forms only a shape resonance around 2.3 eV with a lifetime of order



189 10^{-14} s, which decays back to N_2 and a free electron. Nitrogen takes energy and returns the electron;
190 oxygen takes the electron. On the positive side, ionization produces mostly N_2^+ by abundance, but it
191 charge-transfers to O_2^+ within nanoseconds because O_2 has the lower ionization potential (12.07 against
192 15.58 eV), and clusters thereafter. A single positive species at the mean air mass is therefore an adequate
193 coarse-graining, and the model is slightly optimistic about ion mobility because the terminal cluster ions
194 are heavier.

195 **2.6 The pair separation is derived, not chosen**

196 When a molecule ionizes, the ion and the electron must be placed. Placing them at the same point is
197 wrong in a way that is easy to miss: the pair is then bound. Its own mutual Coulomb field exceeds the
198 ambient field, the electron is drawn back, and no free charge results. In the first implementation a fixed
199 offset of 60 m was used, at which the pair's mutual field is 0.111 in model units against an ambient 0.058;
200 every pair was bound, the products accelerated into one another and left the domain at a 15 km spread.

201 The correct separation follows from equating the two. Setting the pair's mutual field equal to the ambient,

$$202 \quad q / (2d)^2 = E \quad \Rightarrow \quad d = 1 / (2\sqrt{E}),$$

203 in model units with unit carrier charge. Below this the split does nothing; above it the ambient field wins
204 and the products separate. Evaluated at the measured gap fields this returns 118 to 147 m consistently
205 across every run. It is the coarse-grained analogue of Onsager field-assisted dissociation: in real air the
206 Coulomb binding of an electron-ion pair is overcome at Ångström scale by thermal energy and the
207 ambient field, but a carrier here represents some 10^{10} hydrometeors' worth of charge, so the same balance
208 moves out to tens or hundreds of metres. The separation is fixed by the carrier charge and the local field,
209 and is therefore a prediction of the coarse-graining rather than a choice.

210 **2.7 Softening of the Coulomb force**

211 A carrier is not a point. Anchored to 1 nC m^{-3} it stands for roughly 0.35 C, and treating that as a point
212 charge is wrong at separations below the parcel size. Unsoftened, the near field of the nearest neighbour
213 swamps the collective field of the charge layers. Measured on a settled column, an electron takes steps of
214 order 128 m under the local field but nets only about 100 m over 24 iterations: the coherent axial
215 component is roughly 3 per cent of what it feels, and products scatter rather than drift.

216 Plummer softening at the mean inter-carrier spacing removes the spurious near field and leaves the
217 structure. This is standard practice in N-body work for exactly this reason. The softening length used
218 throughout is 6 model units (240 m) against a measured carrier spacing of 244 to 291 m. Section 8 reports
219 the sensitivity.

220 **2.8 The sub-clock and its anchor**

221 Electrons in air drift at 10^4 to 10^5 m s^{-1} . One model unit is 40 m and one host iteration is about 24 s of real
222 time, so an electron would cross the 16 km domain many times within a single host step; it cannot be
223 integrated on the host clock at all. The air species therefore runs on its own timestep while the
224 hydrometeors are held still. That is operator splitting, and it is also the physical picture: a flash is finished
225 long before a hydrometeor has moved anywhere. Because the hydrometeors are stationary during a



226 discharge their field is constant, and it is evaluated once on a grid and interpolated thereafter; the plasma's
227 own space charge is refreshed on the same grid periodically.

228 The sub-clock has to be anchored, and one number does it. Requiring that the model's drift ceiling
229 represent the physical electron drift velocity gives

230
$$\text{one sub-step} = \text{max_step} \times L_0 / v_{\text{drift}} \text{ seconds.}$$

231 Which drift velocity matters. At the observed initiation altitude of 8.4 km the air density gives $N = 9.3 \times$
232 10^{24} m^{-3} , so the 250 kV m^{-1} threshold corresponds to a reduced field of $E/N = 27 \text{ Td}$. That is a low
233 reduced field, and deliberately so: the model uses the observed thundercloud field with hydrometeor
234 enhancement folded into the threshold rather than the conventional breakdown field. The value adopted
235 here is $v_{\text{drift}} = 4 \times 10^4 \text{ m s}^{-1}$. It is the one external number the model takes from outside itself, and it is
236 stated as an assumption rather than derived: it lies in the range that dry-air swarm compilations give at
237 low reduced field (Dutton, 1975) and is reproducible by a two-term Boltzmann solution for 77 % N_2 / 23
238 % O_2 at 27 Td with a standard cross-section set (Hagelaar and Pitchford, 2005; Pitchford et al., 2017).
239 Because it enters only as a multiplier, every duration and every speed reported below scales as $(4 \times 10^4 \text{ m}$
240 $\text{s}^{-1} / v_{\text{drift}})$ and $(v_{\text{drift}} / 4 \times 10^4 \text{ m s}^{-1})$ respectively, and a reader who prefers a different value can
241 rescale the results without rerunning anything.

242 It must be the ambient value and not the value at the enhanced field where ionization occurs, because an
243 electron spends nearly all of its path in the ambient field and the clock measures transport. It must also not
244 be the host anchor, which describes hydrometeor advection: applying it to electrons would give them
245 hydrometeor speeds, which is precisely what the sub-clock exists to avoid. Two populations whose
246 mobilities differ by ten orders require two clocks, and anchoring them separately is a requirement rather
247 than a convenience.

248 With $v_{\text{drift}} = 4 \times 10^4 \text{ m s}^{-1}$, one sub-step is 400 μs and represents 16 m of carrier travel. Every duration
249 reported below follows from that single number, and the front speed of Sect. 6.7 becomes an output.

250 **2.9 The ionization threshold**

251 The threshold is set in real units at 250 kV m^{-1} , within the 150 to 400 kV m^{-1} window that balloon
252 soundings give for maximum thundercloud fields (Marshall et al., 1995; Stolzenburg et al., 1998). That is
253 roughly an order of magnitude below conventional breakdown at these altitudes. The difference is
254 hydrometeor field enhancement: an elongated conductor in an ambient field concentrates it at its tips by
255 one to two orders of magnitude, which is what initiates a streamer (Petersen et al., 2008; Dubinova et al.,
256 2015). That enhancement occurs at millimetre scale, nine orders below one model unit, so it is irreducibly
257 sub-grid and belongs in the threshold. Section 8 reports the sensitivity to the value chosen. It should
258 nonetheless be said plainly that this is the one number in the model chosen to place the trigger in an
259 observationally reasonable range rather than derived from within it, and that it carries physics – the tip
260 enhancement of a millimetre-scale hydrometeor – which the model cannot resolve and does not attempt
261 to. A reader who rejects the coarse-graining should read every field reported here as a statement about the
262 sub-critical regime rather than about breakdown.

263 **3. Method**



264 **3.1 Matched-neutral paired controls**

265 The gap field varies by about 6.6 per cent over an observation window from the column's own evolution,
 266 which is larger than several of the effects reported here. Independent runs cannot resolve past that, and an
 267 early sweep that used them found nothing at any infusion density – a null result that turned out to be a
 268 property of the measurement rather than the mechanism.

269 Every comparison reported below is therefore paired. Each seed is settled once and monitored to the
 270 trigger, and the identical column is then continued twice. Both arms receive the same air particles at the
 271 same positions with the same velocities. In the control arm those particles carry no charge. Nothing
 272 differs between the arms except whether the infused matter ionized, so the difference between them is the
 273 effect of the ionization and nothing else.

274 A second confound had to be removed. Because infusion adds matter, an earlier design gave the ionized
 275 arm more particles than the control, and the vortex sorted those extra carriers into the layers. The
 276 matched-neutral control removes this: the arms have identical populations at identical positions and differ
 277 only in charge.

278 **3.2 Geometry of the infusion**

279 The air fills the entire annular tube the layers form, from the lowest layer to the highest, not one gap.
 280 Filling a single gap confines the discharge by construction, since there is no fuel outside it, and the
 281 question of whether the collapse spreads cannot then be asked. The fill density is a multiple of the
 282 simulation's own initial particle density; the multiple must be well above unity, because real air molecules
 283 outnumber hydrometeors by some twenty orders of magnitude and an air fill at the hydrometeor density is
 284 so thin that electrons are captured before they find a molecule to ionize. At a multiple of one the
 285 avalanche never starts; the runs below use ten.

286 Initial ionization is confined to the firing gap and its two bounding layers. This is what separates
 287 propagation from independent ignition: several gaps sitting above threshold when the air arrives will each
 288 ignite on their own, and from the outside that is indistinguishable from a discharge spreading. Section 6.2
 289 shows the two conditions side by side.

290 Some of the ionization occurs beside the layers rather than only mid-gap, and this matters more than it
 291 appears. In potential terms an electron born mid-gap sits at a maximum of ϕ , which for a negative charge
 292 is the bottom of a well; measured on this column it needs 203 to 244 MeV to reach any neighbouring gap
 293 and therefore cannot leave. An electron born beside a negative layer sits at a minimum of ϕ , the top of its
 294 energy landscape. Beside a layer is also where hydrometeors are densest and tip enhancement strongest,
 295 and that enhancement is sub-grid, so the ambient field sampled there does not show it; a relaxed threshold
 296 within a band of the layer stands in for it. The stripe-side seeds are additional to the mid-gap population,
 297 not a replacement for it: replacing rather than adding costs more than half of the local field collapse.

298 **4. What the mechanism requires**

299 The discharge scheme acts on the gap between two oppositely signed layers. How those layers came to be
 300 there is, on the face of it, irrelevant to it. That can be tested directly by building the layers by hand and
 301 running the identical discharge on them.



302 The prescribed column has no vortex, no charge exchange and no settling. Alternating slabs of charge are
 303 placed in an annulus matched to the settled column on every quantity the discharge sees: layer spacing
 304 800 m, annulus 1.8 to 3.8 km, the same column height, the same number of charged carriers, and the same
 305 anchored carrier charge. The only thing varied between conditions is how the carriers are arranged
 306 WITHIN each layer.

307 **Table 2** *A layered charge structure assembled by hand, with no vortex. The layers, the carriers, the signs*
 308 *and the geometry are identical in every row; only the arrangement within each layer differs. A smooth*
 309 *layer produces a field an order of magnitude below threshold and never discharges. Gathering the same*
 310 *carriers into local concentrations raises the field tenfold. The settled column of Figure 1 still exceeds*
 311 *every hand-built arrangement.*

Arrangement within each layer	Strongest gap field	Discharges?
Smooth	19 kV m ⁻¹	no
Concentrations, 120 m scatter	104 kV m ⁻¹	no
Concentrations, 160 m scatter	156 kV m ⁻¹	no
Concentrations, 240 m scatter	196 kV m ⁻¹	no
Concentrations, 320 m scatter	161 kV m ⁻¹	no
Settled column (Figure 1)	278 – 384 kV m ⁻¹	yes

312

313 Three things follow. Layering alone is not sufficient: a smooth layered structure carrying exactly the
 314 charge of the settled column produces 19 kV m⁻¹, more than an order of magnitude below the ionization
 315 threshold, and never discharges however long it is left. Gathering the same carriers into local
 316 concentrations raises the field by a factor of ten without adding any charge, which establishes by
 317 construction that the field between layers is set by the fine structure within them. And the settled column
 318 exceeds every hand-built arrangement tried, so the rotation produces a configuration that a two-parameter
 319 construction does not reproduce.

320 The requirement is therefore a layered AND locally concentrated charge structure, not a rotating one.
 321 Rotation is how this model produces such a structure, and Figure 1(a) shows it doing so, but any process
 322 that concentrates charge into alternating layers at these scales would serve. It should be said plainly that
 323 this is a statement about what the discharge requires and not a demonstration that a non-rotational route
 324 exists: charge placed by hand is an imposed condition, not a mechanism. The observational support for
 325 the wider claim is separate, and it is that the layered structure is reported in convective regions generally
 326 rather than only in rotating storms (Stolzenburg et al., 1998). That widens the scope of what follows
 327 beyond rotating columns, and it also identifies what a charging model must deliver before any discharge
 328 treatment can be applied to it.

329 5. Initiation

330 The trigger locates the gap itself from the axial charge profile, with no region specified in advance.
 331 Across eleven seeds it fired at 258 to 459 kV m⁻¹, inside the observed thundercloud window, at altitudes
 332 of 6.8 to 8.4 km. One seed in ten did not reach threshold within 600 host iterations.



Initiation is therefore a result of the charge structure rather than a placement. Where within the column it occurs, and at what field, follow from where the layers happen to form.

6. Results

6.1 Collapse of the field in the firing gap

Paired against the matched-neutral control over eleven seeds, the axial field in the gap that fired falls by 55.8 per cent, with a standard deviation of 6.5 per cent across seeds. Charge is conserved exactly at every event; nothing is deleted.

The mechanism is legible in the counts. A median of 167 hydrometeors is neutralised per terminating event by electron capture, against layer net charges of 50 to 120 carriers, so the charge removed is comparable to the entire net charge of the layer involved. At the anchored carrier charge this is a median 58 C transferred, range 39 to 71 C, and a charge moment of 48 C km, range 29 to 59, against 1 to 50 C and 10 to 300 C km for observed intracloud flashes.

6.2 Response of neighbouring gaps

With ignition confined to the firing gap and its bounding layers, any response in another gap cannot be independent initiation. Eleven seeds gave 41 gap measurements – eleven firing gaps and thirty neighbours.

Table 5 Field response against distance from the firing gap, pooled over eleven seeds. Ignition was confined to the firing gap and its two bounding layers, so a response elsewhere is propagation rather than independent ignition. The firing gap itself falls 55.8 per cent, standard deviation 6.5.

Separation	n	Mean response	sem	t
0.6 – 0.7 km	12	–30.0%	4.3	–6.95
0.7 – 1.1 km	5	–23.5%	3.7	–6.34
1.1 – 1.6 km	6	–6.0%	2.2	–2.74
1.6 – 2.2 km	4	0.0%	—	—
beyond 2.2 km	3	0.0%	—	—

The response is monotone, significant to 1.6 km and identically zero beyond. A linear fit over the neighbours crosses zero at 2.16 km. The discharge therefore collapses the gap it starts in by about half and relieves neighbouring gaps out to roughly two kilometres.

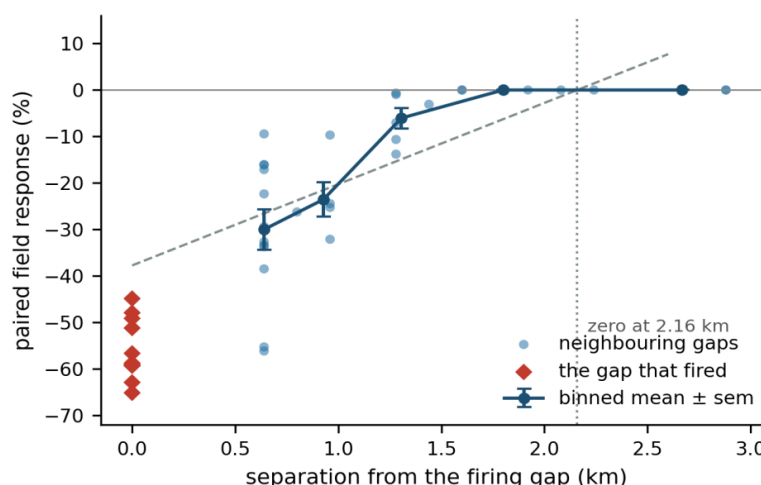


Fig. 2. Paired field response against separation from the gap that fired, eleven seeds and 41 gap measurements. Ignition was confined to the firing gap and its two bounding layers, so a response elsewhere is propagation and not independent ignition. Diamonds are the firing gaps themselves; the dashed line is a least-squares fit over the neighbours, crossing zero at 2.16 km.

Whether this constitutes propagation was tested directly. With air filling the whole tube but ignition unrestricted, every gap in the column responded; with ignition confined to the firing gap, the neighbours gave +5, +0 and -4 per cent – nothing. Those two conditions look identical from the outside and are physically quite different, and only the confined-ignition figures in Table 5 are propagation.

6.3 Individual trajectories

Every electron and ion was followed from birth: where it started, how far it travelled, how many layers it crossed and what ended it. Five seeds, 11,202 electrons and 5,601 ions.

Table 6 Fate of individual electrons and ions, five seeds. Ranges are across seeds. The three electron fates separate by distance without anything having been imposed: those captured by a positive layer were born beside one and had nowhere to go.

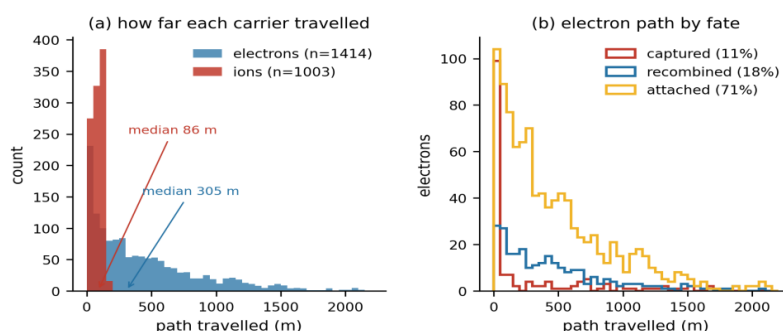
Fate	Share	Median life	Median path
Electrons – alive at the end	53 – 57%	—	1,243 – 1,431 m
Electrons – recombined with an ion	35 – 36%	55 – 61 steps	464 – 510 m
Electrons – captured by a layer	8 – 13%	0 – 10 steps	13 – 83 m
Ions – alive at the end	67 – 71%	—	5 – 8 m
Ions – neutralised by an electron	29 – 33%	84 – 93 steps	4 – 10 m

Electrons travel about 200 times further than ions – some 1,300 m against 7 m – over the same interval in the same field. That is the mass ratio of Sect. 2.4 doing what it should. The ions are effectively stationary



space charge on the discharge timescale: they screen and wait to be neutralised, but carry the event
nowhere. Everything that propagates is carried by electrons.

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Fig. 3. Distance travelled by every carrier in one discharge. (a) Electrons against ions on the same axis: the medians differ by a factor of about two hundred, which is the electron-to-molecule mass ratio expressed as transport. (b) Electron paths separated by fate. Those captured by a positive layer travel almost nowhere because they were born beside one; those that recombine cover roughly half a gap; the survivors exceed a kilometre.

Between 32 and 40 per cent of electrons cross at least one charge layer, with a median path of 1,313 to 1,485 m among those that do and a maximum of 2,094 m. Ions cross in 1.7 to 2.5 per cent of cases and move 6 to 16 m when they do.

6.4 Why the birthplace decides whether an electron can travel

The potential along the tube was computed directly from the settled column. The swing across the column is 264 MV, which is the right order for a thundercloud and was not tuned to be. For an electron the potential energy is $U = -e\phi$, so it sits highest in energy beside a negative layer and lowest mid-gap.

Table 7 Energy an electron must have to reach the next site, computed from the axial potential of the settled column. The quantity is the climb relative to where the electron starts, not the peak-to-trough swing between gaps. Two of the five transitions from a negative layer cost nothing at all.

Launched from	To	Energy required
Firing gap (ϕ maximum)	any neighbouring gap	203 – 244 MeV
Negative layer, 6.63 km	6.94 km	0 MeV
Negative layer, 6.94 km	7.86 km	4.1 MeV
Negative layer, 7.86 km	9.11 km	41.0 MeV
Negative layer, 9.11 km	10.50 km	0 MeV

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The column therefore contains connected paths along which an electron travels at no energy cost. Which paths are available depends entirely on where the electron is born, and this is why some of the ionization must occur beside the layers: an electron born mid-gap is in a 200 MeV well and cannot leave, whatever the collisions do.

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6.5 Cascade structure

Each impact ionization is credited to the electron that caused it and flagged according to whether that electron had already crossed a layer; each new electron records its generation in the descent from a seed. Between 24.8 and 27.6 per cent of all ionization occurs after the responsible electron has crossed a layer. That is new ionization in territory the seeds never occupied, produced by carriers that made the crossing, and it is the propagation step measured rather than inferred.

Table 8 Cascade generations, where 0 is a seed electron from field ionization and each subsequent generation is produced by impact. Each generation is roughly half the previous one, sustained through seven to nine generations: subcritical branching, which is what produces events of finite and varied size rather than either fizzling or consuming the column.

Seed	0	1	2	3	4	5	Deepest
12345	1,003	517	269	134	65	28	9
13345	1,476	773	427	197	83	33	7

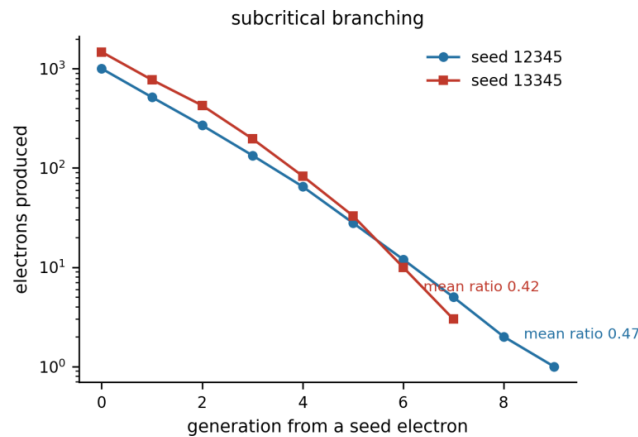


Fig. 4. Electrons produced in each generation of the cascade, logarithmic ordinate. Generation zero is a seed electron from field ionization; each subsequent generation is produced by impact. The ratio between consecutive generations is close to one half and holds through seven to nine generations, which is subcritical branching sustained rather than either runaway or immediate extinction.

The branching ratio near 0.5 is worth dwelling on. A value just below unity is what a mechanism needs in order to produce events of finite, varied extent; the spatial expression of the same decay is the attenuation in Table 5. The decay is caused by electrons running out of energy and fuel, not by any cap.

6.6 Termination requires an attachment loss

Run to exhaustion rather than to a computational limit, the discharge does not stop. The electron population grows – 960 at the start, 1,492 after 400 ms – only 8 per cent of the fuel is consumed, and the



front creeps at about $1,600 \text{ m s}^{-1}$. Two conclusions from an earlier, capped analysis must be corrected: the front speed measured over the first 80 ms is a transient of the opening phase, and the cascade is subcritical per generation but not in aggregate, because continued seeding replenishes the population faster than branching decays it. Without an electron loss term the model produces a sustained glow rather than an event.

Attachment on oxygen is the missing term, and it is the dominant electron loss in real air.

Table 9 *Effect of the attachment length. Without attachment the discharge never terminates. With it, duration and front speed become measurements rather than lower bounds, and both fall inside the interquartile range of the mapped storm in Table 11 at an attachment length of 30 model units.*

Quantity	No attachment	Attach 1.2 km	Attach 2.4 km
Terminates	no	yes, 574 steps	yes, 1,348 steps
Duration	—	229 ms	539 ms
Front speed, advancing	$8.96 \times 10^3 \text{ m/s}$	$1.64 \times 10^4 \text{ m/s}$	$2.17 \times 10^4 \text{ m/s}$
Final reach	1,285 m, rising	845 m	952 m
Firing gap	−59%	−52%	−58%
Neighbours	−7 / −16 / −10%	−2 / −5 / −8%	−2 / −7 / −9%

Repeating the terminating configuration over ten seeds, every discharge ended by exhausting its electrons and none reached the safety limit. Table 10 gives the resulting statistics; they are measurements rather than bounds.

Repeating the terminating configuration over ten seeds, every discharge ended by exhausting its electrons and none reached the safety limit. Table 10 gives the resulting statistics; they are measurements rather than bounds.

Table 10 *Ten terminating discharges. Every one ended by exhausting its electrons; none reached the safety limit, so duration and reach are measurements rather than lower bounds. Attachment length 1.2 km, 30,000 carriers.*

Quantity	Median	IQR	sd
Trigger field (kV m^{-1})	331	278 – 384	58
Duration (ms)	190	175 – 217	26
Front speed, advancing (m/s)	1.44×10^4	$1.18 - 1.75 \times 10^4$	8.0×10^3
Final reach (m)	856	780 – 886	83
Hydrometeors neutralised	167	135 – 180	31
Impact ionizations	402	302 – 438	117
Charge transferred (C)	58	—	39 – 71 range
Charge moment (C km)	48	—	29 – 59 range

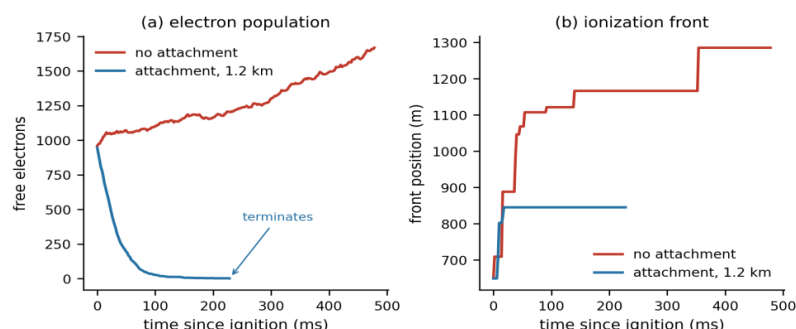


Fig. 5. Why the discharge needs an electron loss. (a) Free electrons against time. Without attachment the population grows and the event never ends; with attachment on oxygen it decays and the discharge terminates by exhaustion at 229 ms in this seed. (b) The ionization front. Both advance quickly for about 100 ms and then stall, which is what limits the reach; the unattached case continues to creep because electrons remain available.

This introduces the central tension in the present state of the model: the term that makes the duration realistic is the term that suppresses the propagation. Without attachment the event spreads but never ends; with it the event ends on time and at the right speed but reaches a quarter as far as observation.

Note also that reach is not speed multiplied by duration – the median $1.44 \times 10^4 \text{ m s}^{-1}$ over the median 190 ms would be 2.7 km against 856 m measured. The front advances quickly for about 100 ms and then stalls while the population decays in place. Real flashes do show fast initial propagation followed by continued activity within the volume already reached, so the shape is not obviously wrong, but the stall is what costs the reach and it is not explained here.

6.7 Front speed as a prediction

Once the clock is fixed by the carrier drift velocity, the speed at which the leading edge of ionization advances is an output. A front cannot outrun its own carriers, so it must come in at or below $4 \times 10^4 \text{ m s}^{-1}$; where within that bound it falls is not something the model was told.

Over the advancing phase the model gives 3.8×10^3 to $1.2 \times 10^4 \text{ m s}^{-1}$ without attachment, and a median $1.44 \times 10^4 \text{ m s}^{-1}$ over ten terminating discharges with it, against an observed range of 10^4 to 10^5 m s^{-1} for in-cloud VHF source propagation. Section 7 makes the comparison against a specific dataset.

7. Comparison with mapped flashes

Two Lightning Mapping Array datasets are used: a West Texas winter storm of 24 December 2023 and an Oklahoma storm of 31 May 2017. Both are reduced with the model's own definitions rather than compared against published flash statistics. This matters more than it may appear. Model quantities and published flash statistics are often defined differently – a per-iteration union of channel cells against a per-flash extent, or a layer thickness against a layer spacing – and comparing them directly manufactures agreement or disagreement that is an artefact of the definitions.

The model reports, for one discharge, an origin, a reach defined as the greatest displacement from that origin along the column axis, a duration from first to last ionization, and a front speed equal to reach divided by duration. The LMA is reduced identically: the first source of a flash is the origin, the reach is



the greatest vertical displacement from it, and the duration is first to last source. Sources are retained at $\chi^2 \leq 1$ with at least six stations; flashes are clustered at $\Delta t \leq 0.15$ s and $\Delta r \leq 3$ km and kept if they contain at least ten sources. The instrument locates VHF sources in three dimensions by time of arrival across a network of stations (Rison et al., 1999); the quality cuts applied here follow the accuracy analysis of Thomas et al. (2004), which sets the location error against source altitude and station count.

Table 11 *Model against mapped flashes, both measured with the model's definitions. Medians with interquartile ranges. The front speed is the quantity the model predicts once its clock is anchored; the reach is the quantity it gets wrong.*

Quantity	Model	OKLMA 2017	WTLMA 2023
Flashes	10	23	47
Sources per flash	—	12 (10–14)	118 (23–493)
Front speed (m/s)	1.44×10^4 (1.2–1.8)	2.05×10^4 (1.6–2.7)	1.69×10^4 (1.1–2.4)
Duration (ms)	190 (175–217)	156 (131–188)	192 (101–324)
Vertical reach (km)	0.86 (0.78–0.89)	3.21 (2.7–3.6)	3.32 (2.6–4.3)
Initiation altitude (km)	6.8 – 8.4	12.8 (11.1–14.8)	5.36 (4.3–7.3)

Front speed and duration both fall inside the WTLMA interquartile range. The duration medians are 190 ms against 192 ms, and the front speed medians differ by 15 per cent. Neither was fitted: the speed follows from a clock anchored on swarm data at a reduced field computed from the model's own initiation altitude and threshold, and the duration follows from the attachment length required for the discharge to terminate at all.

The reach is short by a factor of about four. Since reach, speed and duration are not independent and two of the three agree, the discrepancy is localised rather than distributed: the front advances at very nearly the right speed for very nearly the right length of time, and then stops earlier in space than a real flash does. Three features of the model can produce that, and they are separable.

The first is the softened force law of Sect. 2.7. Softening at the carrier spacing removes the spurious near field, but it also removes the long coherent axial field that would accelerate an electron across several layer periods: the coherent component surviving softening is about three per cent of what a product feels locally, so the model systematically under-drives electrons that have already left the gap they were born in. The second is the absence of a conducting channel. A real bidirectional leader carries its own potential forward as it extends, so the field at the tip is regenerated rather than inherited, and the distance a flash travels is not bounded by the geometry of the gap that started it. The present model has no such object; its front can advance only as far as free electrons are carried by a field the discharge does not renew. The third is carrier density. Section 8.2 shows that below about 100,000 carriers the strongest fields sit at the layers rather than between them, so a front that has crossed one layer enters a region weaker than the sheet geometry assumes.

The first and third are testable within the present code. The second is not, and it is the reason this paper claims a mechanism for initiation and for local field relief rather than a mechanism for flash extent.



Initiation altitude overlaps the winter storm at its upper quartile and does not reach the Oklahoma storm at all. The model column tops out at 10.8 km, so a deep summer storm initiating near 13 km lies outside the configuration rather than contradicting it.

What the comparison does not establish should be stated alongside it. The observables are related but not identical. LMA sources are VHF emissions from fast breakdown and negative-leader processes; the model's front is the leading edge of impact ionization, and a systematic offset between them would not be surprising. The clustering criteria are a common choice but not a published algorithm, and the results will shift somewhat with them. The Oklahoma dataset yields twelve sources per flash, which suggests a distant or poorly detected storm and argues for weighting it below the West Texas set. The model's interquartile range for duration, 175 to 217 ms, is far narrower than the observed 101 to 324 ms: the model produces less variety than nature does, which is expected of a single configuration and is itself a limitation.

8. Sensitivity

8.1 Recombination probability

Electron-ion recombination was initially certain whenever the two came within the collision radius. That is far too fast – two-body recombination in air has a coefficient of order $10^{-13} \text{ m}^3 \text{ s}^{-1}$, and free electrons are lost mostly to attachment rather than to positive ions – and it made recombination the dominant loss, holding ionizations and recombinations equal to within 0.1 per cent and killing every electron before it could travel.

Table 12 *Sensitivity to the recombination probability per encounter, same three seeds throughout. Across a factor of twenty the result moves by about one percentage point; it degrades only at unity, the unphysical extreme. The ionization count in the last column shows the recycling that certain-on-contact recombination produces.*

Probability	Firing gap	Neighbours < 1.1 km	Impact ionizations
0.005	−57.4%	−20.4%	765
0.02	−57.7%	−20.1%	1,058
0.1	−56.3%	−19.3%	1,865
1.0 (certain)	−55.6%	−13.2%	36,468

The spreading result therefore does not depend on the value chosen. It depends on recombination not being certain, which is a statement about physics rather than about a parameter.

8.2 Force softening and carrier density

With point charges the field collapse is a single-iteration spike of about 26 per cent that has vanished by the next sample: a polarization transient. With softening at the carrier spacing it is smaller at the instant of the split and then persists and deepens, 5 to 13 per cent sustained over at least eight iterations. That is the difference between a dielectric response and a discharge, and it appears only once the spurious near field stops scattering the products.



Carrier density matters and is not innocent. Two oppositely charged sheets confine their field to the gap between them, which is the geometry the mechanism assumes, but a layer behaves like a sheet only when its carriers are packed closely relative to its distance from the opposing layer. The preference of the strongest fields for gap regions over layer regions rises from 0.50 at 20,000 carriers through 0.88 at 50,000 to 1.04 at 100,000. Below about 100,000 the field peaks at the layers rather than between them. The runs reported here use 30,000 carriers for tractability, which is below that crossing, and this is a real limitation rather than a detail: it means the trigger is not always located where the mechanism assumes.

That leaves the question of whether the softening length itself sets the result, which is the natural objection to Sect. 2.7: if the coherent axial field surviving softening is only three per cent of the local field, is the collapse an artefact of having suppressed the near field by a particular amount? Table 13 answers it directly. The paired experiment is repeated at three softening lengths spanning a factor of four, under a shortened protocol – a 400 sub-step cap and two host steps – chosen so that the three conditions cost the same and can be compared with each other. The shortened protocol gives a shallower collapse than the full runs of Sect. 6.1, so these figures should be read against one another rather than against the headline value.

Table 13 *Collapse of the field in the firing gap at three softening lengths, identical shortened protocol and identical seeds throughout. The softening also alters the settled column, so these are three columns rather than one column under three force laws; the discharge is measured on whatever column each condition produces.*

Seed	$\varepsilon = 3 \text{ u (120 m)}$	$\varepsilon = 6 \text{ u (240 m)}$	$\varepsilon = 12 \text{ u (480 m)}$
12345	–37%	–30%	–50%
13345	–26%	–36%	–48%
mean	–31%	–33%	–49%

Over a factor of four in softening length the collapse stays between –26 and –50 per cent, and such trend as there is runs towards a deeper collapse at longer softening. That is the opposite of what the objection predicts: if the collapse were an artefact of suppressing the near field, lengthening the softening would weaken it. The result is not an artefact of the value chosen. What the softening does change is the column, since it acts on the charging model as well as on the discharge, and the triggering gap is at a different altitude in each condition – so the invariance reported here is the stronger kind, across three different settled states rather than across one state treated three ways.

8.3 Air fill density

At an air fill equal to the hydrometeor density there are zero impact ionizations: electrons meet a hydrometeor and are captured before they find a molecule. The avalanche requires a fill well above unity, and this is physically correct, since real air molecules outnumber hydrometeors by some twenty orders of magnitude. The results here use a factor of ten.

9. Implications for lightning research



Three of the results above are statements about real storms rather than about the model, and each of the three can be tested against observations that have already been collected.

9.1 A structural criterion for initiation

Why lightning begins at fields near a tenth of the conventional breakdown value is the oldest unresolved question in the subject (Marshall et al., 1995; Petersen et al., 2008; Dubinova et al., 2015), and the explanations offered for it are local ones: field enhancement at the tips of elongated hydrometeors, runaway electrons seeded by cosmic ray showers, positive streamers launched from large ice particles. The result of Sect. 4 adds a condition of a different kind, geometric rather than microphysical, and independent of which of those local processes supplies the first electron. Identical charge, identical layers, identical spacing, identical carrier count: spread smoothly through each layer the structure produces 19 kV m^{-1} and never fires, and gathered into local concentrations the same charge produces up to 196 kV m^{-1} and does. What determines whether a gap can reach the ionization level is therefore not the layer-averaged field. It is the concentration of charge within the layer.

That is a claim about storms and it is falsifiable. It predicts that initiation should correlate with the small-scale heterogeneity of charge inside a layer rather than with the mean field across it, so that two soundings yielding the same layer-mean field should differ in initiation rate according to the structure within the layers. Balloon soundings resolve the electric field at metre scale and lightning mapping arrays locate initiation points to tens of metres. The two quantities can be placed side by side in data that already exists, without a new instrument or a new campaign.

9.2 What stops a flash

With the electron attachment loss removed the discharge does not terminate at all (Sect. 6.6): it exhausts the sub-step budget with its electron population still growing. With attachment on oxygen, every one of ten discharges terminates by exhausting its electrons, at a median 190 ms against 192 ms for the mapped winter storm. The attachment length was not fitted to the observed duration. It was bounded by the requirement that the discharge terminate at all, and the agreement in duration followed from that bound rather than being imposed on it.

If flash duration is set by dissociative attachment on oxygen rather than by channel geometry or by the quantity of charge available, then it should scale with the oxygen number density and so should fall with altitude. Flash duration and initiation altitude are both routine products of a lightning mapping array, which makes the predicted trend directly measurable in existing archives, and its absence would falsify the identification.

9.3 A charge budget that closes

The stochastic dielectric-breakdown scheme used in cloud-resolving electrification models sets the charge inside the grown channel to zero, which removes net charge from the domain at every flash (Sect. 1). Any quantity that depends on the storm charge budget across more than one flash therefore inherits an unphysical sink: the recharge time between flashes, the equilibrium charge structure that the storm relaxes toward, and the flash rate that follows from both. Flash rate is precisely the statistic that lightning parameterizations in weather and climate models are asked to deliver.



603 The scheme described here conserves charge at every reaction by construction, and conservation is
 604 asserted in code at each event rather than assumed to hold. It is not offered as a drop-in replacement for a
 605 breakdown lattice – it is far more expensive, and Sect. 10 sets out what it does not yet do – but it
 606 establishes that a charge-conserving discharge is achievable inside a particle model, and it provides a
 607 reference against which the charge error of a cheaper scheme can be measured rather than tolerated.

608 None of the three depends on the reach agreeing with observation. The shortfall reported in Sect. 7
 609 bounds what this model can say about how far a flash travels. It does not bear on where flashes begin, on
 610 what brings them to an end, or on whether charge is conserved while they proceed.

611 10. Limitations

612 The charging model is a layer generator, and the discharge results are conditional on the layered structure
 613 it produces rather than on the process that produced it. That conditionality is demonstrated and not merely
 614 asserted: Sect. 4 runs the identical discharge on layers assembled by hand in a column no vortex has ever
 615 acted on, and the discharge behaves the same way. The structure it requires is also observed
 616 independently of any model, since balloon soundings find four to six alternating layers of a few hundred
 617 metres in real storms (Stolzenburg et al., 1998). The mechanism therefore rests on a measured feature of
 618 thunderclouds rather than on a modelled one.

619 Gravity is nonetheless zero in the runs reported here, and its absence should be placed correctly rather
 620 than either dismissed or overstated. Differential sedimentation of oppositely charged graupel and ice
 621 crystals is what atmospheric electricity credits with building the storm-scale vertical dipole (Takahashi,
 622 1978; Saunders et al., 2006), and a model without it cannot claim to reproduce that structure, nor the
 623 cloud-to-ground discharge that spans it. It is a weaker constraint on what is examined here. The
 624 mechanism acts on the field in the gap between two adjacent layers a few hundred metres apart, and the
 625 events it is compared against in Sect. 7 are intracloud flashes propagating within and between such layers.
 626 For that geometry the quantities that matter are the layer spacing and the concentration of charge inside
 627 the layers, both specified in Sect. 4 and matched to observation, and not the buoyancy-driven process that
 628 set the layer altitudes in the first place. The absence of gravity bounds what the charging model may
 629 claim about the large-scale charge structure. It does not bound the discharge result, which begins after that
 630 structure exists.

631 The carriers themselves remain coarse. They have no size spectrum and no fall speeds, their charge-to-
 632 mass ratio is far from that of real hydrometeors, and each stands for of order 10^{10} of them, so a contact
 633 between two carriers is not a hydrometeor collision. This is why the charging component is described as a
 634 generator of layered structure and not as a microphysical model of electrification.

635 Within the discharge itself, four limitations are worth naming. The model produces no light, so it cannot
 636 be compared against optical or VHF observations except through the geometric proxies used in Sect. 6. It
 637 produces one event per run and cannot generate a flash rate, which is the statistic most often reported for
 638 real storms. All propagation measured is axial, whereas intracloud flashes propagate horizontally through
 639 charge layers at least as much as vertically. And the model contains no conducting channel: a real leader
 640 carries its own potential forward as it extends, which is how charge crosses the hundred-megavolt
 641 structures measured in Sect. 6.4, and nothing here corresponds to that object.



642 The drift velocity on which the clock is anchored is the single external constant in the model. It is not
643 measured here and it is not derived here; it is taken to be $4 \times 10^4 \text{ m s}^{-1}$ at 27 Td on the strength of dry-air
644 swarm compilations, and every duration reported scales inversely with it while every speed scales with it.
645 A two-term Boltzmann solution for the exact mixture, temperature and reduced field would fix it to better
646 than the ten per cent that separates published cross-section sets, and until that is done the absolute
647 durations quoted here should be read as accurate to a factor of order unity. Nothing else in the paper
648 depends on it: the field collapse, the attenuation length, the path-length ratio, the crossing fractions and
649 the generation depth are all dimensionless or in metres, and are unaffected.

650 11. Conclusions

651 A discharge scheme built from ionization of the air between charge layers, with no channel and no
652 propagation rule, conserves charge exactly and produces localised events that relieve the field where they
653 start and, to a lesser degree, for about two kilometres on either side. What it requires of the charge
654 structure is layering together with local concentration within the layers: a hand-built smooth layered
655 column carrying identical charge produces a field an order of magnitude too small and never discharges,
656 while gathering the same carriers into concentrations raises the field tenfold. Two quantities that would
657 ordinarily be free are derived: the separation at which a newly created pair is unbound, from the balance
658 between its own Coulomb field and the ambient; and the timestep, from the electron drift velocity at the
659 reduced field the model itself produces.

660 Individual trajectories show the transport asymmetry that the electron-to-molecule mass ratio requires,
661 with electrons travelling some two hundred times further than ions, a third of them crossing a charge
662 layer, and a quarter of all ionization occurring beyond the layer the responsible electron was born behind.
663 The cascade is subcritical per generation at a branching ratio near one half, sustained through seven to
664 nine generations.

665 Without an electron attachment loss the discharge does not terminate. With attachment on oxygen every
666 one of ten discharges terminates by exhausting its electrons, at a median duration of 190 ms and a median
667 front speed of $1.44 \times 10^4 \text{ m s}^{-1}$ against 192 ms and $1.69 \times 10^4 \text{ m s}^{-1}$ for flashes measured in a mapped
668 winter storm using the model's own definitions, and neither quantity was fitted to it. The reach remains a
669 factor of four short, and the term that makes the duration realistic is the term that suppresses the
670 propagation. That tension, and the stall that produces it, are the clearest open problems this work leaves.

671 Code and data availability

672 The Thunder model v1.0, the analysis scripts, the Lightning Mapping Array reduction described in Sect. 7
673 and the configuration for every run reported here are archived at Zenodo (Harkiolakis, 2026). The model
674 is written in Python 3 and depends only on NumPy; it runs on a single core of a standard desktop
675 computer, and the longest run reported here completes in under ten minutes. Licence: [to be stated at
676 deposit]. A browser implementation of the same scheme, in which the twelve parameters listed in Sect. 2
677 are fixed in source and not exposed through the interface, is included in the archive as a single self-
678 contained HTML file so that the results can be replicated without installing anything.

679 Every result in this paper regenerates from the deposited code with the commands listed in the archive
680 README. The random number generator is seeded deterministically, so a given seed reproduces a bit-



681 identical column and a bit-identical discharge. The Lightning Mapping Array observations used in Sect. 7
682 are from the West Texas LMA for 24 December 2023 and the Oklahoma LMA for 31 May 2017; the
683 reduced source files and the clustering script that produced Table 11 from them are included in the same
684 archive.

685 **Author contribution**

686 NH designed the study and the discharge mechanism, wrote the model and the analysis code, performed
687 all simulations, carried out the analysis, and prepared the manuscript.

688 **Competing interests**

689 The author declares that they have no conflict of interest.

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691 Large language model assistance (Anthropic Claude) was used in implementing and debugging the
692 simulation code, in executing and tabulating the numerical experiments reported here, and in editing the
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