Cloud Electrification

- **Observations**
  - Clouds need to be 3-4km thick before we notice significant electrification. The deeper the clouds the more electrification (lightning)
  - Only cold clouds show significant electrification (ice is important)
  - Electrification observed in clouds with strong updraft velocities
  - The charged regions in clouds depend on temperature.
Observations

• The charging of clouds is related to the development of rain in clouds
• The first lightning discharge in storms occurs 15-20 min after the detection of large particles (rain, hail, graupel,...) in clouds
• Length of electrical activity in cloud is ~30 min and starts before the rain.
• Location of lightning is close to the heaviest precipitation.
Schematic tripole structure of thunderstorms (the “classical view”)

![Schematic diagram of thunderstorms](image)
The updated view (Stolzenburg et al., JGR, D103, 14097-14108, 1998)
Cloud Hydrometeor Sizes and Fall Speeds

- Cloud droplets: \( r < 0.1 \) mm, \( V \sim 0.01 \) m/sec, \( n=1,000,000 \) per liter
- Drizzle: \( 0.25 \) mm > \( r > 0.1 \) mm, \( V > 0.3 \) m/sec
- Rain: \( r > 0.25 \) mm, \( V > 0.5 \) m/sec, \( n=1 \) per liter
- Cloud Ice, size = \( F(T) \), \( n= F(T) \)
- Snow (aggregates, crystals): \( V \sim 0.3 – 1.5 \) m/sec
- Graupel (soft hail): \( V \sim 1-3 \) m/sec ; Density \( \sim 0.7 \) g/cm^3
- Hail: \( r > 10 \) mm ; \( 50 \) m/sec > \( V > 3 \) m/sec
# Thunderstorm Categorization

*Williams, JGR, 100, 1503-1505, 1995*

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Start if from Precip. \ Winter</th>
<th>Ordinary Thunderstorm</th>
<th>Super Hailstorm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash Rate (min⁻¹)</td>
<td>0.1 - 1</td>
<td>1 - 50</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>Updraft (m s⁻¹)</td>
<td>&lt; 1</td>
<td>1 - 50</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>Ice Precipitation</td>
<td>Low density graupel, aggregates</td>
<td>High density graupel</td>
<td>Wet growth hail</td>
</tr>
<tr>
<td>Ice particle speed (m s⁻¹)</td>
<td>1 - 3</td>
<td>3 - 10</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>LWC (g m⁻³)</td>
<td>&lt; 0.2</td>
<td>0.2 - 5</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>Predominant polarity of CGs</td>
<td>positive</td>
<td>negative</td>
<td>positive</td>
</tr>
<tr>
<td>Dipole polarity in ice region</td>
<td>negative</td>
<td>positive</td>
<td>Positive (?)</td>
</tr>
</tbody>
</table>
Cloud Electrification

The process of thundercloud electrification can be broken into 3 stages:

1. Charge separation within cloud particles (droplets and ice)
   1.1 Inductive processes (within an external electric field)
   1.2 Non-inductive processes (connected to melting, temperature gradients)

2. Generation of charged cloud particles
   2.1 Breakup of droplets and ice
   2.2 Collisions between particles (charge transfer between particles)
   2.3 Ion capture by cloud particles

3. Charge Separation on the cloud scale by updrafts and downdrafts within the cloud. Large particles fall towards the cloud base faster than small particles, while small particles can be transported aloft to the cloud top more easily than large particles. In order to explain the charge distribution in clouds, the larger particles need to get negative charges, and the smaller particles positive charges.
Charging of clouds by the external field: screening layer and convection

- Clouds create a discontinuity in the fair-weather electrical current flow between the ionosphere and ground.
- The drift of ions in the ambient field will result in the accumulation of negative charge in cloud base and positive charge on cloud top.
- A screening layer is formed due to the ion-droplet attachment.
- The field within the cloud is increased by the charge accumulated at the boundary.
Convective charging
(Grenet (1947), Vonnegut (1953))

• The mechanism is based on the vertical transport of atmospheric ions by cloud updrafts inside the developing cumulus cloud and by compensating downdrafts outside.

• Since positive ions are more abundant near the ground (the electrode effect and point discharges), they are carried aloft and attract small negative ions from the clear air above the cloud.

• The negative ions attach to cloud particles and create a screening layer at the outer cloud boundary, that is carried by downdrafts to the lower part of the cloud, increasing positive ion production by point discharge and forming a positive-feedback.

• In experiments by Moore et al. (JGR, 94, 13,127-34,1989) large amounts of negative ions were released from the ground and ingested into developing cumulus clouds. The expectation was to produce an inverted dipole with positive charge below the negative charge. One case showed the expected result, suggesting that ions in the boundary layer play a role in cloud charging.
Fig. 3.15. Convective charging mechanism. (a) As a small growing cumulus cloud forms, it ingests positive space charge and forms a negative screening layer at the cloud boundary. (b) Organized transport of negative charge occurs as cloud particles on the boundaries move down the sides toward the cloud base. Inflow of positive charge continues in the updraft, and current continues to flow to the top of the cloud to adjust to the newly ingested positive charge and to the loss of screening-layer charge from the top due to transport down the sides of the cloud. (c) The electric field from negative charge in the lower part of the cloud becomes strong enough to produce corona at Earth’s surface, thereby increasing the flux of positive charge into the cloud base. Transport of negative charge continues down the sides of the cloud from cloud top. (B. Vonnegut, personal communication, 1996, with permission)
1. Charge separation within drops and ice particles

1.1 **Inductive Processes** (what is induced charge due to external field)

If we start with the electric field $E_o$ (that can change as the cloud develops).

![Diagram of a neutral conductive sphere with charge distribution]

The distribution of charge on a neutral conductive sphere with radius $a$, within a vertical electric field.
Equations within drop (total charge is zero):

\[ \nabla \cdot \mathbf{E} = 0 \]

\[ \nabla^2 V = 0 \]

\[ \mathbf{E} = -\nabla V \]

Boundary conditions for the potential:

1. As \( r \to \infty \)
   \[ \mathbf{E} = -\nabla V = E_0 \]

2. At \( r=a \)
   \[ V = \text{const} = 0 \]

Solution:

\[ V = \left( \frac{a^3}{r^3} - 1 \right) \mathbf{E}_o \cdot \mathbf{r} \]

This solution fulfils the equation and the boundary conditions, and is a unique solution.

\[ \mathbf{E} = -\nabla V = - \left[ -3 \frac{a^3}{r^4} (\mathbf{E}_o \cdot \mathbf{r}) u_r + (\frac{a^3}{r^3} - 1) \mathbf{E}_o \right] \]

Where \( u_r \) is the unit vector in the direction \( r \).
On the surface of the sphere:

1. \( \mathbf{E} = 3(\mathbf{E}_o \cdot \mathbf{r}) \mathbf{u}_r = 3 \mathbf{E}_o \cos \theta \mathbf{u}_r \)

2. The surface charge density \( \rho = \varepsilon_o \mathbf{E} = 3 \varepsilon_o \mathbf{E}_o \cos \theta \)  
   (\( \mathbf{E} \) is normal to surface)

3. The charge on half the sphere is: 
   \[ Q = \int_{\text{Half sphere}} 3 \varepsilon_o \mathbf{E}_o \cos \theta \, ds \]

If we divide the sphere into rings around the axis parallel to the electric field:

\[ ds = 2 \pi a \sin \theta \, a \, d\theta = -2 \pi a^2 \, d\cos \theta \]

\[ Q = \int_0^{\pi/2} 3 \varepsilon_o \mathbf{E}_o \cos \theta (-2 \pi a^2) \, d\cos \theta \]

\[ = -6 \pi a^2 \varepsilon_o \mathbf{E}_o \int_0^{\pi/2} \cos \theta \, d\cos \theta \]

If \( x = \cos \theta \)

then   \( \theta = 0 \rightarrow x = 1 \) \[ Q = -6 \pi a^2 \varepsilon_o \mathbf{E}_o \int_0^1 x \, dx = 3 \pi \varepsilon_o a^2 \mathbf{E}_o \]

If \( \theta = \pi/2 \rightarrow x = 0 \)
4. Conclusion: This is the maximum charge allowed by inductive processes (if we cut the sphere exactly in the equatorial plane into two equal parts). Generally, only part of this maximal charge is reached, but

\[ Q_{\text{ind}} \propto a^2 E_o \]

As the field increases, so does the induced charge. Likewise if the particle (drop or ice) grows in size in the field, so does the induced charge.

5. Estimate:
The maximum observed fields in thunderstorms are \( E_{\text{max}} \sim 4 \times 10^5 \text{ V/m} \)
If \( a \sim 1 \text{ mm} \)

\[ Q \sim \frac{3}{4} (4\pi \varepsilon_o) a^2 E_o = \frac{3}{4} \frac{1}{9 \times 10^9} \times 10^{-6} \times 4 \times 10^5 = 3 \times 10^{-11} \text{ Coulombs} \sim 2 \times 10^8 \text{ e} \]

\[ M \sim \frac{1}{2} \left(\frac{4\pi a^3}{3}\right) \rho_w \sim 2 \times 10^{-9} \text{ kg} \quad (\rho_w \sim 1 \text{ kg/m}^3) \]

\[ \frac{Q}{M} \sim 0.015 \text{ Coul/kg} \]
1.2 *Non-inductive Charging*

1.2.1 *The Thermoelectric effect (in ice)*

a) For all temperatures > 0K some of the water molecules separate into $H^+$ and $OH^-$ ions.

b) The concentration of ions increases with temperature

c) $H^+$ has a much higher mobility than $OH^-$ (order of magnitude difference.)

\[
\begin{align*}
&T_1 \\
&H^+OH^- \quad \text{H}^+OH^- \\
&H^+OH^- \quad \text{H}^+OH^- \\
&T_2 > T_1
\end{align*}
\]

\[
\begin{align*}
&H^+ \quad \text{OH}^- \\
&H^+OH^- \quad \text{H}^+OH^- \\
&H^+ \quad \text{H}^+OH^- \\
&H^+OH^- \quad \text{OH}^-
\end{align*}
\]

\[
\frac{-dV}{dT} \frac{dT}{dx} = - \frac{dV}{dx} = E = k_T \frac{dT}{dx}
\]

\[
k_T = \frac{-dV}{dT} \sim 2 \text{ mV/°C}
\]
For a sphere:

\[ \rho_{th} = \varepsilon_o E_{th} = \varepsilon_o k_T \frac{\Delta T}{R} \]

\[ \rho_{ind} = 3\varepsilon_o E_o \cos \theta \sim \varepsilon_o E_o \]

\[ \frac{\rho_{th}}{\rho_{ind}} \sim k_T \frac{\Delta T}{RE_o} \approx 0.2 < 1 \]

Therefore, generally the inductive charging is greater than the thermoelectric charging.

If the drop freezes from the outside inward (drop carried up into cold region of cloud), because the density of ice < density of water, or volume of ice > volume of water, the outer ring of ice will explode, leaving a large particle with negative charge, and many smaller ice crystals charged positively.

The thermoelectric effect is characteristic of water ice only due to the ionic structure of water molecules. This process occurs in the upper parts of the cloud where temperatures are well below 0\(^\circ\)C.
1.2.2  *Water-ice potential* (Faraday, 1843)
It is generally possible to get charging of any material due to friction between the liquid and solid phase of the same material.

a) In water there is normally higher concentrations of ions (lower activation energy).

b) As before, the mobility of the positive ions $H^+$ are higher than the negative ions.

\[ \Delta V \approx 0.15 \text{ V} \]

The phenomenon occurs during collisions between drops and ice crystals.
Positive ions are released into the water while the negative ions remain trapped in the ice. This is opposite to the thermoelectric effect. For the thermoelectric effect charge is produced by ions that migrate within the ice crystal. For electro-freezing the charge is formed by ions that do not manage to escape during freezing.

Summary: When a drop freezes charge is separated such that the negative charge is on the surface of the ice crystal. If after freezing we continue to cool the ice, the temperature gradient results in the opposite charging with positive charge on the surface. The same situation is created by collisions between hail and cloud drops.
1.2.4. *The Water-fall effect* (Lenard 1892)

Measurements show that electric fields exist at the bottom of water falls. The water droplets carry a positive charge while the air has a negative charge.

**Explanation:** Organisation of the water molecules in the outer layer of the water drops. Due to friction with the air, negative charge is transferred to the air. The presence of foreign atoms within the water reduces the effect.

![Schematic of a water molecule](image)

*Fig. 3.8.* Schematic of a water molecule. The numerical values shown are typical for liquid water.

1.2.5 Release of air bubbles within water drops (melting ice) – the bubbles are negatively charged.
2. Generation of Charged drops

2.1 Selective Ion Capture (Wilson Effect, 1929)

![Diagram of charged drops]

a) for a neutral sphere

\[ u < v_+, v_- \]

b) for a negatively charged sphere

\[ u > v_+, v_- \]

We can consider the sphere as if standing still and the ions of opposite charge being attached to the opposite poles at the same rate.

Ions are attached to the bottom of the sphere. The faster the velocity \( u \) the greater the charging, and the larger the particles, the larger the charging.
Fig. 3.10. Selective ion capture. (a) Collision between an uncharged water drop polarized in an electric field and a negative ion. (b) Deflection of a positive ion from an uncharged polarized drop.
2.2  **Breakup of drops and ice**

Drops breakup as they fall through the cloud

<table>
<thead>
<tr>
<th>Type of breakup</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheet – vertical shear</td>
<td>55%</td>
</tr>
<tr>
<td>Neck – rotational shear</td>
<td>27%</td>
</tr>
<tr>
<td>Disk – horizontal shear</td>
<td>18%</td>
</tr>
<tr>
<td>Bag</td>
<td>&lt;0.5%</td>
</tr>
</tbody>
</table>

Ice breaks up due to collisions, leaving small positively charged particles, and large negatively charged particles.
2.3 Charge transfer by collisions (Elster and Geitel effect, 1888)

After collision:
small sphere has + charge
large sphere has - charge

Charge transfer:

“Zero-order” assumption: \[ \Delta Q \sim -\rho_R(\theta) \pi r^2 \]

Contact area

\[ \sim -3\epsilon_0 E \cos\theta \pi r^2 \propto -E r^2 \cos\theta \]
Corrections:

1. **Drop shape**: If the drop is oval (instead of spherical) the charge density can be higher, therefore:

   \[ \Delta Q = -\gamma_1 \varepsilon_o E \cos \theta \ r^2 \]

   where \( \gamma_1 \) is a coefficient related to the drop drop geometry.

2. **Time of contact**: The charge transfer depends on the surface electrical conductivity of the water/ice. For an ice particle in the lower atmosphere the conductivity is low, i.e. a long time is needed for the charge transfer. If the time is long relative to the time of contact, the charge transfer is not efficient.

   \[ \Delta Q = -\gamma_1 \varepsilon_o E \cos \theta \ r^2 (1 - e^{-t_c/\tau}) \]

   Where \( t_c \) – time of contact during collision \( 10^{-4} – 10^{-6} \) sec
   
   \( \tau \) - electrical relaxation time depends on temperature

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>( \tau ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-19</td>
<td>( 3 \times 10^{-2} )</td>
</tr>
<tr>
<td>-10</td>
<td>( 7 \times 10^{-3} )</td>
</tr>
</tbody>
</table>

   \[ 1 - e^{-t_c/\tau} \sim 3 \times 10^{-5} - 1.5 \times 10^{-2} \]
3. Charge on the large sphere:
The more the large sphere is charged due to the collisions, the harder it becomes to transfer additional charge. If the large sphere has a charge $Q$, then the charge density on the surface is given by the superposition:

$$\rho_R = 3\varepsilon_0 E_0 \cos\theta + \frac{Q}{4\pi R^2}$$

Where the two terms are opposite in sign. Therefore:

$$\Delta Q = -(\gamma_1 \varepsilon_0 E_0 \cos\theta + \gamma_2 \frac{Q}{R^2}) r^2 (1 - e^{-tc/\tau})$$

$\Delta Q < 0$ as long as

$$\gamma_1 \varepsilon_0 E_0 \cos\theta > \gamma_2 \frac{Q}{R^2}$$

<table>
<thead>
<tr>
<th>$r/R$</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_1$</td>
<td>4.9</td>
<td>3.9</td>
<td>3.1</td>
<td>2.6</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

$$Q < \frac{\gamma_1}{\gamma_2} R^2 \varepsilon_0 E_0 \cos\theta = Q_{\text{max}}$$

After drop reaches $Q_{\text{max}}$ it starts to lose negative charge, therefore:

$$Q_{\text{max}} \sim E_0 R^2$$
4. Charge on the small sphere: If we look at the simple case of charge transfer between two charged spheres

\[ R, Q_1, Q_2 \quad \text{and} \quad r, q_1, q_2 \]

Conservation of charge: \( Q_1 + q_1 = Q_2 + q_2 \)

Comparison of potential: \( \frac{Q_2}{R} = \frac{q_2}{r} \)

Therefore \( q_2 = \frac{r}{R} Q_2 \)

\[ Q_1 + q_1 = Q_2 \left(1 + \frac{r}{R}\right) = Q_2 \frac{R+r}{R} \]

\[ Q_2 = \frac{R}{R+r} (Q_1 + q_1) \]

\[ \Delta Q = Q_2 - Q_1 = \left(\frac{R}{R+r} - 1\right) Q_1 + \frac{R}{R+r} q_1 \]

If \( w = \frac{R}{R+r} \) then \( \Delta Q = \left[-\gamma E_o \cos \theta r^2 + (w-1) Q + wq\right] (1 - e^{-tc/\tau}) \)

This correction includes the previous correction as well.

\[ \Delta Q = \left[-\gamma E_o \cos \theta r^2 + w_1 Q + w_2 q\right] (1 - e^{-tc/\tau}) \]
The final rate of charging due to collisions is:

\[
\frac{dQ}{dt} = \pi (R+r)^2 \ (V-v) \ n \ \Delta Q
\]

- \(\pi (R+r)^2\) - Cross section
- \(V-v\) - relative velocity
- \(n\) - particle density

The rate of charging of the big particle as a result of collisions with all the small particles.
Non-inductive graupel-ice interaction

T, LWC

Riming Graupel

Supercooled water

Ice particle

- A 3 mm diameter rod (ice target, simulating the graupel) was rotated through a cloud of super-cooled droplets and vapor-grown ice crystals at speeds of 9 m s⁻¹.

- At temperatures warmer than minus 10°C the rod was charged positively at all LWCs.

- At colder temperatures, intermediate LWCs produced negative charge on the graupel.

Charge (in fC) gained by the rimed graupel as a function of temperature and liquid water content. Open circles indicate positive charge, solid ones indicate negative charge.
Saunders et al. *(JGR, 96, 11,007-11,017, 1991)*
Saunders & Brooks *(JGR, 97, 14,671-14,676, 1992)*

- Previous experiments by the UMIST group showed that liquid droplets not colliding with riming graupel target had no effect on the charging process.
- Defined an “Effective LWC” to compensate for the fact that some of the droplets are swept away from the particle due to aerodynamic forces.
- EW is determined by the LWC multiplied by the fraction of droplets in the graupel path that are collided and adhered to the graupel.

The charging zones as a function of temperature and effective liquid water content. The velocity of the graupel target was 3 m s\(^{-1}\) (three times slower than Takahashi, 1978)
The Integrated View

• Bold dashed lines denote the charging regions according to Saunders et al. (1991), as translated from EW to LWC (by noting that EW is usually 0.5 of the present LWC)
• It is superimposed on the charging regions found by Takahashi (1978)
• The results are in broad agreement even though the experimental settings were different
Non-inductive graupel-ice interaction: Microphysical explanations in light of observational constraints

- Significant charging occurs only when the larger particle is rimed and at least a small amount of cloud liquid water are present.
- If liquid water contents are large, graupel becomes positively charged.
- At small liquid water contents graupel tends to become negatively charged.
- Near 0°C, graupel charges positively for most of the range of liquid water contents.
- Though the amount of charge per collision increases with size of the ice crystal size, it approaches a limit.
- The results of a single interaction can differ substantially from the mean.
The maximum charge on a hydrometeor

- Average charge magnitudes for cloud and precipitation particles.
  - $C_1$ and $C_2$ refer to the cloud stage
  - $R_1$ and $R_2$ refer to rain stage in shallow and deep convection
  - $H_1$ and $H_2$ refer to hail stage

Taken from Beard and Ochs, 1986
Cloud Electrification - Summary

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4x10^5 V/m
or 400 kV/m
Consensus: inductive charging is a secondary mechanism

- “The inductive mechanism is attractive because it is simple but in view of the difficulties it is hard to imagine how it may operate as a viable charge generation mechanism in thunderstorms”. (Jayarante, 2003; in “The Lightning Flash” by V. Cooray)
- “Because the inductive mechanism has appeared most likely to have a significant effect when the preexisting electric field is substantially larger than the fair weather field, the role usually hypothesized for the mechanism has been to intensify the electrification initially achieved by other mechanisms”. (MacGorman and Rust, 1998).
- “The significance of the mechanism to thunderstorm electrification is still open to question. There are strong doubts about its ability to act as the primary charging mechanism since it is unable to account for the observed charges in the early stages of thunderstorms... It seems more likely that it acts as a contributory mechanism in the later stages of electrification....”(Brooks and Saunders, 1994).

Consensus: non-inductive charging is primary mechanism
Fig. 3.2. Depiction of the charge structure of a thunderstorm as derived from measurements by Simpson and colleagues. A thunderstorm is described as a positive dipole (positive above negative charge) or a tripoles, which is shown here. The lower positive charge center in this simple model may not always be present.
Fig. 4.2. Typical thundercloud cell illustrating its dimension, electric charge distribution, and convective winds.
FIGURE 8.1 An isolated thundercloud over Langmuir Laboratory in central New Mexico and a rudimentary picture of how electric charge appears to be distributed inside and around the thundercloud, as inferred from in-cloud and remote observations.
Summary

• Electrification of clouds needs convection of at least 3-4km, ice phase microphysics, and strong updrafts (w>10 m/sec)
• For clouds to get electrically charged we need:
  - charge separation within drops or ice
  - generation of particles with net charge (+ or -)
  - separation of charged particles to regions of + and – charge
• Main charging mechanism is the non-inductive mechanism
• Thunderstorms have positive charge near their tops, and negative charge near their base.