MECHANISMS OF CLOUD ELECTRIFICATION

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ATMOSPHERIC CONDUCTIVITY

IONS PRODUCED BY

- cosmic rays
- radioactive substances in the crust (U238, U235, Th232 which emit α,β,γ rays)

2 CATEGORIES

- ***small ions*** = singly charged molecules
  B_+^{small} [m²/sV] = $1.4 \cdot 10^{-4}\, e^{0.14z[km]}$
  B_-^{small} [m²/sV] = $1.9 \cdot 10^{-4}\, e^{0.14z[km]}$
- ***large ions*** = attach to much larger particles
  $B^{big} \sim 10^{-8}$ [m²/sV] → little contribute

production processes

distruction processes

$$p = \alpha n^2 + \beta n N$$ small ions concentration

αn^2 = ricombination between small ions

βnN = capture from other particles of concentration N

ELECTRICAL BALANCE IN ATMOSPHERE

CONDUCTION CURRENT DENSITY DUE TO IONIC DRIFT $\vec{j}_{q,cond} = \Sigma_i n_i q_i \vec{v}_i$

DRIFT VELOCITY $\vec{v}_i = (q_i/|q_i|)B_i\vec{E}$

$\Rightarrow \vec{j}_{q,cond} = \lambda_{air}\vec{E} = (\lambda_+ + \lambda_-)\vec{E}$

where $\lambda_+ = en_+B_+$

$\lambda_- = en_-B_-$

$j_{q,cond} \sim 2.7 \cdot 10^{-12} A/m^2$ (observed)

CONSTANT AIR-TO-EARTH CONDUCTION CURRENT DENSITY

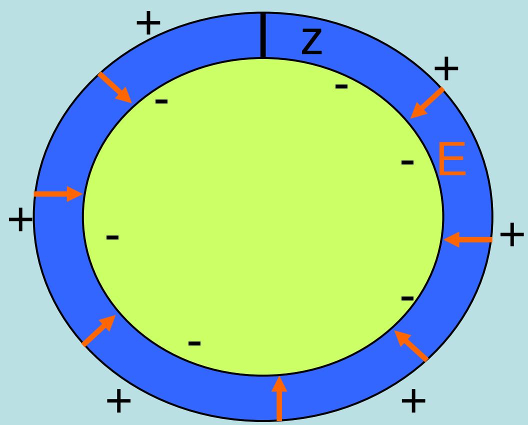
$\lambda_{air} = 2.7 \cdot 10^{-12}/130 \sim 2.1 \cdot 10^{-14} \Omega^{-1} m^{-1}$

FAIR WEATHER SEA LEVEL CONDUCTIVITY

(for other levels: $\lambda = 130\lambda_{air}/E$)

THE GLOBAL CIRCUIT

FAIR WEATHER ELECTRICAL STATE → Background conditions to which an isolated cloud is exposed



EARTH SURFACE/ CONDUCTIVE LAYER Z = SPHERICAL CONDENSATOR

$$\begin{cases} E\,(z=0) = 4\pi\sigma_0 = \sigma/\varepsilon_0 \sim -130\,V/m \\ E\,(z=18km) = 0\,V/m \end{cases}$$

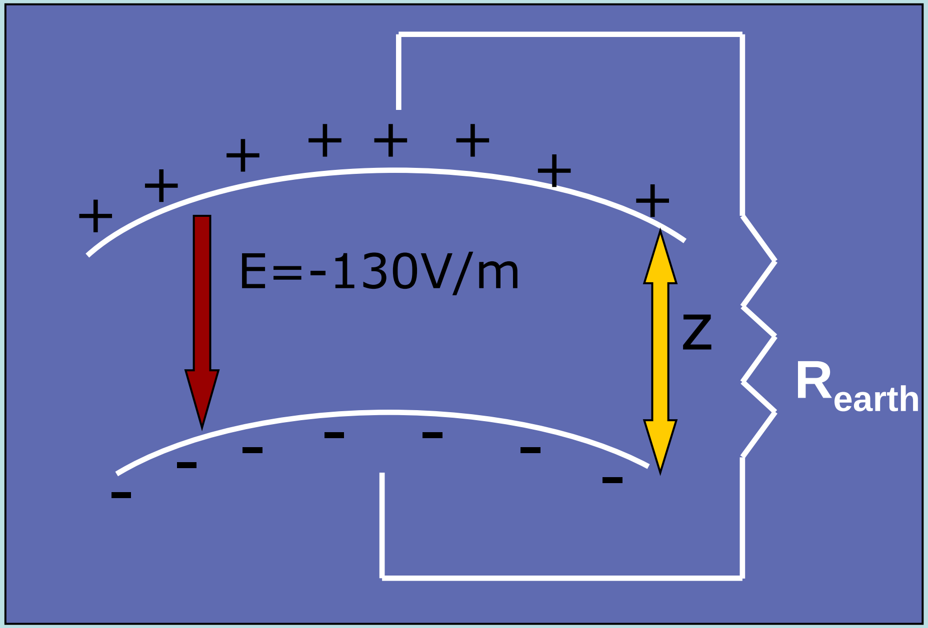
surface charge density
$\sigma_0 = -3.4\cdot10^{-4}\ e.s.u.cm^{-2} = -1.1\cdot10^{-9}Ccm^{-2}$

surface area
$A_s=5\cdot10^{14}m^2$

⇒ Total fair weather charge

$Q=5.1\cdot10^5C$

THE ATMOSPHERE-EARTH CONDENSATOR



$$R_{column}(z) = \int_0^z dz/\lambda(z)$$

$R_{earth} = 200\Omega$

$I_{earth} = 1800A$

$C_{earth} = 0.25F$

$$\frac{dR_{column}(z)}{dz} \longrightarrow 0 \quad \Rightarrow \quad z \sim 18km$$

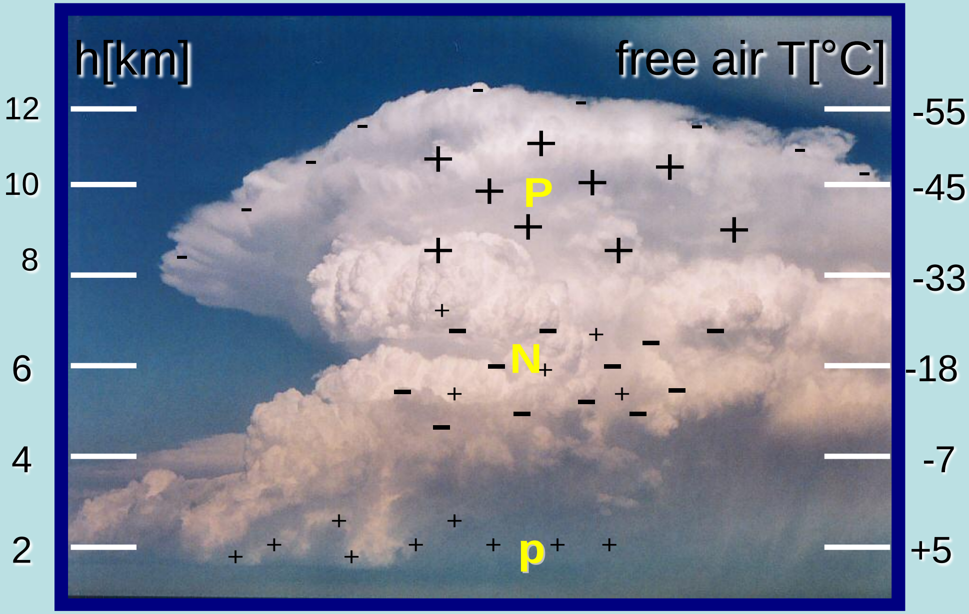
IF NO CHARGING MECHANISMS EXISTED TO MANTAIN σ_0:

$\tau_{earth} = R_{earth}C_{earth} \sim 50s$ → field reduction of an e-factor

COSTANT FIELD OBSERVED → EXISTENCE OF A VERY ACTIVE EARTH CHARGING MECHANISM

= 3000/5000 thunderstorms ($I_{single\ cell} \sim 0.5A$)

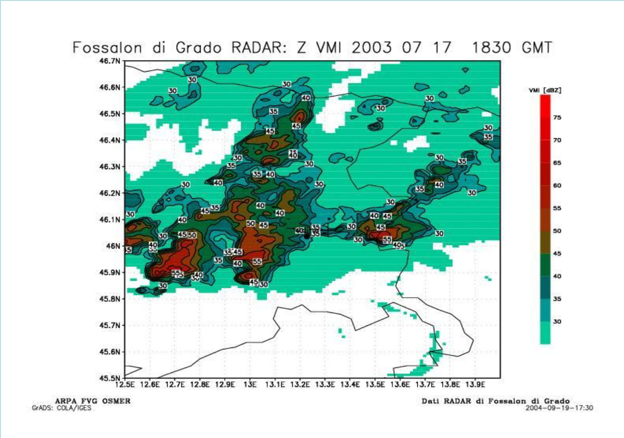
CHARGE DISTRIBUTION IN CLOUDS



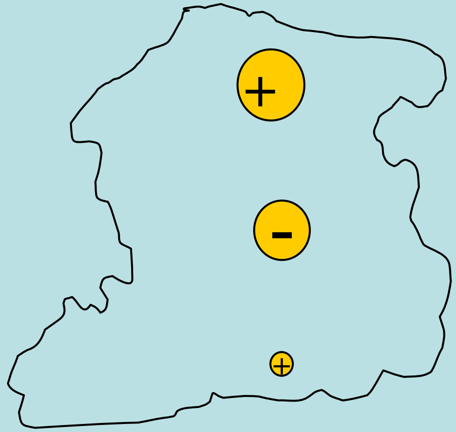
[P=+40C, N=-40C, p=+10C]

TRI-POLAR STRUCTURE

- UPPER POSITIVE CHARGE T<-20°C, moves upward with time
- NEGATIVE CHARGE CENTER -20°C<T<-15°C,constant altitude
- LOWER POSITIVE CHARGE T~0°C, not bound to be related to the melting level



Z>35/45 DbZ



STRONG CONNECTION REFLECTIVITY/BUILD UP OF ELECTRIC FIELDS

REQUIREMENTS FOR A CLOUD CHARGING MECHANISM

1. Single mechanism for the tripolar structure or two mechanisms for the dipole and the lower charge;
2. Sufficient charge to produce a 25min thunderstorm → I=1A, Q=1500C, flash rate=2min^{-1};
3. Sufficient charge to produce a breakdown electric field within 20min, E_b=100to400kVm^{-1};
4. High electric fields ≡ high RADAR reflectivity ≡ precipitation-sized particles;
5. Significant electric activity positioned in solid (ice crystals-graupel) particles;
6. Charge density of 1to10Ckm^{-3};
7. Charges carried by particles of Ø=1to3mm→Q=10to100pC.

CHARGING MECHANISMS: CHARGING BY DIFFUSION OF IONS

Stored electric energy on a droplet ($=(1/2)Q^2/a$)

⇕

Thermal motion energy of the ions kT

Symmetric charge distribution on cloud droplets centered near zero charge with Q~0

VERY SMALL CHARGE ⇒ SIGNIFICANT ONLY FOR WEAK ELECTRIFIED CLOUDS

CONVECTION CHARGING

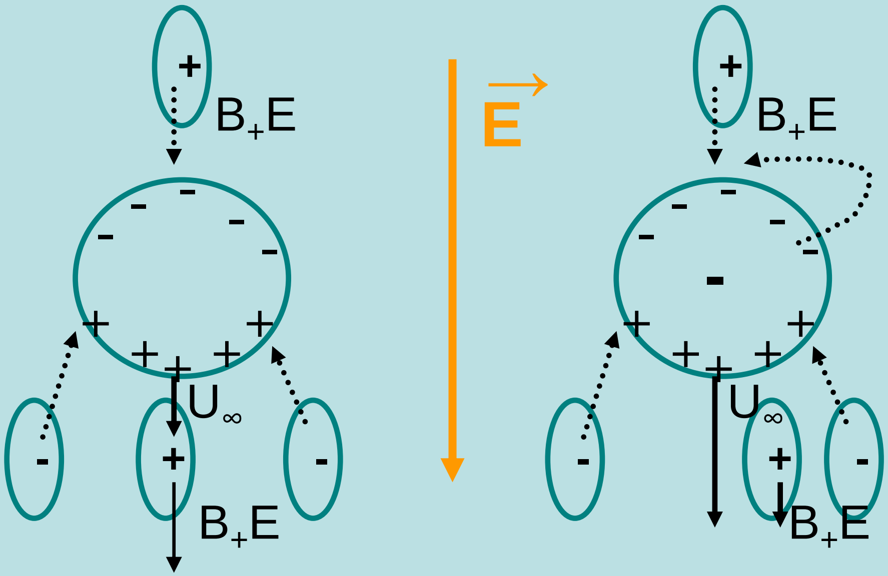
CONVECTIVE CLOUD≡ELECTROSTATIC ENERGY GENERATOR

•UPDRAFT CARRIES POSITIVE SPACE CHARGE FROM THE LOWEST LEVELS OF THE TROPOSPHERE INTO THE GROWING CLOUD

•NEGATIVE CHARGE SCREENING LAYER AT ITS TOP AND EDGES DUE TO CLOUD PARTICLE CAPTURE OF NEGATIVE IONS

•DOWNDRAFT CARRIES NEGATIVE CHARGES TO THE EARTH SUFFICIENTLY TO INITIATE POSITIVE POINT DISCHARGE (CORONA EFFECT) WHICH ENHANCES THE POSITIVE CHARGE ENTERING THE CLOUD VIA UPDRAFT

INDUCTIVE MECHANISMS: SELECTIVE ION CAPTURE



$B_+E>U_\infty$	$B_+E<U_\infty$
LITTLE CHARGING	LARGE NET CHARGING

POLARIZED PARTICLES SELECTIVELY CAPTURE IONS OF ONE SIGN AS THEY FALL

Lower surface attract and capture ions of opposite charge

vs

Upper surface not as effective

LARGE SEPARATION OF CHARGE

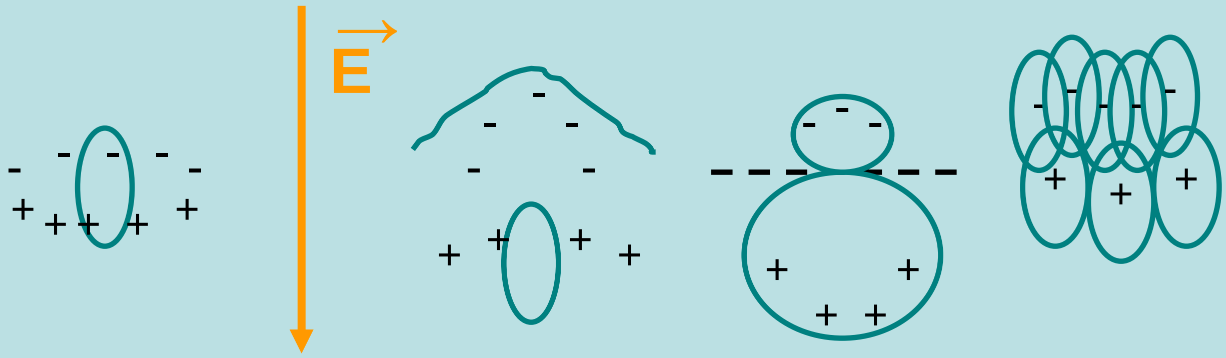
CONDITION: $U_\infty > B_+E$

U_∞=terminal fall velocity drop

B_+=mobility of positive ions

BUT: $E<10^2$V/cm, 3 orders below thunderstorms values

INDUCTIVE MECHANISMS: DROP BREAKUP CHARGING



POLARIZED DROP

$\sigma(e.s.u.)=(3/4\pi)E\cos\theta$

$Q=3Ea^2/4$

DROP OF r=3mm SLICED IN EXTERNAL FIELD

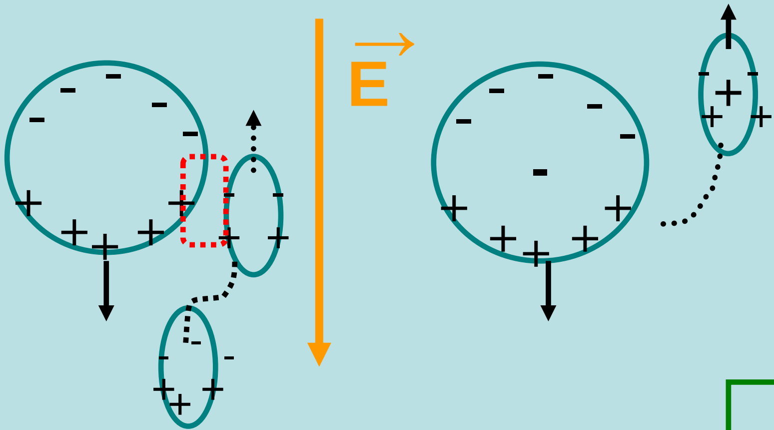
- $E=500V/cm \rightarrow \sigma_{fragment}=1e.s.u./g$
- $E=1.5kV/cm \rightarrow \sigma_{fragment}=5.5e.s.u./g$

SIGNIFICANT CONTRIBUTE TO THE CHARGING OF THE LOWER POSITIVE CHARGE POCKET OF A CLOUD

- Large fragments=+charge
- Smaller fragments =-charge

BUT: large drops generally break up as a result of collision or by instability generated by internal/external fluid dynamics

INDUCTIVE MECHANISMS: PARTICLE REBOUND CHARGING



COLLISIONS BETWEEN POLARIZED CLOUD PARTICLES AND SUBSEQUENT BOUNCE

↓

MOMENTARY ELECTRICAL CONTACT

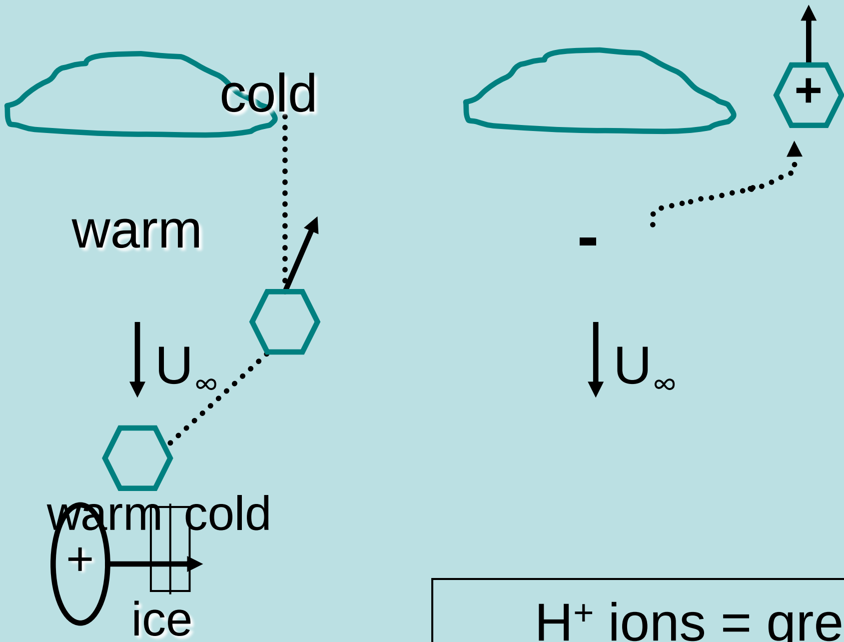
NET NEGATIVE CHARGE ON THE LARGER PARTICLE

NET = POSITIVE CHARGE ON THE SMALLER ONE

VERY COMPLEX PROBLEM: AMOUNT OF CHARGE DEPENDS ON:

- Contact angle;
- Contact time;
- Separation probability;
- Charge relaxation time;
- Net charge on the drops;
- Magnitudes of the polarization charge.

NON INDUCTIVE MECHANISMS, COLLISION WITH PARTICLES: THERMO-ELECTRIC EFFECT



HAIL PELLET CHARGED AFTER COLLISIONS WITH ICE CRYSTALS WITH AN INTERNAL GRADIENT OF TEMPERATURE

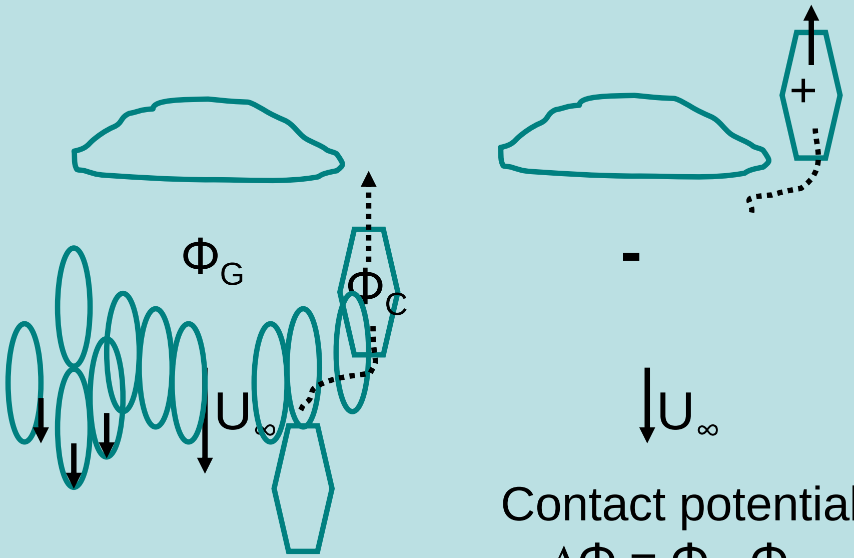
EFFECT OF THE DIFFUSION OF H IONS DOWN THE T GRADIENT IN THE REGION OF CONTACT

H^+ ions = greater mobility than OH^- ⇒ Excess of positive charge on the colder portion

AMOUNT OF CHARGE DEPENDS ON:

- Impact velocities;
- Temperature differences;
- Contact areas;
- Impurities.

NON INDUCTIVE,COLLISION: CONTACT POTENTIAL EFFECT



Contact potential
$\Delta\Phi = \Phi_G - \Phi_C$

CHARGING DUE TO DIFFERECES IN ELECTRIC SURFACE POTENTIAL BETWEEN THE TWO COLLIDING PARTICLES

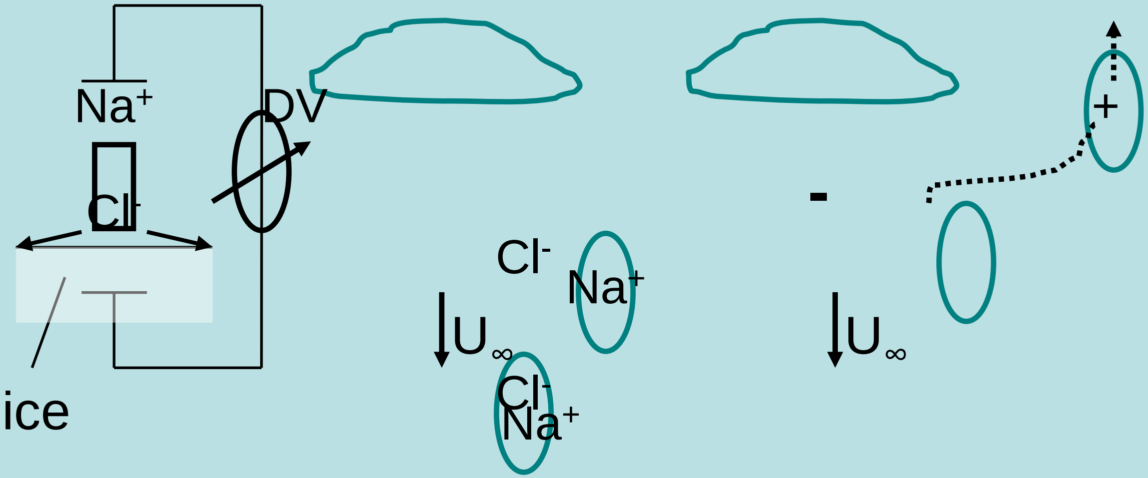
2 EXPERIMENTAL FACTS:

1. Positive charge during diffusional growth/negative during evaporation;
2. Riming target negatively charged for -20°C<T<-15°C/positively charged for -10 °C<T<-5°C

AT PRESENT NO COMPREHENSIVE THEORY; POTENTIAL DIFFERENCES DEPEND ON:

- Surface texture of the riming graupel;
- Impact velocity;
- Impact angle;
- Temperature difference between the colliding particles.

NON INDUCTIVE, COLLISION:
THE WORKMAN-REYNOLDS EFFECT



LARGE POTENTIAL DIFFERENCES AT THE ICE/SOLUTION INTERFACE

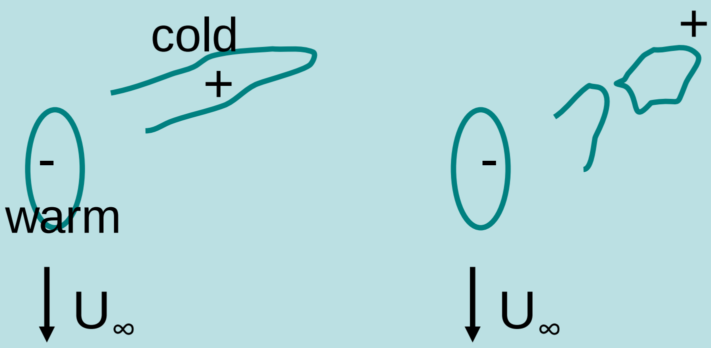
↑

SELECTIVE ION INCORPORATION INTO THE ICE LATTICE

POTENTIAL DISAPPEARES ONCE THE FREEZING PROCESS IS COMPLETED ⇒ NO SIGNIFICANT CHARGE TRANSFER

SIGN AND MAGNITUDE DEPEND ON:
- Concentration of the ions;
- Freezing rate;
- Type of ions.

NON INDUCTIVE CHARGING INVOLVING THE BREAK UP: SPLINTERING OF A FREEZING DROP



FREEZING DROPS PRODUCE ICE SHELL

SHELL FRACTURES OR PRODUCES SPIKES WHICH SPLINTER
(HALLET-MOSSOP EFFECT)

Main ice particle negatively charged

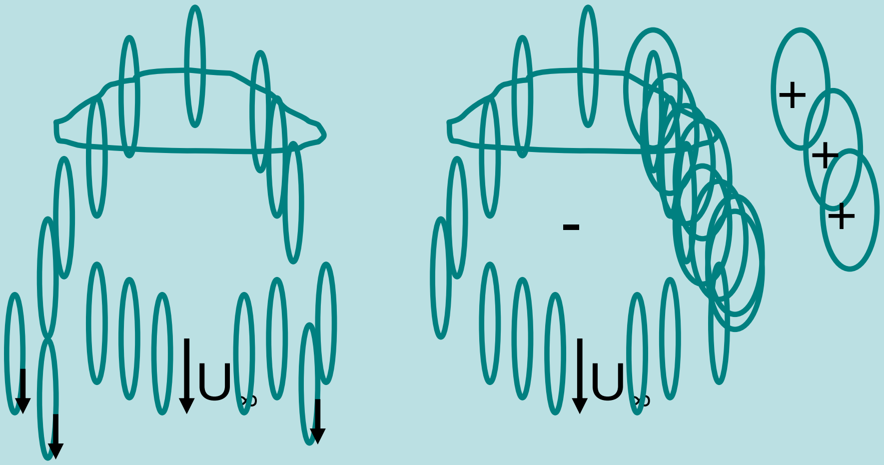
Ice splinters positively chaged

UNCERTAINTIES:

•Only a small and unpredictable proportion of freezing drops shatters or produces spikes which fracture;

•Variability of thickness and of the proportion of the shell.

NON INDUCTIVE, BREAK UP: SPLINTERING DURING RIMING



SMALL DROPS OF Ø=20to90μm IMPACTING ON AN ICE SPHERE OF Ø=5mm

⇩

Eject positively charged ice splinters

⇩

Ice sphere negatively charged

$(dQ/dt)_{vol} = 0.5 Ckm^{-3}min^{-1}$

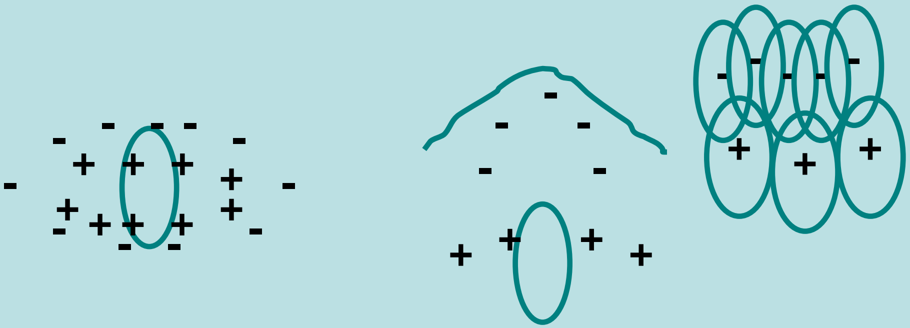
[Mason, 1971]

BUT:

- Splintering during riming limited to -5°C<T<-8°C;
- Required the presence of drops with r~25μm impacting at a critical impact speed.

⇨ VERY LIMITED CONTRIBUTE TO CLOUD CHARGING

NON INDUCTIVE, BREAK UP: DROP BREAKUP



BREAK UP BY HYDRODYNAMIC INSTABILITY OR BY COLLISION

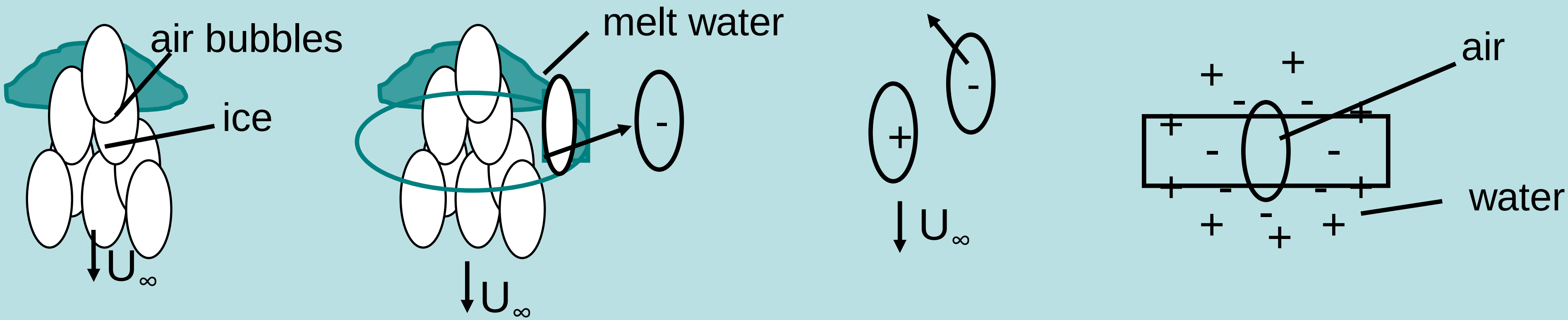
ELECTRONS ARE STRIPPED OFF AND ATTACHED TO AIR MOLECULES

Main body positively charged

$Q = 2 \cdot 10^{-2}$ e.s.u./g

ACCOUNT ONLY FOR THE POSITIVELY CHARGED LOWER REGIONS OF A CLOUD

NON INDUCTIVE, BREAK UP: GRAUPEL MELTING



ICE CONTAINING AIR BUBBLES ACQUIRES A POSITIVE CHARGE ON MELTING

Ejection of negative minuted droplets produced by bursting air bubbles

SUFFICIENT FOR THE POSITIVE CHARGE NEAR THE 0°C LEVEL

BUT

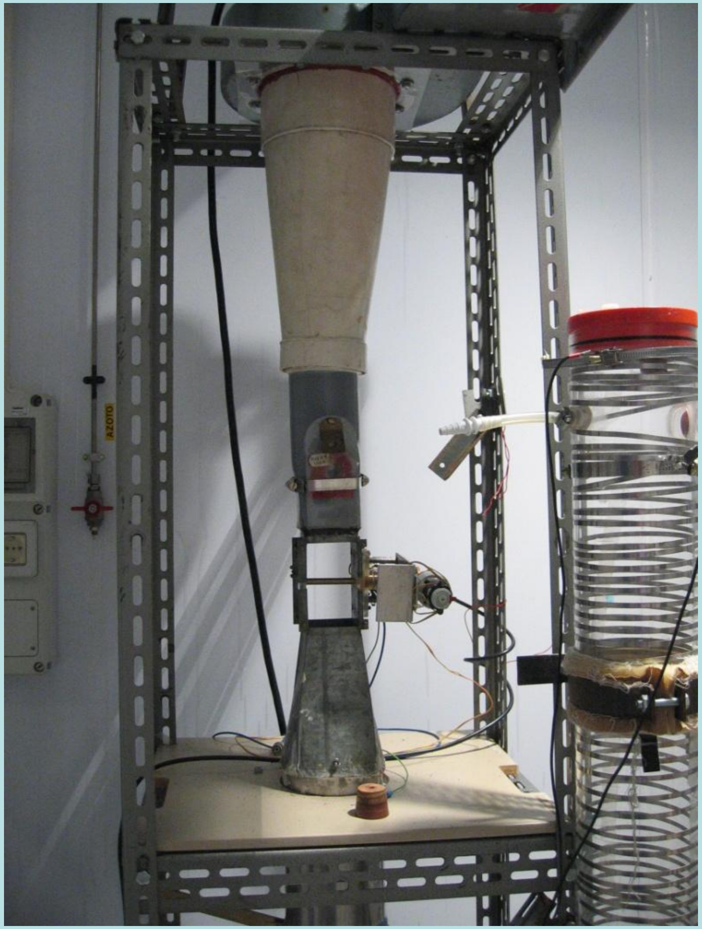
CANNOT EXPLAIN THE POSITIVE CHARGE ABOVE THE MELTING LEVEL

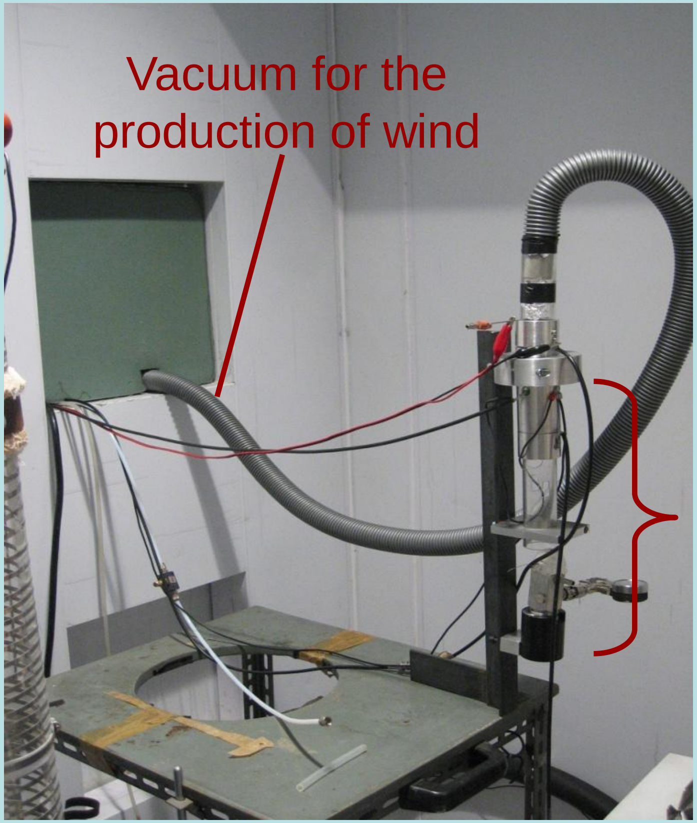
CHARGING DEPENDS ON:

- Radius of the escaping air bubbles;
- Bubble content of the ice;
- Ion content of the melt water.

ON GOING RESEARCH

Studies on mechanism for electric charge separation by ejection of charged particles from an ice particle growing by riming





- three channel signal amplifier;
- computer for online check and offline signal processing

THE PROCESS

• supercooled drops are drag up in the wind tunnel and pass through the inferior induction ring to reveal initial charges;

• in the middle of the tunnel some droplets go on and others collide with the target, which acts as an ice nucleus;

• during the process some splinters may be ejected: if these splinters are charged, the target will reveal an electric charge.

POSSIBLE SCENARIES:

• simultaneous signal from the target and the superior ring = emission of charged particles;

• no signal from the target, simultaneous signal from the rings = the charged particle did not collide with the target;

• no signal from the superior ring, simultaneous signal from the inferior ring and the target = deposit of the drop on the target;

• simultaneous signal from the three detectors = ejection of a charged splinter after deposition on the target.