ATMOSPHERIC ELECTRICITY ON EARTH AND PLANETS

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OUTLINE (1)

TERRESTRIAL ATMOSPHERIC ELECTRICITY

1- THE GLOBAL ATMOSPHERIC CIRCUIT
   - The Conductive Atmosphere and Boundaries
   - Generators
   - Coupling with outer space

2- PHYSICAL PROCESSES
   - Charging/Discharging Mechanisms in Clouds and Thunderstorms
   - High Altitude Phenomena: Transient Luminous Events
   - Acceleration Processes: Transient Gamma Ray Flashes
   - EM emissions and Schumann resonances

PLANETARY ATMOSPHERIC ELECTRICITY

1- PLANETARY GLOBAL ELECTRICAL CIRCUITS
   - Terrestrial Planets: Venus, Mars
   - Giant Planets: Jupiter, Saturn and their moons

2- OBSERVATIONS
OUTLINE (2)

INSTRUMENTATION

1- MEASUREMENT CONDITIONS
   - Ground Based Observations
   - Observations from Space
   - Balloons

2- MEASUREMENTS TECHNIQUES
   - Conductivity
   - Electric Fields and Waves

3- SOME EXAMPLES
THE EARTH’S GLOBAL ATMOSPHERIC ELECTRIC CIRCUIT

From M.J. Rycroft et al., JASTP, 2000
ATMOSPHERIC CONDUCTIVITY

Production Mechanisms
- Soil radioactivity at low altitude
- Cosmic rays
- Solar sources: UV, X-rays,
- auroral and polar regions: magnetospheric electrons, solar protons

Charged Particles
- Positive and Negative cluster ions

Conductivity profile
- $10^{-14}$ S/m at ground, scale height $H_\sigma \sim$ atmospheric scale height $\sim 6$-$7$ km
- Isotropic till $\sim 70$ km, anisotropic in the ionosphere $\sigma/\parallel >> \sigma$ Hall, $\sigma$Pedersen
- day/night and latitude variations
Fig. 3. Total conductivity and corresponding relaxation time under a variety of conditions.

From Hale, ASR, 1984
GENERATORS, THUNDERSTORMS

CHARGING MECHANISMS

Convective air motion in thunderstorm clouds, temperature profile
Collisional Charging between graupels and rain drops
Electrical structure of Thunderstorm clouds

Fig. 1. Illustration of the tripole structure of thunderclouds based on in situ measurements by Simpson and Scrace [1937].

From Marshall & Rust, JGR, 1991
GENERATORS, LIGHTNING

(a) Negative Cloud to Ground, CG-

(b) Positive Cloud to Ground, CG+

(c) Intracloud IC

(d) Cloud to Cloud CC
GENERATORS, LIGHTNING

Geographic Average Distribution

Figure 4. The annualized distribution of total lightning activity (in units of fl km$^{-2}$ yr$^{-1}$).

From Christian et al, JGR 2003
GENERATORS, LIGHTNING

SEASONAL VARIATIONS

DJF
MAM
JJA
SON
GENERATORS, HIGH ALTITUDE DISCHARGES, TLE’ s

PHYSICAL PROCESSES
TLE’ s (Sprites, Blue Jets, Elves, Gigantic jets) are electrical discharges in the stratosphere and mesosphere above active thunderstorm clouds

Sprites
Large Electric Field between cloud and ionosphere following a +CG
Break-down threshold reached at ~ 70 km

Elves
Initiated from the EMP following a CG Ionization and luminous halo produced in the mesosphere at ~ 90 km

Blue Jets and Gigantic Jets
Streamer initiated at cloud top (~ 15-18 km) by localized intensification of the electric field
Propagate up to ~40 km for BJ, ~ 70 km or GJ
GENERATORS, HIGH ALTITUDE DISCHARGES, TLE’s
GENERATORS, HIGH ALTITUDE DISCHARGES, TLE’s
ACCELERATION PROCESSES, TGF

PHYSICAL PROCESSES

Acceleration of Electrons up to ~ 100 MeV

- Relativistic Runaway Electron Avalanche from cosmic ray generated electrons initially proposed. But
  (i) cosmic ray showers not a sufficient electron source
  (ii) RREA cannot account for the intensity of TGF fluxes.
- Two mechanisms recently proposed (Dwyer2007, 2008):
  - Relativistic Feedback mechanism from backward propagating positrons and scattered X,γ rays
  - Runaway Electron production in large E-fields reproduces the duration and intensity of TGF

From Dwyer, 2011
ACCELERATION PROCESSES, TGF

Simulation/Observations comparisons

Electron fluxes:
RHESSI data (black dots)
Simulated fluxes (red curve)
(Dwyer, JGR, 2008)
ELECTRO-MAGNETIC EMISSIONS

Sferics
- frequency spectrum peaked at ~ 10 kHz, extends up to a few MHz

Whistlers
- Ionospheric propagation along Earth’s magnetic field and ducts at ELF/VLF

Transverse Resonance
- Between the surface and the lower ionosphere, ~ 1.5 to 3 kHz

Schumann Resonances
- Resonant modes of the Earth-Ionosphere wave guide $\omega \sim [n(n+1)]^{1/2} (c/R)$
- frequencies 7.8, 14.3, 20.8, 27.3, 33.8, …
COUPLING WITH OUTER SPACE

Diagram showing the interaction between the Earth's magnetosphere and the solar wind, including labels for bow shock, magnetosheath, plasma mantle, polar cusp, plasmasphere, plasma sheet, radiation belt and ring current, polar wind, and magnetopause.
COUPLING WITH OUTER SPACE

From Rycroft, 2011
### PLANETARY ATMOSPHERIC ELECTRICITY

**CONDITIONS FOR A GLOBAL ELECTRICAL CIRCUIT ON OTHER PLANETS**

<table>
<thead>
<tr>
<th>Planet</th>
<th>Ion mobility in lower atmosphere</th>
<th>Upper Conductive Boundary</th>
<th>Lower Conductive Boundary</th>
<th>Clouds</th>
<th>Electrification Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>yes</td>
<td>Ionosphere</td>
<td>Yes</td>
<td>σ&lt;sub&gt;g&lt;/sub&gt; small</td>
<td>yes</td>
</tr>
<tr>
<td>Mars</td>
<td>yes</td>
<td>Ionosphere</td>
<td>σ&lt;sub&gt;g&lt;/sub&gt;? Water reservoirs?</td>
<td>Faint, high altitude</td>
<td>Dust impact</td>
</tr>
<tr>
<td>Jupiter</td>
<td>Probably not in deep atmosphere</td>
<td>Ionosphere</td>
<td>? Deep layers?</td>
<td>yes</td>
<td>Charge separation, lightning</td>
</tr>
<tr>
<td>Saturn</td>
<td>Probably not in deep atmosphere</td>
<td>Ionosphere</td>
<td>? Deep layers?</td>
<td>yes</td>
<td>Charge separation, Lightning</td>
</tr>
<tr>
<td>Titan</td>
<td>Yes, weak at low altitude</td>
<td>Ionosphere</td>
<td>Buried ocean</td>
<td>yes</td>
<td>? Lightning not observed</td>
</tr>
</tbody>
</table>
VENUS

Whistler mode ELF signals from the Venus Express magnetometer
Indicating the existence of lightning

Russel et al., ASR 2008
MARS

**Conductivity**
- profile similar to Earth
- $\sigma$ at surface $\sim 10^3 \sigma$ on Earth

**Electrification Mechanism**
- Dust Impact
- Charge depends on size, material
- Breakdown at $\sim 10$ kV/m

**Generators**
- Dust storms
- Dust Devils

**Observations**
- SR of extremely high amplitude (?)

(Kok, Renno, 2007)
« Saturn Electronic Discharges » (SED) observed by RPWS on Cassini
EM emissions from lightning
SATURN and JUPITER

Comparison between Saturn, Jupiter and Earth lightning

Lightning sources:
- **Saturn**: Giant convective storm systems 3000 km in diameter, equator or 35°S
- **Jupiter**: numerous storms in ~ 5° latitude bands at ~ 50° N and S
- Updrafting water clouds at levels of ~ 10 bar (Saturn), ~ 5 bar (Jupiter)

Characteristics
- Frequency spectrum: up to 20 MHz / a few kHz / a few MHz
- Spectral power at MHz frequencies 100 W/Hz / ~10 / 0.01

Physical process
- **Saturn**: Elves more likely than Sprites
- **Jupiter**: lightning a few ms long

Desch et al., 2002; Fisher et al., 2008
TITAN

36 Hz peak in ELF AC electric field spectrum interpreted as the second harmonic of Schumann resonance of the planet-ionosphere wave-guide due to a buried ocean at ~ 60-80 km depth

Simoes et al., Icarus, 2007
Beghin et al, 2012
INSTRUMENTATION AND OBSERVATIONS

1- CONDUCTIVITY

2- ELECTRIC FIELDS AND WAVES

3- CURRENTS

4- EXAMPLES OF OBSERVATIONS
   - Stratospheric balloon measurements
   - Huygens probe measurements in the atmosphere of Titan
ATMOSPHERIC ELECTRICITY PARAMETERS AND THEIR MEASUREMENTS


From M.J. Rycroft et al., *JASTP*, 2000
ATMOSPHERE ELECTRIC CONDUCTIVITY (1)

Gerdien Condenser

\[ \sigma^+ = \sum e.n_i \mu_i \]

Relaxation method

\[ \sigma = \varepsilon_0 / \tau = \varepsilon_0 RC \]

Mutual Impedance

\[ Z(\sigma, \varepsilon) = V/I \]
ATMOSPHERE ELECTRIC CONDUCTIVITY (2)

Gerdien condenser
- gives access to the ion mobility spectrum
- relaxation method can be included
- requires accurately controlled air flow
- complexity (fan, electronics…)

Relaxation method (with electrostatic probes)
- simple, can be easily implemented on double probe
- accurate technique for large enough $\sigma$ and stable electric field
- analysis difficult with a variable background electric field
- requires specific modeling in case of space charge

Mutual impedance
- accurate in atmospheres with both ions and electrons
- able to provide soil measurements if landed on planetary surface
- complexity (booms, electronics…)
TERRESTRIAL CONDUCTIVITY PROFILES

From W. Gringel, Prometheus, 1977

From R.H. Holzworth, JGR, 1991
ELECTRIC FIELD MEASUREMENTS

INDUCTIVE COUPLING
THE « FIELD MACHINES »

RESISTIVE COUPLING
THE DOUBLE PROBE INSTRUMENT
ELECTRIC FIELD MEASUREMENTS

\[ V_{out} = [(V_1 - V_2) + (WF_2 - WF_1)] \cdot \left[ \frac{Z_i}{Z_i + Z_s} \right] \]
ELECTRIC FIELD MEASUREMENTS

Transition frequency \[ \omega_s = \frac{1}{R_s \cdot C_s} \]

Low Frequency limit \[ V_{out} = (V_1 - V_2) \cdot \frac{R_i}{R_i + R_s} \approx (V_1 - V_2) \quad \text{if} \quad R_i \gg R_s \]

High Frequency Limit \[ Z_s \approx \frac{1}{\omega C_s}, \quad Z_i \approx \frac{1}{\omega C_i} \quad V_{out} = (V_1 - V_2) \cdot \frac{C_s}{C_s + C_i} \]

DC-ELF : spherical sensors (with polarization current)

HF : cylindrical long antenna
ELECTRIC FIELD MEASUREMENTS

INDUCTIVE COUPLING, THE « FIELD MACHINES »
- high impedance, can operate in very low $\sigma$ (Earth’s surface)
- can measure large DC electric fields
- Some directional capability, 2D measurement with 1 sensor
- innovative designs in progress, miniaturized devices, vibrating system, ASIC
- low sensitivity
- electro-mechanical device (harsh environments, dust, EMI…), signal processing
- low temporal resolution and low frequency capability (no waves)

RESISTIVE COUPLING, THE DOUBLE PROBE INSTRUMENT
- simple device and electronics
- high sensitivity (in AC better than $1\mu V/mHz^{1/2}$)
- high temporal resolution (lightning), high frequency capability (MHz)
- direct measurement, no signal processing
- high amplitude DC and AC electric field measurements in dedicated modes
- booms (deployment, mass,…)
- limited to $\sigma \geq 10^{-13}$ S/m (on Earth above ~ 8 kilometers)
ATMOSPHERIC CURRENT MEASUREMENTS

From A.J. Bennet and R.G. Harrison, Sub. Adv in Geosciences
ELECTRIC FIELDS AND CONDUCTIVITY MEASUREMENTS ON STRATOSPHERIC BALLOON FLIGHTS

HVAIRS Gondola
AMMA Campaign in Niger

Electric Field Instrument

- Vertical component of Electric Field
  - DC to 3 kHz
  - Large signal « DC channel »
    \[ \sim \pm 50 \text{ mV/m to } \pm 200 \text{ V/m} \]
    (up to \( \pm 10 \text{ kV/m} \) in special mode)
  - Small signal « AC channel »
    sensitivity \( \sim 30\mu\text{V/m. Hz}^{1/2} \)

- Conductivity measurements
  - relaxation method

Optical sensors

- photodiode lightning detectors

On-Board Data Storage
HVAIRS_AMMA, Meteorological Conditions (1)
HVAIRS_AMMA, Meteorological conditions (2)
HVAIRS_AMMA, Conductivity Measurements

4943 s, altitude
\( \tau = 23.8 \pm 1 \text{ s} \)
\( \sigma = 3.7 \pm 0.15 \times 10^{-13} \text{ S/m} \)

6023 s, altitude
\( \tau = 29.6 \pm 0.5 \text{ s} \)
\( \sigma = 3 \pm 0.1 \times 10^{-13} \text{ S/m} \)

\( \sigma \sim 6.4 \times 10^{-13} \text{ S/m} \)
\( \sigma \sim 2 \times 10^{-12} \text{ S/m} \)
\( \sigma \sim 1.4 \times 10^{-12} \text{ S/m} \)
HVAIRS_AMMA, AC ELECTRIC FIELDS
Background noise during ascent and Schumann resonances

Ascent 0-20 km

Ascent 20–22.5 km and ceiling

~ 8
~ 14
~ 20
~ 26.5
~ 32.5
~ 38.5
HVAIRS_AMMA, LIGHTNING and DC ELECTRIC FIELDS
DC Electric Fields variations induced by lightning
Intra-Cloud Charge neutralization

Dejnarakintra, 1973
HV-AIRS LIGHTNING and E-FIELD
Precursors and Continuing Currents

Precursors

Continuing current
HVAIRS_AMMA, DC Electric Fields
ULF signatures of stratospheric charged clouds
HVAIRS_AMMA, DC Electric Fields
ULF signatures of stratospheric Charged Clouds

Balloon ascent

Charged volume

$H = 30 \text{ m}$

$\Delta t \sim 50 \text{ s}$

$\Delta t \sim 6 \text{ s}$

$H \sim 30 \text{ m}$

$L \sim 50-100 \text{ m}$

$Q \sim 10-30 \mu\text{C}$

$\sim 1 \text{ V m}^{-1}$
HV-AIRS AMMA, LIGHTNING, EM Pulse and Transverse resonance

E AC

Frequency ~ 2 kHz

E DC

Lightning

DC Field [Vm]

AC Field [Vm]
LIGHTNING DETECTION FROM ORBIT
DEMETER Observations at 650 km altitude

Date (yyyy/mm/dd): 2006/04/01
Orbit: 09296_1 (1)
LIGHTNING DETECTION FROM ORBIT
DEMETER Observations at 650 km altitude

DEMETER
Date (yyyy/mm/dd): 2008/05/01
Orbit: 20470_0 (1)

ICE VLF Spectrogram burst E12

Frequency (Hz)

UT/LT
Lat.  35.09  33.27  31.46  29.65
Long. 132.60 132.10 131.62 131.15
L       1.34   1.29   1.25   1.22
THE HASI/PWA EXPERIMENT ON HUYGENS

PWA aimed at contributing to answering the following questions:

• What are the ion and electron conductivity profiles?
• What is the role of aerosols in atmospheric chemistry?
• Is there lightning on Titan?
• Do standing waves form in the surface-ionosphere cavity?
• What are the dielectric properties of the surface?
• Does a global electric circuit exist on Titan?
PWA ELECTRODES

Relaxation Probe RP

Mutual Impedance Probe MIP
PLANETARY CONDUCTIVITY PROFILES: TITAN

HASI_PWA experiment on HUYGENS

conductivity profile measured with the PWA-MI probe

electron density profile

From M. Hamelin et al., PSS, 2007.
HUYGENS: Relaxation Curve with plateaus
Aerosol structure

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>Thickness [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>94.5</td>
<td>3.3</td>
</tr>
<tr>
<td>70</td>
<td>0.3</td>
</tr>
<tr>
<td>69.7</td>
<td>0.1</td>
</tr>
<tr>
<td>62.2</td>
<td>0.1</td>
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<td>57.1</td>
<td>0.2</td>
</tr>
<tr>
<td>54.3</td>
<td>0.2</td>
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<tr>
<td>56.6</td>
<td>0.1</td>
</tr>
<tr>
<td>50.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

No artefact has been found to explain this behaviour.

Plateaus likely correspond to absence of electrons - aerosol layers or bubbles (ongoing work).

RP measured positive ions and negative ions + electrons

López-Moreno et al., 2008