EPSC Abstracts
Vol. 8, EPSC2013-564, 2013
European Planetary Science Congress 2013

Upper-atmospheric electricity in giant gaseous planets: the case of Saturn

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Abstract

We discuss the ligthning-induced coupling between lower and upper layers of the atmospheres of giant gaseous planets. Taking Saturn as the best characterized example, we investigate quasi-electrostatic and electromagnetic-pulse-driven effects of lightning on the lower ionosphere of this planet. We present scaling arguments and numerical results about the relevance of electromagnetic pulses in Saturn.

1. Introduction

Electrical phenomena appears to be prevalent in gaseous giants. It has been unambiguously detected in Jupiter and Saturn and hinted by radio emissions from Neptune [1]. On Earth, low-altitude electricity has a counterpart in the upper atmosphere in the so-called "Transient Luminous Events" (TLEs). Located at 60-100 km above ground, these are short, intense light emissions caused by a lightning stroke. The electromagnetic pulse (EMP) of an impulsive discharge induces expanding, torus-shaped emissions named *ELVES* (Emission of Light and Very low frequency perturbations due to Electromagnetic pulse Sources), whereas the quasi-electrostatic (QE) field from an unbalanced cloud charge induces diffuse, pancake-like emissions called *halos* or, if it is strong enough, bright filamentary structures called *sprites*.

Two properties of terrestrial TLEs justify the quest for TLEs in other planets: (a) they are observable from space and (b) they influence the electrical properties and chemical balance of the upper atmosphere.

2. Saturnian lightning and TLEs

Both space-based [2] and, recently, ground-based radio observations [3] as well as optical images from the Cassini spacecraft [4] have established the existence of electrical storms in Saturn and constrained the altitude range and total dissipated energy of lightning strokes. Thanks to this relative abundance of data, Saturn is the best case study for the theoretical investigation of TLEs in other planets, in particular in gas giants.

A detailed analysis of the available data [5] points to lightning events that last a few milliseconds and generate electrical dipoles with a Charge Moment Change (CMC) of the order of $10^4 - 10^6\,\mathrm{C\,km}$ at about 130 km below the 1 bar level. Following the convention for terrestrial lightning, we define the CMC as half of the electrical dipole moment. Strokes in Saturn are about 1000 times more energetic than on Earth.

2.1. Quasi-electrostatic fields: halos and sprites

We have recently studied the possible existence of halos and sprites in Saturn [5]. We concluded that very strong lightning dicharges, with a CMC of about $10^6\,\mathrm{C\,km}$, would induce halos and possibly sprites. The resulting light emissions, mostly in the blue and ultraviolet spectral regions, are slightly below the detection threshold of Cassini, but may be realistically targeted by future instruments.

2.2. Electromagnetic pulses: ELVEs

ELVES are the most frequent type of TLEs on Earth [6], but the possible existence of ELVES in other planets has not received much attention. Part of the reason is that terrestrial ELVES are short-lived, lasting about one millisecond, and usually dimmer than halos and sprites. Extrapolating from these terrestrial characteristics, one may expect that ELVES will be harder to detect in other planets than halos and sprites.

However, the scaling behaviour of the electromagnetic radiation suggests that ELVES are more significant in gas giants than on Earth. Whereas a quasi-static dipolar field decays as $\sim P/r^3$, where P is the dipolar moment and r is the distance from the dipole, a radiated field scales as $\sim P/(r\tau^2)$, where τ is the characteristic time of the discharge.

For large planets, with powerful lightning but with characteristic atmospheric lengths longer than on Earth, the slower $(1/r)$ decay of an electromagnetic pulse may turn ELVEs into the brightest events in their upper atmosphere.

2.3. Modeling electromagnetic pulses

We are presently developing a Finite-Differences, Time Domain (FDTD) numerical code [7] to model electromagnetic wave propagation in the atmosphere of Saturn. The code is two-dimensional, assuming a cylindrically symmetrical discharge; this forces the modelled discharge to be perfectly vertical. Nonlinear effects such as changes in the conductivity due to impact ionization have not been incorporated so far, so we are underestimating the total photon emissions.

Our preliminary results, shown in Figs 1 and 2, suggest that ELVEs may be indeed bright events close to the threshold of detectability by Cassini.

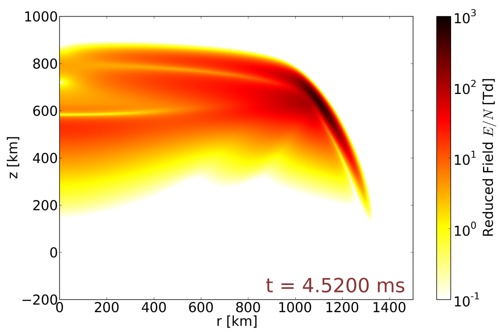

Figure 1: Reduced electric field E/N caused by a vertical lightning stroke with a current source between $-160\,\mathrm{km}$ and $-130\,\mathrm{km}$, relative to the 1 bar level ($z = 0$), $CMC = 10^5\,\mathrm{C\,km}$. The rise time of the discharge was $\tau_r = 500\,\mu\mathrm{s}$ and the decay time $\tau_f = 5\,\mathrm{ms}$. We have assumed a conductivity profile with a "low ionosphere" extending down to 600 km above 1 bar created by an hypothesized hydrocarbon layer between 600 and 1000 km.

3. Conclussions

Scaling arguments and preliminary numerical results suggest that the coupling between lower and upper atmospheric layers due to electromagnetic pulses (EMP) is stronger in large planets than on Earth. The light emissions caused by EMPs may be close to or above the threshold of detectability by the Cassini spacecraft, currently orbiting Saturn.

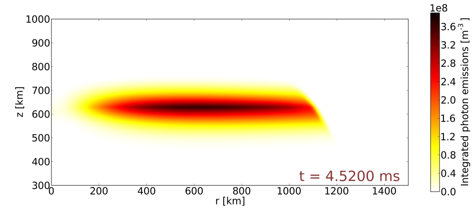

Figure 2: Time-integrated photon emissions of the ELVE in Fig.1. The total number of emitted photons is about 10^{25}, which puts the ELVE on the threshold of visibility by Cassini.

Acknowledgements

This work was supported by the Spanish Ministry of Science and Innovation, MINECO under projects AYA2011-29936-C05-02 and by the Junta de Andalucia, Proyecto de Excelencia FQM-5965. AL was supported by a Ramón y Cajal contract, code RYC-2011-07801. DD was supported by the Ilan Ramon scholarship from the Israeli Ministry of Science, grant no. 0603416282, the Research Authority of the Open University of Israel, and by the Israeli Science Foundation grant 117/09. Cooperation was facilitated by the support of the European Science Foundation, grant no 5269.

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