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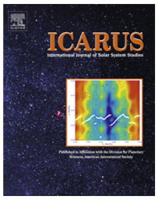

Impact of lightning on the lower ionosphere of Saturn and possible generation of halos and sprites

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ABSTRACT

We study the effect of lightning on the lower ionosphere of Saturn. A self-consistent one-dimensional model of the electric field and electron density is used to estimate the changes of the local electron and photon emissions. The chemical fingerprint and ion densities are determined using a detailed self-consistent kinetic model. Charge moment change, depth of lightning flashes and their duration are estimated based on the known constraints of saturnian lightning activity. We test two electron density profiles and find that the conservative estimation of lightning charge moment change 10^4 to 10^5 C km could lead to faint halos and possibly sprites if the base of the ionosphere is located at 1000 km above the 1 bar level; if the base of the ionosphere is located at 600 km then only the extreme scenario of a 10^6 C km charge moment change could induce considerable ionization, halos and possibly sprites. We found that H_3^+ ions are rapidly produced from the parent H_2^+ ions through the fast reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$, so that H_3^+ becomes the dominant ion in all the scenarios considered. The resulting light emissions, mostly in the blue and ultraviolet spectral regions, are below the detection threshold of Cassini.

1. Introduction

Lightning has been observed on several planets in the Solar System, and indirectly inferred on others (most recently reviewed in Yair (2012)). On the gas giants Jupiter and Saturn lightning activity is concentrated in thunderstorms with large physical dimensions, which exhibit vigorous convection and associated cloud systems. The existence of lightning flashes on Saturn was inferred from multiple observations of high frequency radio signals, known as Saturn Electrostatic Discharges (SED) (see review by Fischer et al. (2008)), as well as from optical observations by the Cassini spacecraft (Dyudina et al., 2010, 2013). The most recent storm on Saturn, which started early December 2010 and lasted almost a year, was exceptionally active (Fischer et al., 2011; Dyudina et al., 2013); lightning activity persisted for 9 months (Sayanagi et al., 2013). Lightning storms on Saturn are rare and are found at specific latitudes, many of them around 35° in both hemispheres. They typically occur in the respective hemisphere's summer.

Lightning activity on Earth is accompanied by transient luminous events (TLE) in the mesosphere above the thunderclouds (Pasko et al., 2012). TLE is an inclusive term which describes the electric breakdown in the mesosphere induced by a quasi-electrostatic field (sprites and halos), and the illumination of the lower ionosphere by the lightning electro-magnetic pulse (elves), as well as other phenomena. In this paper our focus is the quasi-electrostatic discharges that may include a visible diffuse region (a halo) and a lower filamentary region, which is commonly known as sprite. Our analysis deals with the formation of halos and sprites.

Sprites are observed mainly at night-time in the altitude range of 40–90 km, below the ionosphere. According to the commonly accepted model of sprite formation on Earth, they form as a result of the quasi-electrostatic field (QES) due to a charge moment change (CMC) in the thundercloud. The induced electric field will cause rapid growth in the electron density if it is strong enough. Eventually the electric field will be screened by the free electrons, and the process will stop. This process is accompanied by the excitation of molecules and optical emissions, perceived as an upward propagating visible halo, a diffuse brightening of Earth's upper mesosphere. The chemical influence of halos in the upper atmosphere of the Earth between 50 km and 85 km has been recently modeled by Parra-Rojas et al. (2013). The halo is sometimes followed by bright tendrils at lower altitudes, similar to streamer discharges at standard pressure. For a comprehensive review of TLE

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physics and their chemical effects we refer the reader to Pasko et al. (2012).

The existence of powerful lightning discharges in other planetary atmospheres led Yair et al. (2009) to examine whether sprites can form in extra-terrestrial atmospheres, by analogy with the processes occurring on Earth. The conventional view on the occurrence conditions of discharges above terrestrial thunderclouds goes back to Wilson (1925). While the ionosphere is highly conducting and therefore rapidly screens the suddenly changing electric field above a lightning stroke, the electric field can exceed the classical break-down field in the low conductivity region of the night time terrestrial mesosphere, creating electric breakdown, in the form of halos and sprites. Yair et al. (2009) compared the electric field induced by various charge configurations with the local conventional breakdown field E_k, as calculated by Sentman (2004) for the respective atmospheric compositions. This approach, however, neglects the finite conductivity in the weakly ionized atmosphere below the ionosphere.

In this paper we examine the response of Saturn's ionosphere to the lightning flashes in the water–ice clouds. The paper is organized as follows: In Section 2 we describe the known constraints on the lightning discharge, and derive possible CMC values and flash duration. In Section 3 we discuss the electron density at the bottom side of Saturn's ionosphere. In Section 4 we examine the response of the atmosphere at various altitudes to an externally applied electric field, taking the local conductivity into account. We find that $E > E_k$ is not always a sufficient criterion to predict whether the local electron density is affected. In Section 5 the self-consistent zero-dimensional model of Luque and Gordillo-Vázquez (2011) is used to estimate the change in electron density due to the flash, and the optical features of the event. In Section 6 a detailed self-consistent kinetic model of the reactions taking place in the perturbed saturnian atmosphere (Gordillo-Vázquez, 2008, 2010) is used to estimate the chemical fingerprint and optical emissions of the event.

2. Lightning on Saturn

2.1. Lightning energy

The simulation of TLEs on Saturn requires some assumptions concerning the electric field applied by the lightning flash. We need to know the amount of charge neutralized by the lightning flash, and the duration of the stroke. The average total energy dissipated by a lightning discharge is estimated at 10^{12} to 10^{13} J, based on SED and optical observations (Fischer et al., 2007, 2006; Dyudina et al., 2010, 2013). According to Dyudina et al. (2010) the observed lightning flashes are three orders of magnitude stronger than the median terrestrial lightning and comparable with terrestrial super-bolts. In Fischer et al. (2006) and elsewhere it was assumed that the duration of the lightning discharge is similar to Earth's intra-cloud (IC) discharges, several 10-s of microseconds (values for terrestrial lightning can be found in Uman (2001, p. 124)). Farrell et al. (2007) suggested that a faster discharge ($\sim$1 μs) would fit the observed SED frequency spectrum better, implying significantly lower energies ($\sim 10^9$ J), comparable with typical terrestrial lightning energies. The optical observations by Dyudina et al. (2010, 2013) provide an independent confirmation of the high energy super-bolt like scenario (G. Fischer, personal communication).

2.2. Lightning current and electric field

In this work we follow the high energy scenario suggested by Fischer et al. (2006) and described by Farrell et al. (2007), where the current flowing through the lightning channel follows a bi-exponential function of the form

$$I(t) = I_0(\exp(-t/\tau_1) - \exp(-t/\tau_2)), \quad (1)$$

where τ_2 represents the rise time of the current wave, and is typically 10 times faster than the overall duration of the stroke, represented by τ_1.

The lightning flash is located almost 1000 km below the region of interest (the lower ionosphere between 400 and 900 km above the 1 bar level). At these length scales the full electric field has to be considered. At small angles relative to a vertically oriented dipole-like discharge the vertical component of the electric field E_p is dominated by the quasi-electrostatic (QES) and the induction fields (Bruce and Golde, 1941),

$$E_p(z,t) = \frac{1}{\pi\epsilon_0}\left(\frac{1}{(z-z_p)^3}M(t-(z-z_p)/c) + \frac{1}{c(z-z_p)^2}\frac{d}{dt}M(t-(z-z_p)/c)\right), \quad (2)$$

where $M(t)$ is the charge moment change, z is the altitude where the field is measured and z_p is the altitude of the center of the dipole, ϵ_0 is the permittivity of vacuum, and c is the speed of light. The two terms in Eq. (2) are the QES field and the induction field, respectively. The far field (EMP) component can be neglected at small angles. While the QES component dominates the electric field above the lightning flash on Earth, justifying the commonly used QES heating model of sprites, we find that on Saturn the induction component dominates. An example of the induced electric field on Saturn and on Earth is plotted in Fig. 1.

The induction component of the field rises and decays with the current, Eq. (1), reaching a maximum value on the time scale of the current rise time τ_2; the QES component reaches a constant value $M/(z\text{-}z_p)^3$ after the current has decayed, on the time scale of the flash duration τ_1, and then decays on the time scale of the local Maxwell relaxation time, as will be discussed in Section 4. The induction component is stronger than the QES component, and it is applied faster, as a result it may significantly increase the local

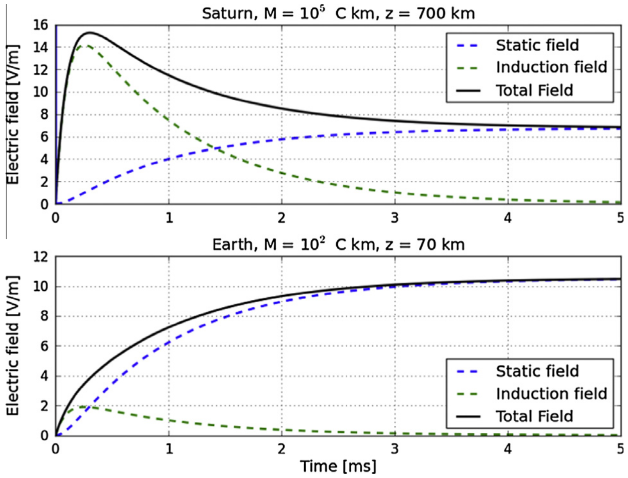

Fig. 1. Top: The time evolution of the applied electric field at 700 km above the 1 bar level due to a stroke with a charge moment change of $M = 10^5$ C km located at -110 km below the 1 bar level. The current follows Eq. (1). The static (blue) and induction (green) components, and the total electric field (black), are calculated according to Eq. (2). The induction field reaches its maximum before the static field does, and then decays. Bottom: The applied electric field due to a cloud to ground flash on Earth induced by a charge moment change of $M = 10^2$ C km, calculated at 70 km above ground. The center of the dipole is at 0 km. The induction component is weaker than the static component. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)