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New results on planetary lightning

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Abstract

We present the latest observations from spacecraft and ground-based instruments in search for lightning activity in the atmospheres of planets in the solar system, and put them in context of previous research. Since the comprehensive book on planetary atmospheric electricity compiled by Leblanc et al. (2008), advances in remote sensing technology and telescopic optics enable detection of additional and new electromagnetic and optical emissions, respectively. Orbiting spacecraft such as Mars Express, Venus Express and Cassini yield new results, and we highlight the giant storm on Saturn of 2010/2011 that was probably the single most powerful thunderstorm ever observed in the solar system. We also describe theoretical models, laboratory spark experiments simulating conditions in planetary mixtures and map open issues.

Keywords: Lightning; Electromagnetic radiation; Sprites; Planetary atmospheres; Discharge processes

1. Introduction

Lightning on Earth and other planets are markers of dynamical and microphysical processes taking place within condensate clouds, from charging to breakdown, to propagation and emission of radiation in various bands of the electromagnetic spectrum. While the specific nature of the charging processes taking place within the particular clouds residing in the different planetary atmospheres may differ, the over-all physics is similar, and entails the generation of large scale electric fields strong enough to surpass the local breakdown value, leading to generation of streamers, leaders and finally discharge channels. The importance of electrical processes and lightning is obvious, due to the ability of the electrical current to break molecular bonds and induce various chemical reactions within the discharge channel. This leads to the emergence of new, non-equilibrium, chemical compounds, some of which may be of biological importance (Miller, 1957). Several review papers of planetary atmospheric electricity have already been published (Levin et al., 1983; Rinnert, 1985; Desch et al., 2002; Aplin, 2006), the most updated and extensive one as a book in the framework of the ISSI Space Science Series (Leblanc et al., 2008). That book gave a thorough review of the myriad electrical processes occurring within the atmospheres of solar system planets, conducive to the generation and maintenance of a global planetary electrical circuit, where conditions allow it to exist. The present paper aims to present recent updates on several key discoveries made since the publication of the book, with specific focus on results from spacecraft observations, laboratory results and numerical models. Although the Moon and Mercury have interesting surface processes involving charging and electrical dust lifting (Renno and Kok, 2008), we adhere to a somewhat traditional approach of describing the existing knowledge according to atmosphere-bearing planets (including Titan), focusing on processes above the surface and below the planets' ionospheres. Thus we shall strive to describe the state of knowledge on lightning and other discharge phenomena occurring in the atmosphere and up to the base

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of the ionosphere, excluding (for example) planetary aurorae and airglow phenomena. We will focus on the newest results obtained since the publication of the ISSI book (which was written in 2007) but will strive to place these results in the context of earlier findings which were reviewed thoroughly by Yair et al. (2008). Finally, we will point out the needed research to answer existing issues and suggest new avenues for progress.

2. Earth

At any given moment, there are approximately 1800 active thunderstorms around the planet with a flash rate estimated $\sim 100\ \mathrm{s}^{-1}$. That "classical" view had been challenged recently by Price et al. (2011) who computed only 750 storms at any given time, based on data from the World Wide Lightning Location Network (WWLLN; http:www.wwlln.net) and a lightning clustering scheme. Based on satellite optical data, global thunderstorms produce an average flash rate of $\sim 44 \pm 5\ \mathrm{s}^{-1}$ (Christian et al., 2003), mainly above the continents in the tropical regions, and diminishing towards higher latitudes. There is little lightning activity above latitude 60°, and none at all in the Polar Regions. Lightning discharges emit a broad electromagnetic spectrum, which at specific frequencies known as Schumann Resonances (SR, and see: Pechony and Price, 2004), are capped in the surface-ionosphere waveguide propagating from the source point around the globe with very little attenuation. Monitoring these frequencies by ground networks allows climatic studies of lightning distributions (Williams, 1992; Williams et al., 2000; Williams, 2005). In a new study, Simões et al. (2011) showed that under some conditions, SR waves can penetrate the ionosphere to be detected by an orbiting satellite. They used the C/NOFS satellite and identified night-time ELF signals in the predicted SR frequencies at altitudes between 400 and 850 km suggesting that the ionosphere is a leaky cavity. This fact allows detection of global planetary lightning activity in the extremely low frequency range, traditionally considered to be effective only for in-situ ground-based measurements. The importance of this new result for future planetary probes is evident.

This flash rate is considered to act as a generator that maintains a global atmospheric electrical circuit (GEC) with an ionospheric potential of 250 kV producing a downward pointing electrical field with an average strength of $130\ \mathrm{V\,m}^{-1}$ at the surface, which shows a marked diurnal cycle (Williams, 2009; Liu et al., 2010). Had these thunderstorms ceased to generate lightning, the potential difference between the Earth and the ionosphere would have been discharged in several minutes by the constant flow of atmospheric ions, with an average current density of $2\ \mathrm{pA\,m}^{-2}$. The inter-tropical convergence zone (ITCZ) migrates slightly with the seasons but exhibits a daily cycle of activity over the three major "chimneys" (Williams, 2005) in Africa, South-East Asia (sometimes referred to as "The maritime continent") and South America. Africa was shown to dominate the planetary lightning activity by a factor 2.8 relative to the Amazon basin in South America ("The green ocean"; Williams and Satori, 2004). The intensity of lightning activity in deep continental convection is 7–10 times stronger compared to maritime deep convective storms (Ávila et al., 2010). There is also a climatic pattern in global lightning related to the ENSO cycles (El-Nino Southern Oscillation; Satori et al., 2009).

Moist convection produces the clouds holding the majority of lightning on Earth: deep cumulonimbus clouds (Zipser, 1994), which develop under unstable conditions and attain large vertical extent, of the order of 12–17 km in summer and 4–8 km in winter. There are almost no reports on lightning in stratiform clouds, and very few rare events of thundersnow occurrence (heavy snow accompanied by lightning, hinting at different electrification conditions than usual; Crowe et al., 2006). Mesoscale convective systems (MCS) and complexes (MCC) excel in lightning production (Mattos and Machado, 2009), as well as hurricanes (Cecil et al., 2002) and other types of tropical storms. The microphysical processes responsible for the generation of electric fields within these clouds rely on the coexistence of super-cooled liquid water and graupel particles, which frequently collide with ice particles. This non-inductive process (the interested reader is referred to the extensive review by Saunders (2008)) is extremely effective in separating charge, such that it is capable of re-generating strong enough electrical fields within the thunderstorm to support huge flash rates, sometimes of the order of $20\ \mathrm{s}^{-1}$ (Fig. 1; Zipser et al., 2006).

In rare occasions lightning discharges appear within volcanic plumes, where complex charging processes occur, unlike those in regular clouds (McNutt and Williams, 2010). Although the volume of the plume directly exposed to lightning is less than 10^{-4}, it has significant chemical effects on the on radical production by reactions with magmatic gases, resulting in production of fixed nitrogen species (Martin and Ilyinskaya, 2011).

Clearly, lightning has significant chemical effects on the surrounding air and is the largest natural source for the production of nitrogen oxides (Lightning-produced Nitrogen Oxides, or LtNOx) in the troposphere. General assessments of the global amount of $\mathrm{NO_X}$ produced by lightning were recently presented by Beirle et al. (2010) and Ott et al. (2010), and this topic is considered of importance critical to the mapping NOx sources in climate models. This problem requires the knowledge of 3 factors: the amount of NOx production per joule of lightning energy (known as PE or production efficiency), the average global value of energy per flash, and the global lightning flash rate. In a seminal paper, Price et al. (1997) presented the first global and seasonal distributions of $\mathrm{LtNO_X}$ based on multiplying the amount of NOx produced per joule of energy with the amount of lightning energy. They used approximated global lightning densities derived from OTD (Optical Transient Detector on board the Microlab-1 satellite, launched