



From the Electromagnetic Power of Lightning on Earth to Lightning-Generated Whistlers in Space

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Abstract

This summary article gathers a series of new results related to the characterization of the electromagnetic properties of lightning strokes both on Earth and in space through lightning-generated whistlers.

1. Introduction

Lightning strokes emit powerful electromagnetic lightning-generated waves. Some of this wave power propagates and escapes into the magnetosphere. These lightning-generated waves (LGW) cause resonant interactions with trapped electrons in the Van Allen belts which in turn cause pitch angle diffusion, leading to scattering of those electrons into the atmosphere. This important process affects the radiation levels encountered by satellites in low Earth orbits [1] and motivate this work on the characterization of the electromagnetic power of lightning as it propagates from Earth to space.

2. Lightning superbolts

Among lightning strokes, lightning superbolts are the most rare and extreme lightning events that were first identified from optical stroke data measured onboard the Vela satellites at the end of the seventies, with an extreme power estimated between 10^{11} and 10^{13} W per stroke [2]. We combine space and ground-based measurements to perform to the characterization of lightning superbolts. In space, we use data from the recent NASA's Van Allen Probes mission (2012-2019), searching superbolts in ~ 7 years of data and determining for comparison the electric and magnetic power of typical lightning measured with two instruments EMFISIS [3] and EFW [4]. On the ground we

use data from a campaign we conducted at CEA in 2012-2013, which covered times and locations where a large number of superbolts occurred, as well as measurements from the VLF ground stations of the World-Wide Lightning Location Network (WWLLN) [5]. Both ground-based and space measurements allow us to reveal for the first time the extreme nature of superbolts in space as well as the attenuation of these electromagnetic waves during their propagation [6]. We report significantly different properties than common lightning flashes.

3. Differences between ground-based and satellite measurements of lightning

As we analyze the statistical analysis of electromagnetic wave amplitudes of very low frequency lightning-generated waves, we also gather the lightning stroke location, timing, and estimated energy on Earth from the ground-based WWLLN to explore differences between satellite and ground-based measurements. We collect the main features of the lightning stroke power on Earth and LGW power distributions in space with respect to position relative to the Sun (local time), magnetic field lines (L-shell, L), longitude, and time (month or season) [7]. We find strong dayside ionospheric damping of the LGW electric power. LGW mean amplitudes drop for $L < 2$, contrary to the root mean squared (rms) and the Earth's intense equatorial lightning activity. We conclude that it is difficult for equatorial LGW to propagate and remain at $L < 2$. Difference of behavior between mean amplitude and rms is attributed to the shape of both distributions, with an important role of the two extreme tails made of low SNR values on one hand and the most powerful waves on the other (among which superbolt waves). We show strong to extreme LGW contribute so importantly to the wave mean

power below $L=2$ that it compensates for the strong increase of low SNR signals that causes the amplitude to decay and the rms not to decay. Extreme events contribute strongly to the overall LGW energy budget at low L -shell.

4. Lightning power attenuation scaling laws

The selection and association of particular lightning strokes on Earth with WWLLN with their Van Allen probes measurements allows us to compute the power attenuation of the waves from Earth to space (e.g. [8]). We find LGW electric (respectively magnetic) field wave power decays with distance mostly quadratically (resp. mostly linearly) in space, with a power varying between -1 and -2 (resp. varying between 0 and -1 according to L -shell and magnetic local time (MLT) [9]. At night only, their respective decay is consistent with ground measurements.

5. Lightning wave-normal angle statistics

The LGW wave-normal angle, i.e. the angle between the LGW wave vector and the Earth's magnetic field, is capital for understanding the origins of the waves, its propagation, and validation of ray-tracing and quasi-linear simulations. LGW wave-normal angles are computed using the SVD method [10], selecting waves with high planarity from the whole Van Allen Probes data. Statistics of the LGW wave-normal angle are shown for the first time with respect to MLT, L -shell, geographic longitude, and season [9]. The distribution of predominantly electrostatic waves (i.e. electric components >> magnetic components) is peaked at large wave-normal angle while the one with large magnetic component and small electric component is peaked at small wave-normal angle. Though, this ideal representation holds for less than ~15% of the data. Other LGW have significant power in both electric and magnetic components. The mean wave-normal angle is $41.6^\circ \pm 24^\circ$. There is a strong MLT-dependence, with the wave-normal angle smaller for daytime. Larger wave-normal angles at night are caused by the propagation in space of larger electric amplitude during the night. We also find an absence of seasonal and continental dependences of the LGW wave-normal angle contrary to lightning activity.

6. Perspectives

The progress made on the knowledge of lightning electromagnetic properties have implications to the physics of atmospheric discharges, climate change, ionosphere-magnetosphere wave transmission, wave propagation in space, radiation belt physics, and remote sensing.

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