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Do the Antennas of DEMETER Spacecraft Detect Dust Impacts?

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Abstract. This study investigates transient pulses detected by the electric field instrument, ICE (Instrument Champ Electrique), onboard the DEMETER spacecraft. Using an automated identification algorithm, we identified and analyzed 2000 short pulses recorded in 2005 and 2010. The spatial distribution of these signals, primarily localized over South America and near the South Atlantic Anomaly (SAA), contradicts the initial assumption that they are generated by dust impacts. The absence of temporal and seasonal variations eliminates other potential sources, such as earthquakes and lightning. Our analysis suggests that energetic electrons are the most plausible explanation for these pulses, supported by the strong spatial correlation between the detected electric field events and high-energy electron fluxes observed by the IDP (Instrument for the Detection of Particle) instrument onboard DEMETER. The equal distribution of pulse polarities and the detection of similar pulses in magnetic field observations further support this conclusion. These findings highlight the importance of carefully evaluating and interpreting pulses attributed to dust impacts, contributing to more accurate interpretations and a better understanding of dust impact signals in various space environments.

Introduction

Hypervelocity dust impacts on a spacecraft body can generate a cloud of free electrons and ions through a process known as impact ionization. The recollection of the impact charges alters the potential of either the spacecraft or the electric field antennas. Electric field instruments can detect these changes in potential as transient pulses.

The detection of dust impacts using electric field instruments has been ongoing since the 1980s, starting with the Voyager missions [*Meyer-Vernet et al.*, 1986; *Pedersen et al.*, 1991]. Over the years, this method has been used to detect dust impact signals in various environments by many other missions, including Cassini [*Wang et al.*, 2006; *Ye et al.*, 2016], Wind [*Wood et al.*, 2015; *Malaspina and Wilson III*, 2016], STEREO [*Meyer-Vernet et al.*, 2009; *O'Shea et al.*, 2017], Cluster [*Vaverka et al.*, 2017], Magnetospheric Multiscale (MMS) mission [*Vaverka et al.*, 2019], Parker Solar Probe (PSP) [*Szalay et al.*, 2020], Solar Orbiter [*Zaslavsky et al.*, 2021] and Mars Atmosphere and Volatile Evolution (MAVEN) mission [*Andersson et al.*, 2015; *Ijaz et al.*, 2024]. Although electric field instruments provide limited information about the direction of impact and composition of dust particles compared to specialized detectors, they have other advantages. Their larger collecting area makes them more sensitive to lower dust fluxes. Moreover, unlike conventional dust detectors, numerous spacecraft are equipped with electric field instruments, which can provide information about dust in different environments. It is noteworthy that not all short pulses in the electric field data originate from dust impacts; some may result from thruster activity, instrumental electronics, interference with other scientific instruments [*Ijaz et al.*, 2024] or Electrostatic Solitary Waves (ESWs) [*Vaverka et al.*, 2018].

The study of dust impact signals using electric field instruments, primarily conducted in the interplanetary medium or within planetary magnetospheres, has left a significant gap in our understanding of these pulses in ionospheric regions. MAVEN is the first planetary mission to detect dust at low altitudes, ranging from 150–1000 km above the surface of Mars [*Andersson et al.*, 2015; *Ijaz et al.*, 2024]. *Ijaz et al.* [2024] utilized the MAVEN measurements and identified as many as 6000 potential dust events in the Martian ionosphere. They observed a notable absence of these pulses during nighttime observations and a higher occurrence at lower altitudes. Furthermore, they discussed the probable sources of signal misinterpretation and the complexities of identifying dust impact signals in dense environments. This initial study on the detection of dust impact signals in the ionosphere has raised several open questions about the origin of such pulses.

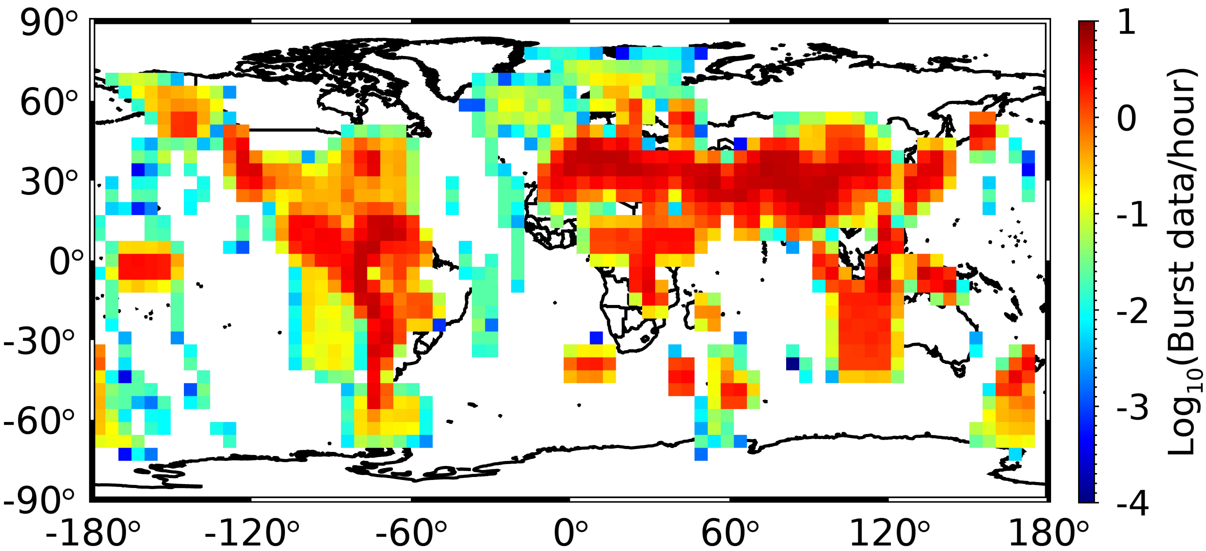

Figure 1. Geographic map of the Earth illustrating the data coverage in the burst mode, represented in hours in each bin.

The motivation of this article is to extend the analysis of dust impact signals to a dense plasma environment like the Martian ionosphere, where the density at 200 km is equivalent to that of Earth at 400 km [*Schunk and Nagy*, 2009]. We use observations from the low Earth orbiting DEMETER spacecraft to investigate pulses that resemble dust impact signals. Section 2 provides an overview of the instrument operation and the data used for this study. The results are presented in Section 3, followed by a discussion in Section 4. The main findings are summarized in Section 5.

Instrument and Dataset

The DEMETER satellite, operational from 2004 to 2010, initially orbited the Earth at an altitude of 710 km, which was subsequently lowered to 660 km in December 2005. The satellite had a polar, circular, Sun-synchronous orbit with an inclination of 98°, primarily operating within geomagnetic latitudes ranging from $-65°$ to $+65°$. Measurements were conducted close to local noon and midnight, around 10:30 LT and 22:30 LT, respectively [*Cussac et al.*, 2006]. DEMETER operated in two modes: Burst and Survey. The primary objective of the mission was to investigate possible ionospheric disturbances related to seismic activities. Therefore, the Burst mode was activated over designated seismic zones, while the Survey mode was used in all other regions. We utilized Burst mode data from the electric field instrument (ICE) and the energetic particle detector (IDP).

The electric field instrument (ICE), equipped with four 60 mm diameter spherical sensors mounted on the ends of 4 m long stacer booms, determined the electric field by measuring the potential difference between the two sensors. This study focuses on very-low-frequency (VLF) data from the ICE instrument in the Burst mode, which records a single electric field component within the frequency range of 15 Hz to 20 kHz. Each waveform is sampled at 40 kHz and with 8192 captured samples covered in about 200 ms time interval. Figure 1 depicts the regions where the Burst mode was activated in 2005 and 2010; nearly 18 million waveforms were recorded. In Burst mode, the IDP measured electron fluxes across 256 energy channels at 1 s resolution, spanning energies from 70 to 2333.5 keV. A more detailed description of the ICE and IDP instruments is provided by *Berthelier et al.* [2006] and *Sauvaud et al.* [2006], respectively.

Observations

The study focuses on the analysis of transient electric field signals detected in the ionosphere of Earth, utilizing the data recorded in 2005 and 2010. While similar pulses are observed in other years, we explicitly select data from the start and end of the mission. The automated routine found 2000

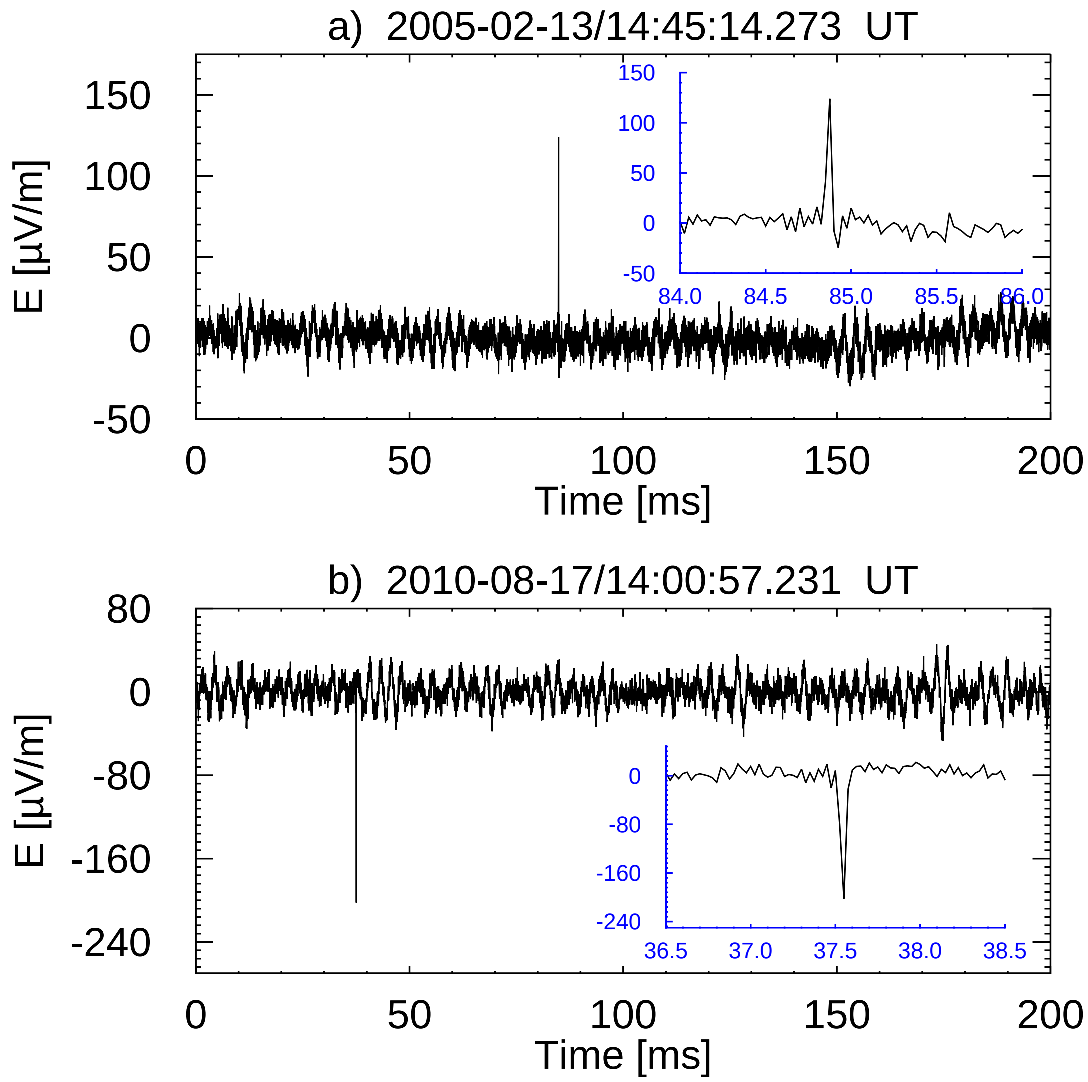

Figure 2. Selected transient signals with opposite polarities, along with corresponding time stamps. Each snapshot shown here lasts for 200 ms, with zoomed-in sections displayed in insets to highlight distinctive features.

events among 18 million waveforms. The main objective of the study is to check the possibility of misinterpretation of signals, which are typically associated with dust impacts.

Identification and Characteristics of Events

The automatic identification process includes the following three steps:

1. The events are preselected automatically by identifying spikes. For this, we take the maximum absolute rate of a change of the electric field (signals with large electric field derivation).
2. The events are chosen based on the ratio of peak-to-peak amplitude (within 2 ms around the maximum derivative) to the mean absolute value of the signal prior to the event. An empirically determined threshold value of 5 is used to remove noise signals.
3. Only events where the peak amplitude is twice the magnitude of the entire snapshot while maintaining a constant polarity are considered. This step effectively eliminates irrelevant events, such as oscillations and waves.

Figure 2 illustrates examples of transient electric field signals detected in the ionosphere of Earth. The detailed views provided in the insets of both snapshots reveal that these signals typically consist of

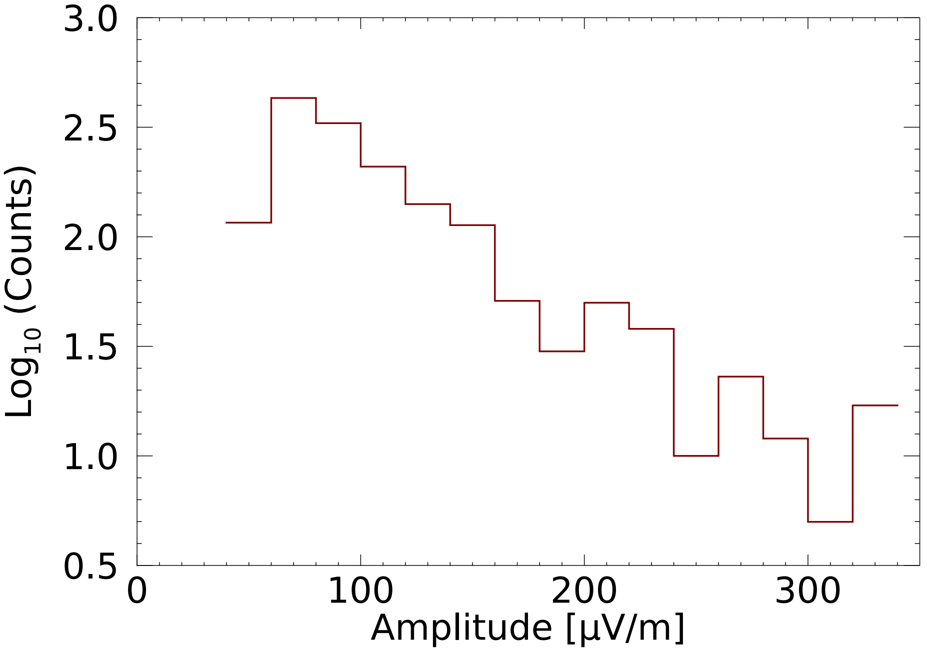

Figure 3. The amplitude distribution of the transient electric field pulses detected in 2005 and 2010.

a single data point, although some events (30 %) display two or three data points. Signals characterized by a sharp rise followed by a rapid decay are often attributed to dust impacts and have been detected in various environments by several spacecraft missions like Cassini, Wind, STEREO, MMS, PSP, Solar Orbiter, and MAVEN, as well as in laboratory-based observations.

The properties of the ambient plasma, such as plasma density, play an essential role in determining the equilibrium spacecraft potential and the duration of the pulses. While theoretical models provide a comprehensive understanding of the correlation between plasma density and pulse duration for monopole configurations [*Zaslavsky*, 2015], the interpretation of signals detected in dipole configurations is more challenging and adds significant complexity to the analysis. The plasma density in Earth's ionosphere around 700 km on the dayside is $\approx 10^6$ cm^{-3}, this decreases notably on the nightside. Consequently, dust impact signals detected by the DEMETER spacecraft, if any, are expected to be short pulses like depicted in Figure 2.

Figure 3, demonstrates the amplitude distribution of electric field signals recorded in 2005 and 2010. The histograms, with a bin size of 20 μV/m, display the number of pulses in the logarithmic scale. The distribution indicates that most pulses have small amplitudes, with larger amplitudes being less frequent. This is generally expected for the pulses generated by the dust impacts or stochastic processes [*Grün et al.*, 1985]. The counting rate of the positive and negative voltage pulses is comparable (not shown). Notably, these events do not exhibit any seasonal variations and show a constant occurrence across different years. It is important to note that we also observe pulses in the magnetic field observations that appear similar to those in the electric field; however, they occur at different time intervals. The possible sources of these dust impact-like signals are discussed later.

Spatial Variations

Figure 4 displays the geographical distribution of events detected in 2005 and 2010. The color bar represents the number of events identified per hour of burst data in the logarithmic scale. Notably, blue regions denote observations made by the spacecraft where no events were detected. The size of the bins used for the 2D histograms is 5°. Figure 4a reveals that the events recorded on the dayside occur primarily in the southern hemisphere over South America. Figure 4b shows the distribution of events in the nightside ionosphere. While there is a significant decrease in the number of detected events compared to the dayside, the overall spatial distribution remains similar. Interestingly, a few positive

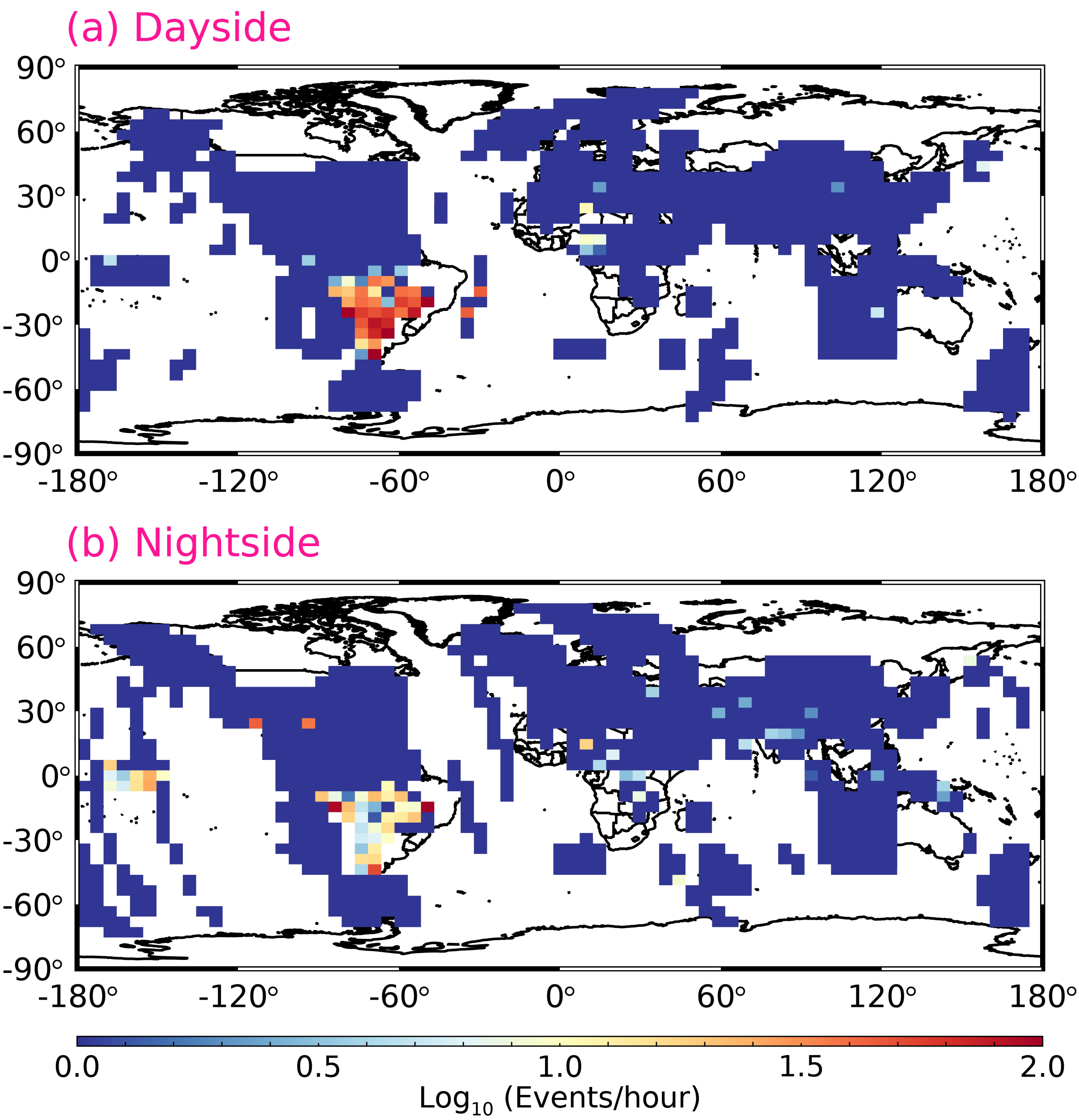

Figure 4. The maps depict the geographical distribution of events per hour of the burst data on the **(a)** Day and **(b)** Night sides for the years 2005 and 2010. The events are color-coded according to the color scale at the bottom.

pulses are observed on the nightside above the Kiribati region in the central Pacific Ocean, suggesting a different origin for these pulses compared to other regions. Pulses in the magnetic field data are also mainly observed above South America (not shown).

Discussion

We used DEMETER spacecraft measurements to identify and analyze dust impact-like pulses in the Earth's ionosphere. Altogether, 2000 events were identified from the years 2005 and 2010 using an automatic identification routine. These findings are consistent across other years, indicating a persistent pattern in the phenomena studied. We investigate a possible origin of these transient signals. The distribution of these signals is spatially localized, making it unlikely that they are generated by dust impacts.

Firstly, we observed no temporal variations for these events, which rules out earthquakes as a po-

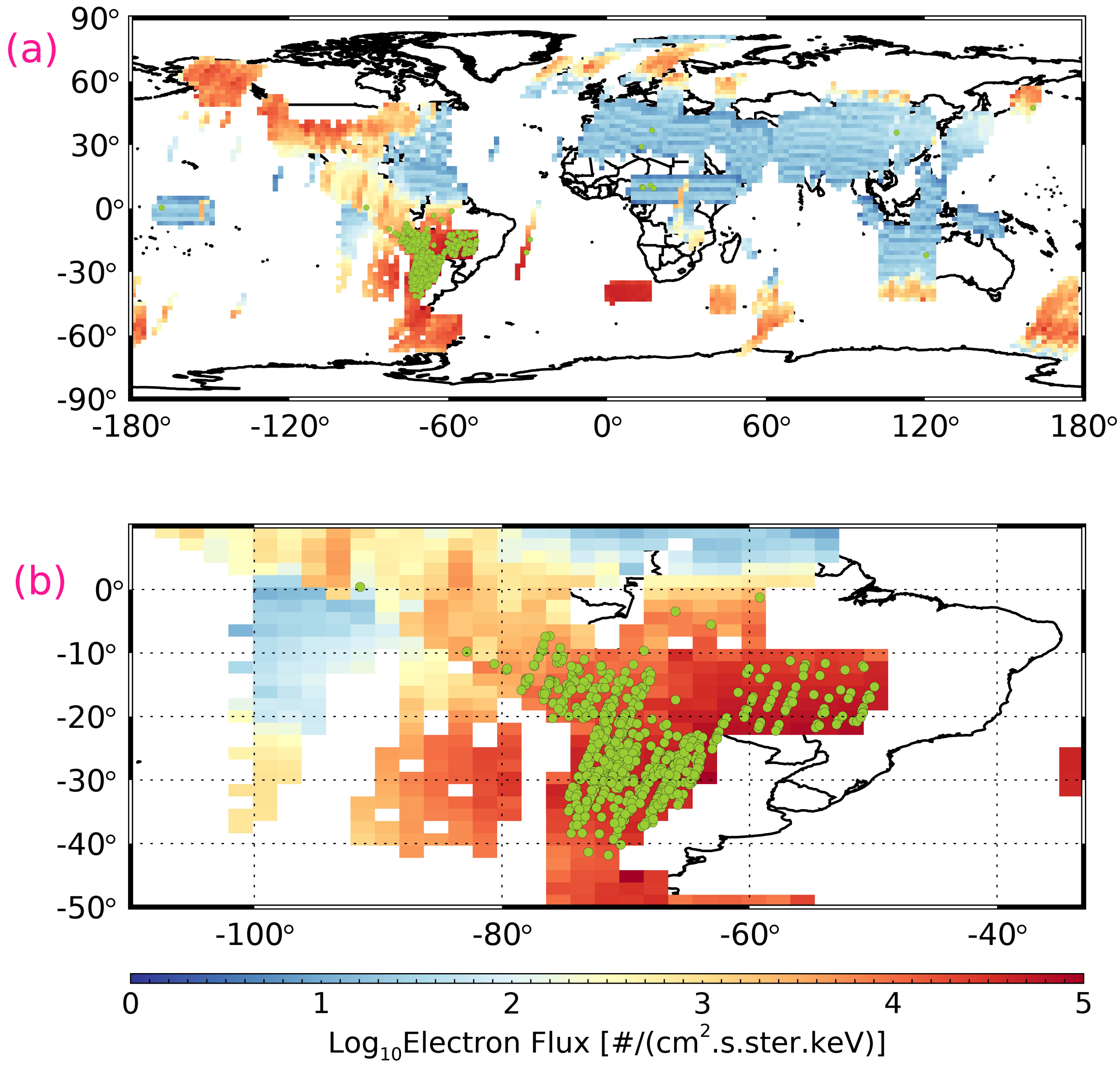

Figure 5. Electron energy spectra as observed by IDP onboard the DEMETER spacecraft in the dayside ionosphere: **(a)** overall spatial distribution **(b)** detailed view over South America. The electric field events are shown as green circles.

tential source. The lack of seasonal variations further suggests that lightning is not the cause of these pulses. Moreover, factors such as noise, interference with other scientific instruments, or instrumental electronics do not exhibit any particular reasons to be localized above specific regions. Our analysis indicates that energetic electrons are the most probable cause of these short pulses. Figure 5 depicts the spatial distribution of high-energy (more than 70 keV) electron number fluxes, summed over all 256 channels detected by the IDP instrument in the dayside ionosphere. The color scale reveals significant fluxes of energetic particles over South America, at the edge of the South Atlantic Anamoly (SAA) [*Anderson et al.*, 2018]. The green circles mark the events observed in the electric field data, which are closely associated with areas of increased electron flux. The distribution of these events corresponds to the SAA. The equal distribution of polarities suggests that the electrons probably interfere with the preamplifier at the end of the boom, influencing the polarity determined by which probe preamplifier from the double probe instrument is affected. The detection of similar pulses in magnetic field observations and the clear spatial dependence strongly demonstrate that the pulses in the electric field data are associated with energetic particles.

Conclusion

Our study utilized DEMETER spacecraft measurements to investigate dust impact-like pulses in the Earth's ionosphere, identifying 2000 events from 2005 and 2010. The strong spatial dependence of these pulses, particularly their concentration over South America and the South Atlantic Anomaly, suggests that energetic electrons are the most reasonable explanation for these pulses.

Considering that energetic particles are everywhere, our study underscores the importance of thorough evaluation and interpretation of pulses attributed to dust impacts. This will lead to more accurate interpretations and a broader understanding of dust impact signals detected across various space environments.

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