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Manuscript

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Electromagnetic Phenomena Related to The Dynamics of Dust Particles in Planetary Atmospheres

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SYNOPSIS

of the dissertation for Academic Degree of Doctor of Philosophy in Physics and Mathematics

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The work will be reviewed at the seminar meeting of the Planetary Physics Department of the Space Research Institute of the Russian Academy of Sciences (IKI RAS).

Scientific supervisor: **Alexander Valentinovich Zakharov** — **Doctor of Physical and Mathematical Sciences**

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The text of the dissertation is available in the library MIPT, Phystech or on the website: https://mipt.ru

Abstract was sent «   » ___________2025 г.

Scientific secretary of
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Description of the dissertation work

Relevance of the research topic.

Dust dynamics in planetary atmospheres has emerged as a subject of increasing scientific interest due to its implications for atmospheric chemistry, surface-atmosphere interactions, and planetary habitability. In recent decades, terrestrial observations and extraterrestrial missions have underscored the complex interplay between dust particle motion and atmospheric phenomena. Dust-laden flows contribute not only to thermal and dynamic modifications of the atmospheric column but also to the generation of electric fields, charge separation, and, under specific conditions, electrical discharges. These phenomena are of both theoretical and practical interest, particularly considering ongoing and planned robotic and crewed missions to dusty planetary bodies such as Mars, Venus, and the Moon, where surface-based systems may be directly affected by charged particle interactions.

The study of electromagnetic phenomena associated with the dynamics of dust particles in planetary atmospheres is of increasing relevance in the context of current and upcoming planetary and lunar missions. Dust-induced processes such as saltation, dust devils, and storm-driven transport play critical roles in generating near-surface electric fields and discharges. These processes can affect atmospheric chemistry and surface modification, as well as pose risks to instrumentation and spacecraft systems [1,2]. On Earth, the electrification of dust is a well-documented feature of desert dust devils and large-scale sandstorms. Observational and experimental studies have demonstrated that when particles collide in low-humidity conditions, significant charge separation can occur despite the overall neutrality of the dust cloud [2,3]. These phenomena are generally understood within the framework of triboelectric charging and electrostatic induction, and their signatures have been measured directly in field campaigns, revealing substantial electric fields.

On Mars, triboelectric charging during dust storms can create electric fields exceeding the local dielectric breakdown threshold, potentially leading to glow and filamentary discharges—a hypothesis supported by laboratory simulations, theoretical models, and remote observations of non-thermal microwave emissions [4–6]. These electrical processes could influence global circulation, dust lifting thresholds, and even the planet's long-term climate evolution [7]. Similarly, Venus exhibits frequent lightning activity within its dense sulfuric acid cloud layers, confirmed by early Soviet Venera missions and subsequent VLF electromagnetic impulse measurements from the experiments aboard Venera 11 and 12, revealing discharge rates of up to 50 per second in active regions [8,9]. In contrast, the Moon and airless environments present a unique case among planetary bodies due to their extremely tenuous exosphere, which exists at pressures comparable to the vacuum conditions in low Earth orbit. These environments are shaped by solar UV radiation, solar wind, and galactic cosmic rays, which charge the regolith and trigger subsurface dielectric breakdown or electrostatic lofting, as evidenced by horizon glow observed during NASA's Surveyor missions [10–12]. These findings collectively underscore the importance of investigating dust-driven electromagnetic emissions across diverse planetary environments, both for advancing scientific understanding and mitigating mission risks.

Despite strong theoretical predictions and indirect observational evidence, direct high-fidelity measurements of dust electrification, discharge initiation, and associated electromagnetic (EM) emissions remain poorly understood. Most previous investigations have focused on large-scale atmospheric dynamics or bulk electrical properties, without capturing the microphysical interactions responsible for charge separation and discharge phenomena. This limitation arises from the absence of experiments specifically designed to investigate these phenomena, the challenges of reproducing planetary boundary layer conditions on Earth, and the lack of instruments sensitive enough to detect weak, non-thermal EM emissions generated by microscale collisions and discharges.

As a result, the main motivation in this work is to investigate the dynamics of dust particles to detect, interpret, and model non-thermal electromagnetic emissions generated by charged dust particle interactions under conditions mimicking those on Mars and Earth, a method that has not previously been employed in planetary studies. By employing a comparative planetary framework, this study advances our understanding of electrostatic and electromagnetic processes across diverse environments, thereby strengthening the scientific and engineering foundations necessary for future planetary exploration and effective risk mitigation.

The objectives of the dissertation

The primary objective of the dissertation is to investigate the mechanisms and characteristics of electromagnetic radiation generation during the interactions of charged dust particles in the near-surface layers of planetary atmospheres, particularly those of Mars and Earth. Special attention is paid to the processes of dust particle charging and discharging under conditions that simulate planetary atmospheric and surface environments, with focus on simulating the near-surface atmosphere of Mars and Earth.

To achieve this goal, the following specific research objectives were formulated:

1. To analyze the physical processes responsible for electromagnetic radiation generated during dynamic collisions and discharges of triboelectrically charged dust particles.

2. To study the interaction of charged dust particles during their dynamics under conditions of simulated Martian and terrestrial atmospheres.

3. To investigate dust-induced electrical discharges under vacuum and low-pressure conditions relevant to the upper atmospheres of Earth and Mars, as well as the surfaces of airless celestial bodies such as the Moon and asteroids.

4. To measure, classify, and interpret electromagnetic signals generated by triboelectric and electrostatic interactions in both laboratory experiments and natural field environments.

5. To validate the experimental discharge models by comparing laboratory-generated data with results obtained during field campaigns in arid terrestrial environments.

6. To adapt and calibrate the Electromagnetic Analyzer (EMA), originally developed for the ExoMars Dust Complex, for use in laboratory simulations and Earth-based field studies of dust-related electromagnetic activity.

7. To refine and expand theoretical models of electrostatic discharge and electromagnetic emission under planetary boundary conditions by incorporating variables such as gas composition, pressure, particle size, and material properties.

8. To develop and apply a data processing and analysis framework for high-resolution signal classification, spectral decomposition, and burst detection across the LF–MF frequency bands, enabling robust time-frequency diagnostics of electromagnetic emissions.

Scientific Novelty

- For the first time, discharge dynamics and electromagnetic signatures arising from the collisions of charged dust particles were experimentally investigated across diverse dust compositions and gas environments representative of Mars, Earth, and near-vacuum conditions. This approach provides a versatile platform for studying dust-related electrification phenomena across diverse planetary settings.
- For the first time, non-thermal electromagnetic emissions were recorded during controlled laboratory simulations of dust-laden flows under terrestrial atmospheric conditions, confirming that triboelectric charging during saltation and uplift can produce detectable broadband radio emissions in dusty planetary boundary layers.
- For the first time, electromagnetic signals were experimentally registered under CO_2-rich, low-pressure environments simulating the Martian atmosphere. The observed emissions, falling within the low-frequency (LF) and medium-frequency (MF) bands, are consistent with theoretical predictions for triboelectric and glow discharge processes occurring below the Paschen breakdown threshold for Mars.
- For the first time, field measurements in a natural arid environment (Kalmykian steppe, Russia) confirmed the generation of triboelectric microdischarges during dust transport events. These emissions, recorded under moderate wind and low humidity, validate the analog modeling approach and demonstrate the practical relevance of laboratory results to

Martian surface conditions.

- For the first time, a unified diagnostic framework was developed to detect and classify electromagnetic signals generated by dust interactions in planetary environments. This framework integrates time-domain analysis, spectral decomposition, and continuous wavelet transforms, and has been validated across multiple experimental environments, providing a foundation for future in-situ instrumentation on planetary missions.
- Custom-designed laboratory setups enabled the simulation of small-scale dust vortices under controlled conditions, replicating the processes of dust storms and vortices occurring in the near-surface layers of Mars (using vacuum chambers and simulated Martian atmospheric composition) as well as in arid regions of Earth. These setups allowed for reproducible testing of discharge conditions and signal generation across various mineral compositions and grain sizes.
- The experimental work was conducted using a modified version of the Electromagnetic Analyzer (EMA), originally developed as part of the Dust Complex (DC) instrument suited for the ExoMars 2022 landing platform. Its adaptation and application in both laboratory and field studies represent a novel methodological advance in planetary instrumentation.

Scientific Statements for the defense

- A new method has been developed for laboratory modeling of the generation of non-thermal electromagnetic radiation during collisions of charged dust particles, simulating electromagnetic processes during active dust dynamics (dust storms, vortices) in terrestrial and Martian conditions. To record electromagnetic radiation, an adapted version of the electromagnetic analyzer (EMA) in the frequency range from 100 kHz to 1500 kHz was used, created for the Dust Complex (DC) instrument, which is part of the scientific equipment of the ExoMars-2022 project. Electromagnetic radiation recorded by this device in simulated environments and in the natural field represents the first measurements of broadband EM signals associated with microdischarges of triboelectrically charged dust particles in the boundary layers of planets.

- Laboratory setups have been developed to simulate the dynamics of dust particles in atmospheric conditions analogous to those on Mars and Earth. These setups have made it possible to create controlled small-scale dust vortices at different pressures and gas compositions, which has made it possible to characterize the conditions and parameters of discharges using dust particles made of different materials.

- Electromagnetic emissions consistent with microdischarges were recorded during collisions of charged mineral dust particles in a CO_2-rich, low-pressure environment simulating the Martian atmosphere. These emissions occurred at electric field strengths lower than those required under terrestrial conditions, corresponding to the reduced breakdown threshold predicted by Paschen's Law for Martian surface pressures. The resulting emissions were recorded in the LF and MF bands, consistent with theoretical expectations for glow discharge modes [5].

- In-situ field observations conducted in the arid region of Kalmykia revealed electromagnetic bursts associated with dust dynamics were generated during natural dust lifting, transport events, and particle collisions. Such processes confirm the occurrence of triboelectric charging of dust particles and microdischarges during their collisions. These signals are modulated by environmental factors such as humidity, wind speed and demonstrate distinct spectral and temporal structures. The results of these measurements confirm analogies with the expected phenomena during the Martian dust storm and confirm the applicability of laboratory modeling for studying field-scale dust electrification processes.

Scientific and practical significance of the work

The scientific significance of this work lies in its contribution to the understanding of dust particles interactions and non-thermal electromagnetic (EM) phenomena in planetary boundary layers. For the first time, systematic laboratory and field investigations were conducted to explore electromagnetic emissions arising from triboelectric effect of dust particles under simulated terrestrial and Martian conditions in addition to natural arid terrestrial environments. These results bridge a longstanding gap between theoretical predictions and the lack of direct in-situ observations of electrical activity in dusty planetary atmospheres. The results provide empirical validation of models predicting electrical discharges, and surface charge separation processes under low-pressure CO_2 atmospheres, contributing directly to planetary physics and atmospheric electrodynamics.

The practical significance of the work is associated with its application in the context of planetary exploration missions. The detection and classification of dust-induced electromagnetic emissions represent a critical advance for environmental monitoring on planetary surfaces, particularly Mars and the Moon, where electrified dust events can interfere with lander operations, communications, and instrumentation. The modified Electromagnetic Analyzer (EMA), originally developed for the ExoMars mission, has been successfully adapted and validated for laboratory and terrestrial field use—marking a key technological development in planetary sensor instrumentation. The findings inform the design of future dust-electricity detection systems, enhance safety assessments for human and robotic missions, and support the modeling of dust-related hazards in space weather environments.

Methodology and Research Methods

The methodological approach of this work is based on a combination of theoretical modeling, laboratory simulation, field measurements, and advanced signal analysis techniques. The study is structured around the investigation of dust charging, discharge mechanisms, and electromagnetic emissions in planetary-like atmospheric environments.

The research methods include:

- Laboratory Experiments in Simulated Planetary Atmospheres: Custom-built chambers were used to simulate terrestrial, Martian and near-vacuum conditions with controlled gas pressure and dust material composition. Dust vortices were generated mechanically and thermally to induce particle collisions and charge separation.
- Use of the Electromagnetic Analyzer (EMA): A specially modified version of the EMA sensor, part of the ExoMars Dust Complex, was deployed for both laboratory and field studies. The device captured time-resolved electromagnetic signals from dust interactions across LF to HF frequency ranges.
- Field Measurements in Natural Arid Environments: Ground campaigns were conducted in dust-active terrestrial regions under low-humidity and moderate wind conditions to validate the laboratory findings under real-world conditions.
- Signal Processing and Analytical Techniques: Collected data were subjected to time-domain analysis, Fourier analysis, frequency-time distribution, and wavelet transformation to characterize the temporal and spectral properties of the EM signals.

Author’s Contribution

The author played a leading role in the design, construction, and execution of laboratory experiments simulating dynamic dust flows in Martian and terrestrial near-surface environments. These activities were carried out primarily in Department 53 of the Space Research Institute of the Russian Academy of Sciences (IKI RAS), with the author taking responsibility for developing specialized laboratory setups that enable the controlled reproduction of dust storm and vortex conditions relevant to planetary boundary layers.

As part of this work, the author conducted a series of laboratory experiments aimed at investigating the generation mechanisms of non-thermal electromagnetic emissions resulting from interactions of triboelectrically charged dust particles. The author also led the analysis of experimental data, including time-frequency signal decomposition and spectral diagnostics.

The author participated in field measurements during an expedition to the arid region of the Republic of Kalmykia (Russia), aimed at registering natural non-thermal electromagnetic emissions associated with dust uplift and transport. These measurements were conducted using the Electromagnetic Analyzer (EMA), a component of the Dust Complex instrument developed in Department 53 of IKI RAS in collaboration with OKB IKI (Tarusa). The expedition was organized by the Institute of Physics of the Atmosphere (IFA RAS), with the author holding a principal role in data collection and post-processing.

In addition to experimental and field activities, the author contributed substantially to the theoretical modeling of electromagnetic radiation generation processes due to charge exchange and discharge mechanisms among dust particles. This included numerical simulations, analysis of particle charge dynamics, and the development of conceptual models linking dust kinematics to breakdown initiation and signal morphology. This theoretical work was conducted in collaboration with specialists from Departments 53 of IKI RAS, as well as colleagues from IFA RAS, with the author playing a central role in integrating the experimental findings into the theoretical framework.

Approbation of the work

The key findings of this dissertation were presented and critically evaluated during a dedicated research seminar at the Space Research Institute of the Russian Academy of Sciences (IKI RAS), supplemented by 13 oral and poster presentations at both international and domestic scientific conferences.

- 21st International Workshop on Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation, Moscow, Russia, April 8, 2025- Electromagnetic Signatures of Dust-Induced Discharges in Simulated Planetary Conditions — M.E. Abdelaal, M.A. Zaitsev, I.V. Dokuchaev, A.V. Zakharov, et al.
- V Russian Conference on Turbulence, Atmospheric Dynamics and Climate, Moscow, RAS, November 19–21, 2024. On Electrical and Electromagnetic Properties of Aeolian Dust Flow Under Moderate Wind Conditions — M.E. Abdelaal, E.A. Malinovskaya, O.G. Chkhetiani, et al.
- 15th Moscow Solar System Symposium (15M-S3), IKI RAS, October 21–25, 2024. Electromagnetic Phenomena in Dust Particle Dynamics Under Simulated Martian Atmosphere: An Experimental Study — M.E. Abdelaal, A.V. Zakharov, et al.
- Venus Science Conference (Venus-SC 2024), Online, India, September 23–24, 2024. Comparative Analysis of Dust Phenomena and Electromagnetic Discharge Processes on Venus and Mars — M.E. Abdelaal, A.V. Zakharov.
  Panel Talk: Dust Particles in Planetary Atmospheres — Presenter: M.E. Abdelaal
- COSPAR 2024 (Committee on Space Research), Busan, South Korea, July 17–18, 2024. Electromagnetic Phenomena in Planetary Atmospheres: Insights from Laboratory Experiments and Planetary Missions — M.E. Abdelaal, A.V. Zakharov et al. (Session: C5.1-D4.1)
- 21st International Workshop on Complex Systems of Charged Particles and Their Interactions with Electromagnetic Radiation, Moscow, Russia, April 7–11, 2024. Comparative Analysis of

Electromagnetic Phenomena in the Atmospheres of Earth, Mars, and Venus — M.E. Abdelaal, A.V. Zakharov.

- III International Scientific and Practical Conference on Innovative Methods of Mathematics and Physics in Environmental and Hydrometeorological Studies, Saint Petersburg, Russia, April 5, 2024. Electromagnetic Oscillations During Electron Tunnel Transitions Between Interacting Dust Particles — E.A. Malinovskaya, M.E. Abdelaal.
- Outer Planets Analysis Group (OPAG) Meeting, Laurel, MD/Virtual, May 2–3, 2023. Electromagnetic Phenomena and the Dynamics of Dust Particles in Outer Planetary Environments — M.E. Abdelaal, A.V. Zakharov, et al.
- XX Conference of Young Scientists "Fundamental and Applied Space Research," IKI RAS, April 12–14, 2023. Electromagnetic Phenomena and the Dynamics of Dust Particles: Insights into Atmospheric Electrification and Charge Transfer Mechanisms — M.E. Abdelaal, I.V. Dokuchaev, A.V. Zakharov, et al.
- 6th Middle East and Africa Regional IAU Meeting, Cairo, Egypt, February 13–16, 2023. Electromagnetic Phenomena and the Dynamics of Dust Particles: Implications for Planetary Atmospheres and Climate Systems — M.E. Abdelaal, A.V. Zakharov, et al.
- 20th International Conference "Modern Problems of Remote Sensing of the Earth from Space," IKI RAS, November 14–18, 2022. Analysis of Low-Frequency Electromagnetic Noise for Assessing Dust Dynamics in the Martian Atmosphere — M.E. Abdelaal, A.V. Zakharov, et al.
- The Inaugural Forming and Exploring Habitable Worlds Meeting, Earth and Planetary Sciences Institute, University of Edinburgh, November 7–11, 2022. The Dynamics of Dust Particles and Electromagnetic Noise on Mars' Surface — M.E. Abdelaal, A.V. Zakharov, et al.
- The Optimizing Planetary in Situ Surface-Atmosphere Interaction Investigations Workshop, Virtual/Boise, Idaho, June 28–July 1, 2022. Dust Particle Dynamics and Electromagnetic Phenomena — M.E. Abdelaal, A.V. Zakharov, et al.

Publications on the thesis topics

Articles in scientific Journals

1. Zakharov, A.V., Dolnikov, G.G., Kuznetsov, I.A., Lyash, A.N., Esposito, F., Molfese, C., Rodríguez, I.A., Seran, E., Godefroy, Abdelaal, M.E. (2022). Dust complex for studying the dust particle dynamics in the near-surface atmosphere of Mars. Solar System Research, 56(6), 351–368.
2. Abdelaal, M.E., Dokuchaev, I.V., Malinovskaya, E.A., Klimov, S.I., Dolnikov, G.G., & Zakharov, A.V. (2024). Experimental modeling of atmospheric discharge phenomena and charged dust particle interactions. Frontiers in Astronomy and Space Sciences, 11, 1347048. https://doi.org/10.3389/fspas.2024.1347048.
3. M. E. Abdelaala, I. V. Dokuchaeva, I. A. Kuznetsova, I. A. Shashkovaa, A. N. Lyasha, A. E. Dubova, Y. A. Oboda, A. A. Kartashevaa, G. G. Dolnikova, A. V. Zakharova. (2025). Electromagnetic noise in the near-surface Martian atmosphere: research methods. Solar System Research, Article ID: SolSys2560014Abdelaal. Accepted, in press.
4. Mohamad E. Abdelaal, Igor V. Dokuchaev, Elena A. Malinovskaya, Yulia N. Izvekova, Andrey N. Lyash, Ilya A. Kuznetsov, Inna A. Shashkova, Andrey E. Dubov, Alexandra A. Kartasheva, Gennady G. Dolnikov, Alexander V. Zakharov (2025). Generation of electromagnetic radiation caused by the dynamics of charged dust particles in a simulated terrestrial environment. AIP Advances, Article ID: ADV25-AR-02186, under consideration.
5. Mohamad E. Abdelaal, Maxim A. Zaitsev, Egor M. Sorokin, Inna. A. Shashkova, Anna S. Kuzovchikova, Elena I. Seran, Alexander V. Zakharov (2025). Electromagnetic phenomena

associated with dust particle dynamics in a simulated Martian atmosphere: an experimental study. Advances in Space Research, Article ID: AISR-S-25-01593, under consideration.

6. Mohamad Abdelaal, Elena Malinovskaya, Otto Chkhetiani, Ilya Kuznetsov, Alexandra Kartasheva, Leonid Maksimenkov, Igor Dokuchaev, Andrey Lyash, Andrey Dubov, Yuri Obod, Inna Shashkova, Gennady Dolnikov, Alexander Zakharov (2025). Electromagnetic phenomena in planetary atmospheres: insights from electrization and discharge of dust aerosol in arid environments. Theoretical and Applied Climatology, Article ID: 5ec58a20-baa3-4daa-b0d8-a44ba7210bf6, under consideration.

Articles in Conference Proceedings

7. Abdelaal, M.E., Zakharov, A.V., et al. (2022). Анализ низкочастотных электромагнитных шумов для оценки пылевой динамики атмосферы Марса. Современные проблемы дистанционного зондирования Земли из космоса. ISBN: 978-5-00015-056-6. DOI: 10.21046/20DZZconf-2022a
8. Malinovskaya, E.A., & Abdelaal, M.E. (2024). Электромагнитные колебания при туннельном переходе электронов между взаимодействующими частицами пыли. In III Международная научно-практическая конференция «Инновационные методы математики и физики в экологических и гидрометеорологических исследованиях», Санкт-Петербург, 5 апреля 2024 года.

The structure of the thesis

The dissertation is structured into an introduction, five core chapters, a conclusion, a list of references, and appendices. Each chapter represents a distinct stage of the research, reflecting a logical progression from theoretical foundations to laboratory and field investigations. The structure is designed to provide a comprehensive understanding of dust-induced electromagnetic phenomena across planetary environments, with an emphasis on experimental validation under simulated Martian, terrestrial, and vacuum-like conditions. The results presented in each chapter align with the thematic scope of individual peer-reviewed publications and conference contributions. In the introduction, the research outlines its objectives, highlights the scientific novelty and practical significance, and presents the key propositions for defense, while also establishing the study's relevance within the broader context of planetary science.

Chapter 1 provides the theoretical and observational foundations for the study of electrostatic and electromagnetic phenomena associated with charged dust particles in planetary boundary layers. The chapter begins with an overview of the physical mechanisms responsible for non-thermal electromagnetic noise generation during dust particle collisions and discharges. It surveys the composition, morphology, and charge-carrying behavior of dust particles in Martian and terrestrial conditions, highlighting the triboelectric and photoelectric processes that contribute to charge accumulation and separation.

The chapter includes a detailed discussion of the Paschen breakdown phenomenon in CO_2-rich environments, emphasizing the reduced discharge thresholds on Mars and the implications for filamentary and glow discharges. Key historical and recent mission data are reviewed, including electromagnetic observations from the Viking, Pathfinder, and ExoMars platforms for Mars, and the Venera and Venus Express missions for Venus. The chapter also introduces Schumann resonance theory as applied to Mars and outlines the potential for low-frequency electromagnetic wave propagation resulting from dust storm activity.

Finally, Chapter 1 describes the instrumentation and methodology used in subsequent chapters, with particular focus on the Electromagnetic Analyzer (EMA) developed for the ExoMars Dust Complex. The rationale for adapting the EMA for laboratory and field studies is justified in relation to its frequency sensitivity and robustness in harsh environments. This chapter forms the theoretical and methodological backbone for the experimental investigations that follow.

Chapter 2 is devoted to the experimental investigation of electromagnetic emissions generated by dust particle interactions under Earth-like atmospheric conditions. It presents the development and implementation of a novel laboratory framework for studying triboelectric charging, discharge events, and associated electromagnetic signatures in granular flows that emulate natural dust lifting and transport processes in arid terrestrial settings.

The chapter begins by addressing the role of triboelectric charging and tunneling charge transfer mechanisms that arise during saltation processes. Particles in the range of 20–150 µm become electrified upon impact, and under sufficient charge densities, localized corona discharges may occur, especially at points of geometric irregularity or sharp surface curvature. These discharges originate when the electric field surrounding the particle exceeds the breakdown voltage.

A theoretical framework is introduced to describe the electrostatic field evolution between asymmetrically sized colliding particles. Utilizing a pairwise interaction model with unequal particle lengths l_1 and l_2, and surface charge density σ, the chapter derives expressions for the electric field contributions E_1 and E_2, highlighting conditions under which charge imbalance and directional tunneling occur. Here ε is a dielectric permittivity of air, ε_0 is an electric constant, r_1 and r_2 are the distances to Particle 1 and 2 from the x-axis point.

$$E_1 = \frac{1}{4\pi\varepsilon_0\varepsilon}\int \frac{\sigma\, dl}{r_1^2} = \frac{2\sigma}{4\pi\varepsilon_0\varepsilon}\int \frac{r\cos\alpha\, d\alpha}{r_1^2} = \frac{\sigma}{4\pi\varepsilon_0\varepsilon}\,\frac{l_1}{r_1^2},\; E_2 = \frac{\sigma}{4\pi\varepsilon_0\varepsilon}\,\frac{l_2}{r_2^2} \tag{1}$$

The resulting electric field configuration promotes charge transfer from larger to smaller particles, and under certain geometric constraints, localized field amplification can lead to breakdown.

This part further elaborates on the spatial distribution of electrostatic potential, the formation of electron clouds through field emission near the particle surface, and how these modulate the effective field strength during the collision process. The dynamics of electron recombination and shielding are shown to influence the amplitude and duration of resulting EM bursts. Theoretical predictions align with experimental observations, where signal amplitude is determined by the charge differential Δσ, while waveform shape correlates with material conductivity and recombination time.

The chapter also draws comparisons with lightning discharge physics in Earth's atmosphere, introducing a current moment model for the return stroke [13] and applying Fourier transformation to obtain emission spectra. The following expression:

$$M(t) = V_0 \tau \sum_k I_k e^{-\frac{t}{\tau_k}} \left(1 - e^{-\frac{t}{\tau_k}}\right) \quad (2)$$

is used to model the temporal profile of the return stroke current. The pulse shape of the electric field emitted during the return stroke for these models is illustrated in Fig. 1. Despite differences in scale, the recorded signals from dust interactions share spectral characteristics with natural lightning, including peak emissions in the 150–350 kHz range. This spectral behavior is linked to earlier peak times in dust discharges (~0.5–1 μs), compared to 2–4 μs in cloud-to-ground lightning, resulting in a shift of the emission maximum toward higher frequencies.

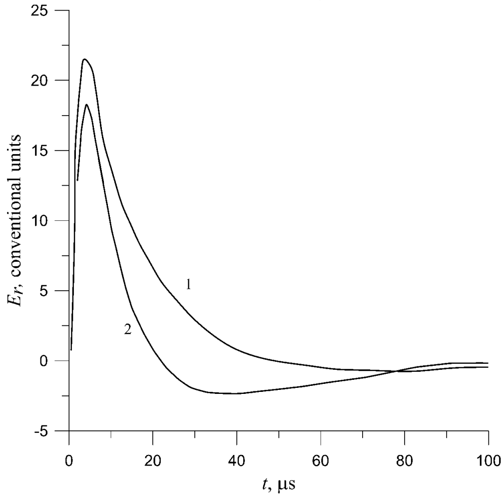


Fig. 1. Form of the electric field pulse waveforms emitted by the return stroke models according to [14] – 1 and [15] - 2.

A custom-designed environmental chamber was built for controlled experiments, enabling the generation of small-scale dust vortices and saltation under adjustable temperature, pressure, and humidity conditions (Fig. 2). The core innovation is the integration of the Electromagnetic Analyzer (EMA), originally developed for the ExoMars Dust Complex, into the laboratory testbed. This device was recalibrated and validated to detect electromagnetic bursts in the low-frequency (LF) and medium-frequency (MF) ranges. The chamber allows for variation of gas composition and dust properties, simulating Earth and partial Martian conditions.

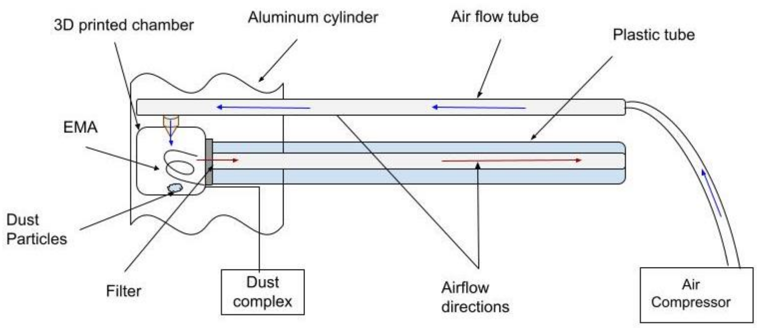
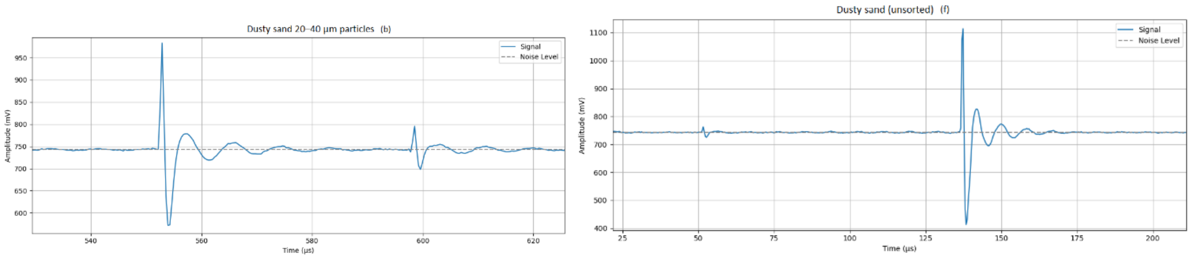


Fig. 2. Schematic view of the experimental setup

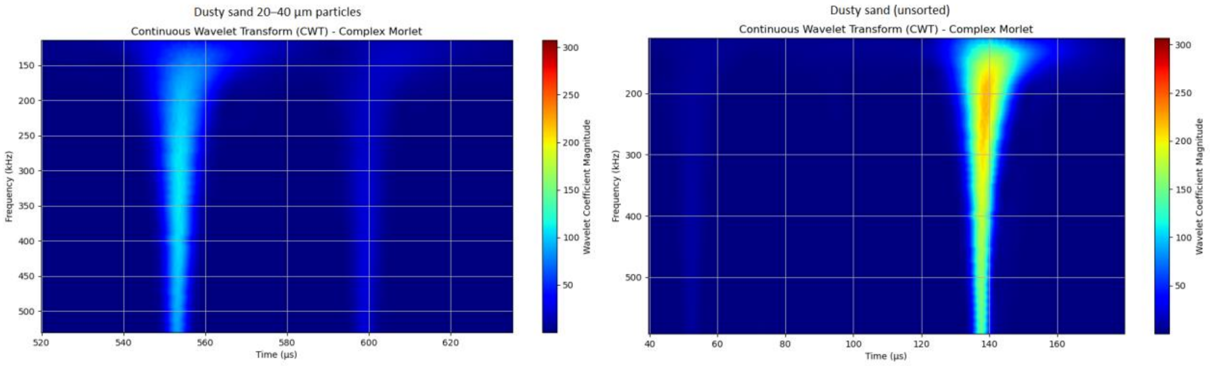
The experimental results demonstrate that fine particles (< 40 µm) produce frequent, lower-amplitude discharges, while coarse particles (> 100 µm) generate less frequent but higher-energy bursts. These discharges emit EM signals with decaying amplitudes that follow a power-law distribution, a finding consistent with theoretical models of triboelectric microdischarges and tunneling-based recombination dynamics. Material analysis confirms that silicate-dominated samples tend to favor charge separation, whereas iron-rich or clay-bearing samples exhibit higher charge retention and localized discharge clustering.

Additionally, time-domain and spectral data acquired via the EMA reveal emission bandwidths consistent with non-thermal origins, differentiating the signals from background noise and confirming their discharge-related genesis. This chapter provides the first experimental confirmation of persistent broadband electromagnetic emissions arising from colliding dust particles in dry, Earth-like conditions. The results serve as a terrestrial analog for understanding similar phenomena expected in Martian and other extraterrestrial dusty environments.

Time-domain analysis and Fast Fourier Transform (FFT) of several bursts from the unsorted sand sample, used as a representative example, revealed fading characteristics in the recorded signals, with an initial amplitude of approximately 700 mV at a frequency of 230 kHz, followed by secondary bursts decreasing to 137.7 mV, 48.3 mV, and 21.7 mV, respectively (Fig. 3). The decay of these secondary bursts followed a power-law behavior, with fitted exponents of approximately ~-0.1 for sorted particles (20–40 µm), ~-0.05 for sorted particles (40–100 µm), and ~-0.01 for unsorted particles. These findings indicate that smaller particles exhibit slower amplitude decay, likely due to enhanced particle overlap and shielding effects, which reduce the rate of energy dissipation.



(a) (b)



(c) (d)

Fig. 3. Time-domain analysis of electromagnetic bursts, showing the signal amplitude (y-axis, in mV) as a function of time (x-axis, in μs) for (a, c) 20–40 μm particles and (b, d) unsorted dusty sand. The lower panel presents a continuous wavelet transform (CWT) analysis of the electromagnetic bursts, illustrating the time-frequency distribution of signal intensity for the same particle categories.

Chapter 3 investigates the fundamental mechanisms of dust-induced discharge under laboratory conditions that replicate the low atmospheric and near-vacuum environments. It focuses on how charged dust particles behave under reduced pressure and low-density air environments, and how these conditions facilitate electromagnetic (EM) emission through microdischarges and breakdown events.

A custom-designed electrostatic dust injector [16] was employed to accelerate charged metallic particles—primarily iron (800 nm to 5 μm) and tungsten (30 μm)—into a vacuum chamber. Through contact with a tungsten needle electrode under potentials of up to 10 kV, particles acquired electric charge and were electrostatically accelerated to velocities ranging from 3 to 100 m/s. The maximum imparted charge was constrained by field emission thresholds (10^9–10^{10} V/m), with positive charging favored to mitigate premature ion emission. The accelerated charged particles entered a vacuum chamber where their collisions and interactions were monitored using the oscilloscope records at specific points and the Electromagnetic Analyzer.

Theoretical analysis drew upon tunneling charge transfer theory [17], in which localized electric fields between particles of different sizes produce asymmetric potential distributions, leading to electron exchange and possible breakdown. The electric field strength and discharge conditions were quantified using relations that consider the ratio of particle dimensions, the number of collisions, and induced dipole effects. Field enhancement near particle tips and curved surfaces contributed to the onset of corona discharge, with breakdown voltages observed between 2–5 kV—consistent with laboratory measurements involving metallized quartz needles [18,19].

Numerical simulations based on Poisson's equation using OpenFOAM confirmed that the electric field inside the induction cylinder was weak and symmetrically aligned, minimizing distortive effects and confirming that the measured signals originated from particle-particle or particle-surface interactions. Additional modeling revealed that particle clouds of opposite polarity could produce dynamic shielding effects and secondary oscillatory discharges, forming damped electromagnetic oscillations analogous to those observed during natural atmospheric lightning.

To further investigate the electric field enhancement that facilitates breakdown initiation at the microscale, additional simulations were conducted for charged micro-needles with opposite polarity. The results demonstrated localized field intensification near the tips, where potential gradients become steep enough to trigger field-induced ionization (Fig. 4). These findings support the interpretation of observed discharge pulses as originating from microdischarges initiated by sharp curvature or asymmetric particle configurations.

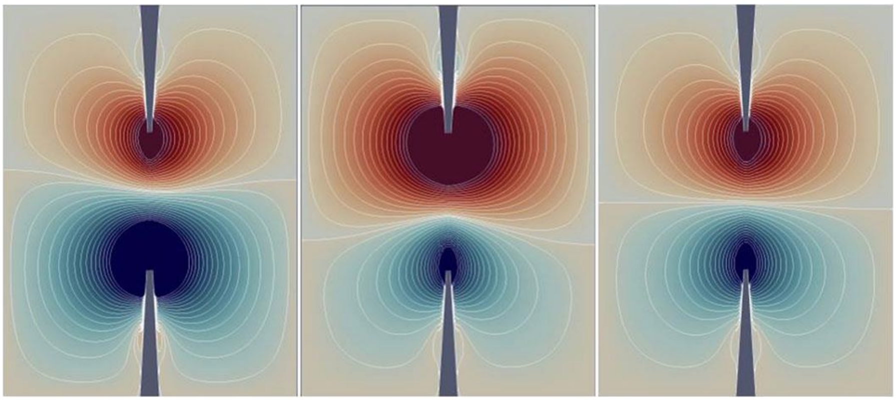


Fig. 4. The change in electric field potential near sharp needles of differing charges, each measuring 10 microns in size. These results are derived from numerical modeling for the Poisson equation, providing insight into the distribution of electric field potential surrounding the needles.

The signal characteristics recorded by the EMA were decomposed into successive stages:

1. Ion emission and acceleration due to localized field enhancement.
2. Avalanche motion and magnetic field generation, resulting in EM pulse onset.
3. Charge recombination and equilibrium, temporarily quenching the field.
4. Reverse ion movement and secondary discharges, creating lower-amplitude oscillations.

These stages reflect a multi-cycle damped EM waveform, with temporal and spectral features strongly dependent on particle material, charge, and distribution. Experimental spectra showed emission peaks in the 150–350 kHz range—consistent with model predictions and previous observations of high-frequency components in Martian dust devils.

Together, these experimental results support the hypothesis that non-thermal electromagnetic emissions can be generated in dusty planetary boundary layers—even in low-density environments—and that such signals are accessible using appropriately sensitive diagnostics.

Chapter 4 is dedicated to the experimental investigation of triboelectric discharges and electromagnetic (EM) emissions generated by dust particle interactions under conditions simulating the Martian near-surface atmosphere. Two main experimental configurations were implemented: (1) the measurement of breakdown voltages to derive Paschen curves for CO_2 and air under low-pressure conditions, and (2) the detection of EM emissions resulting from collisions between charged dust particles under dynamic flow and turbulence conditions. These studies directly address the hypothesis that Martian dust storms may generate lightning-like discharges due to charge accumulation and localized breakdowns.

From a theoretical perspective, triboelectric charging in terrestrial dust events can generate electric fields approaching or exceeding 100–150 kV/m. However, due to the low atmospheric density on Mars, electrical discharges occur at significantly lower electric field gradients, ranging from approximately 5 to 20 kV/m. Consequently, microdischarges and storm-scale electrical discharges are likely to occur within Martian dust devils and dust storms, potentially generating wideband electromagnetic emissions [20]. According to [5], these emissions are expected to fall into two primary frequency ranges. The first type, occurring in the very low frequency (VLF) range of 3–30 kHz, corresponds to extended filamentary discharges driven by large-scale variations in the cloud's dipole moment—phenomena somewhat analogous to terrestrial lightning. The second type, in the medium to high frequency (MF/HF) range of 300 kHz to 30 MHz, arises from short-duration electrical discharges associated with microscopic grain dipole moments. Despite the evident importance of triboelectric charging in Martian dust activity, limited laboratory studies have been conducted under low-pressure conditions to characterize dust-induced electrical discharges and validate these theoretical predictions.

The first experimental setup involved measuring Paschen breakdown curves for both CO_2 and air over a wide pressure range (2–1013 mbar) using a sealed discharge tube and electrode system (Fig. 5). These measurements revealed a lower minimum breakdown voltage for CO_2 than for air, consistent with its higher electron affinity and ionization cross-section. This validates the relevance of CO_2 as an efficient breakdown medium in Martian atmospheric conditions, particularly in the 6–10 mbar pressure range typical of the Martian surface. The experimental Paschen curves exhibit expected minima and match theoretical predictions, confirming the reliability of the setup. These results indicate that, under the low-pressure and relatively uniform electric field conditions characteristic of the Martian surface, Townsend avalanche processes—where free electrons multiply exponentially through ionization collisions—are likely the primary mechanism for electrical breakdown. However, in environments with significant dust activity and highly non-uniform electric fields, the onset of streamer or corona discharges may dominate. Streamer discharges involve the propagation of ionized channels and can lead to larger-scale breakdown events, while corona discharges are localized phenomena occurring near sharp or curved surfaces under high field gradients.

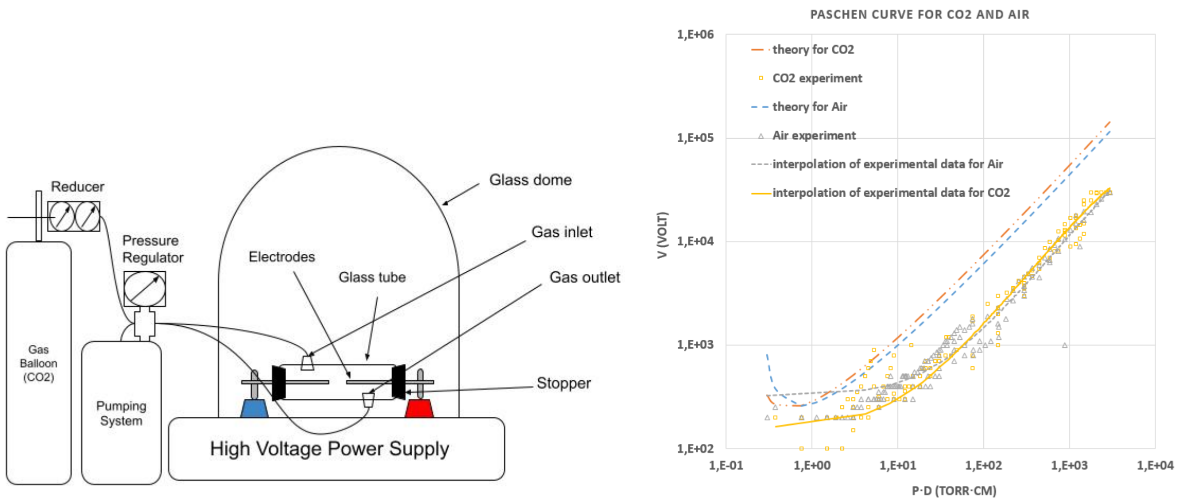


Fig. 5. Schematic diagram of the experimental setup (left) and Paschen breakdown curves for CO2 and air compared with their theoretical values (right).

The second experiment aimed to detect real-time EM signals produced during the collisional dynamics of charged dust particles in a custom-built dust chamber housed within a vacuum system (Fig. 6). Nine different mineralogical dust samples were tested under CO_2 flow at varying pressures (1–4 bar), with dynamic micro-vortices facilitating triboelectric interactions. The chamber was instrumented with a high-sensitivity Electromagnetic Analyzer (EMA) adapted from the ExoMars Dust Complex, capable of detecting emissions in the 120 kHz–1.420 MHz range. This frequency window was chosen based on the expected spectral signature of Martian dust discharges and minimized atmospheric attenuation [21].

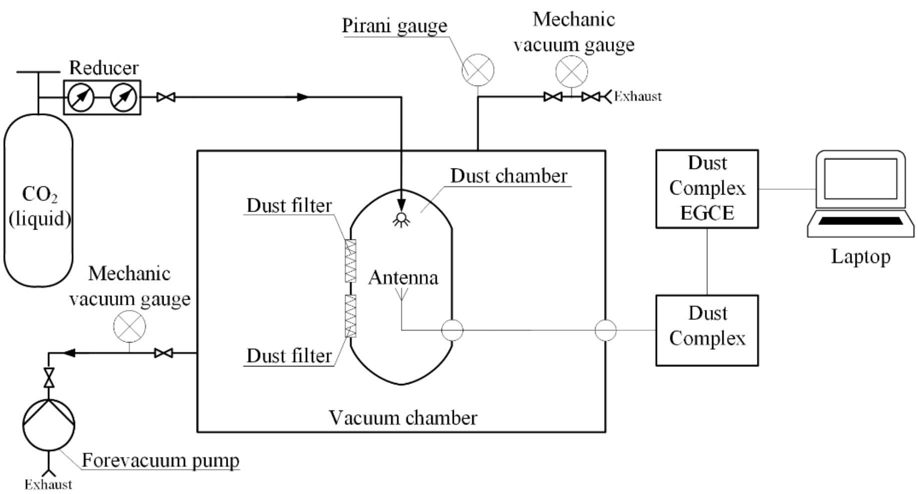


Fig. 6. Schematic diagram of the experimental setup for recording electromagnetic (EM) emissions from collisions of charged dust particles.

The behavior of electromagnetic discharges observed in the experiment was strongly influenced by the interplay between dust particle composition, granulometry, and the characteristics of the surrounding CO_2 atmosphere. The five natural samples (1–5) were dominantly siliceous, with SiO_2 content reaching up to 86 wt.%, and significant levels of Al_2O_3 and K_2O indicating a granitic origin enriched in potassium feldspars. These high-resistivity materials ($\rho \sim 10^{14}$ Ω·cm) exhibit deep electron trap states and long charge retention times, enabling substantial electric field build-up prior to discharge initiation. In contrast, the engineered analogs (6–9) displayed basaltic mineralogy with elevated Fe_2O_3 and TiO_2 contents, consistent with semiconducting phases such as ilmenite and titanomagnetite, which facilitate more efficient charge dissipation through polaronic conduction. Fine-grained samples (<50 μm) yielded higher EM signal counts, attributable to increased surface area and enhanced triboelectric charging efficiency, while larger particles showed lower frequencies of discharge but longer retention of localized field potentials. The use of CO_2 as the discharge medium played a dual role: it increased the breakdown voltage via its high electron attachment cross-section, but simultaneously sustained discharges once initiated due to its molecular density and ionization properties. This balance was reflected in the narrow pressure window where electromagnetic signal (EMS) intensity peaked, validating the critical dependence of breakdown phenomena on both particle properties and gas-phase behavior. Together, these results demonstrate that dust composition, morphology, and the ambient atmospheric medium exert strong control over discharge thresholds, spatial field distribution, and the intensity of resulting electromagnetic emissions under Mars-relevant conditions.

To capture the transient electromagnetic bursts arising from dust discharges, a tri-modal signal processing framework was implemented in python, integrating time-domain signal profiling, spectral decomposition via Fourier transform, and continuous wavelet transform (CWT) analysis (Fig. 7). The (EMA) successfully detected broadband emissions in the 160–500 kHz range, with signal amplitudes varying from 200 to 750 mV, indicative of short electrical discharges associated with microscopic grain dipole moment. Spectrograms revealed characteristic burst patterns modulated by particle type and grain size, while CWT analysis enabled precise localization of non-stationary events across multiple temporal scales. Natural silicate-rich samples produced discrete, high-energy pulses with sharp spectral boundaries, consistent with strong charge accumulation and delayed dissipation. In contrast, Fe–Ti-bearing analogs exhibited lower amplitude, broadband signals attributed to shallow trap release and conductive damping. Notably, Al_2O_3-rich, ultra-fine samples produced sporadic, high-magnitude events suggestive of micro-plasma formation under optimal pressure and field conditions. The variability in spectral power density and multi-scale decomposition confirmed the complex dynamics of dust-plasma interaction in low-pressure CO_2 atmospheres. These findings establish a robust diagnostic methodology for future planetary missions, offering predictive capability for electromagnetic interference risks and guiding the design of sensor payloads and protective shielding in dust-prone extraterrestrial environments.

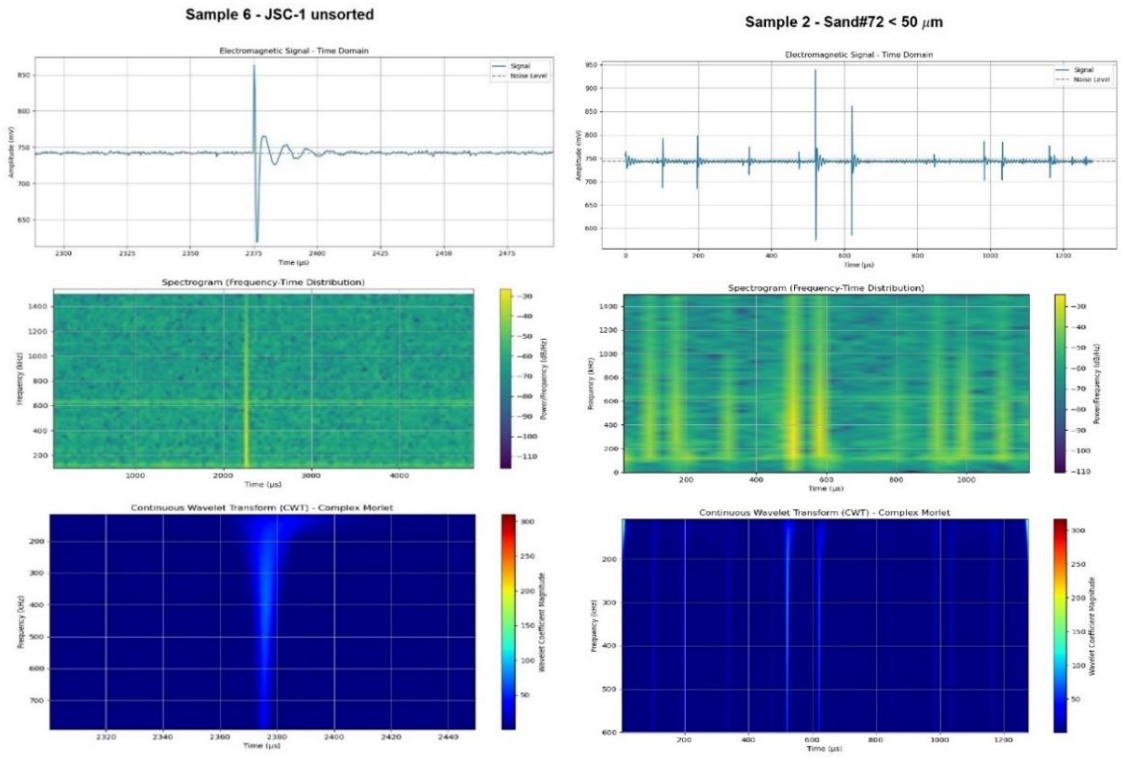


Fig. 7. Time-domain signal and its time-frequency analyses for (a) Sample 6 (JSC-1 unsorted), and Sample 2 (Sand #72 <50 μm). Top panels: Time-series with single discharge events. Middle panels: Corresponding spectrograms showing frequency evolution. Bottom panels: CWT scalograms revealing transient features. Color bars indicate relative intensity.

Chapter 5 explores the manifestation of electromagnetic phenomena under natural terrestrial conditions, emphasizing desert environments that serve as analogs for Martian dust electrification processes. Dust electrization in arid regions arises from triboelectric interactions during saltation, turbulence, and convective flow. These processes generate significant electric fields and, under certain conditions, electromagnetic discharges. This study examines these phenomena through field observations conducted in the Kalmykian desert, linking meteorological parameters such as wind speed, humidity, and temperature to electrostatic and electromagnetic bursts caused by dust collisions.

Triboelectric charging is initiated as dust particles bounce and collide within saltation layers, with mobile grains acquiring a negative charge and surface-bound grains becoming positively charged. This process enhances electrostatic forces, which in turn influence particle trajectories and enable sustained lofting. The resulting electric fields can exceed 10–100 kV/m near the surface and persist at altitudes of several kilometers, as observed during large-scale dust events [22]. The fine aerosol fraction, typically less than 10 μm in diameter, is especially sensitive to electrostatic forces and contributes disproportionately to charge accumulation and atmospheric conductivity.

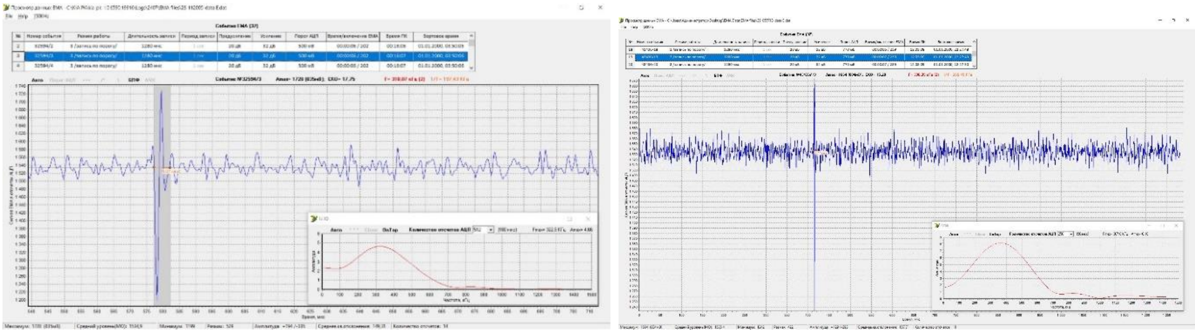
A key component of the investigation involves characterizing the vertical structure of electric field strength and aerosol concentration. Near-surface electric fields are maximized within the first few centimeters, where saltating particles dominate, and decay exponentially with altitude. Empirical data show that electric field strength scales linearly with aerosol concentration under both dry and moderately humid conditions. This behavior is enhanced under low relative humidity conditions due to the balloelectric effect, wherein evaporative charge generation drives additional charge separation as moist grains release electrically charged droplets during desiccation [23].

Laboratory and atmospheric observations further demonstrate that relative humidity, particularly below 40–50%, significantly modulates electrization efficiency. Moisture affects both the cohesion and the contact dynamics of dust particles. At critical moisture levels (~1%), saltation efficiency increases due to the combined effects of particle elasticity and capillary forces. Additionally, temperature and vapor gradients drive vertical moisture flux, altering surface wettability and modifying both detachment and charging behavior. Under moderate wind conditions, these interactions produce spatially coherent electrostatic fields and transient electromagnetic signals.

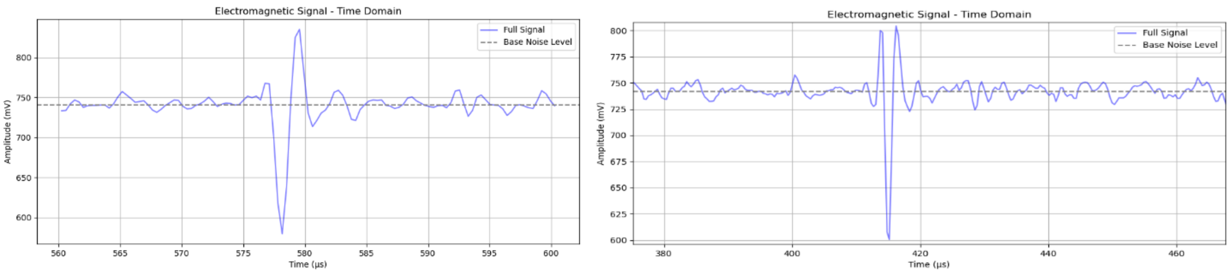
Building upon the contextual and theoretical framework, the second part of this study presents detailed chemical, electromagnetic, and environmental data obtained during field measurements. X-ray fluorescence (XRF) analysis of dust samples collected in the Kalmykian desert revealed high silica content (SiO_2: 79–86.4 wt.%), characteristic of quartz-rich aeolian sediments. Supplementary components included alumina (Al_2O_3 up to 7.2 wt.%) and potassium oxide (K_2O up to 1.6 wt.%), consistent with feldspar minerals typically derived from granitic terrains. The relatively low iron oxide (Fe_2O_3 up to 2.3 wt.%) and minimal loss on ignition (LOI) confirmed the dry, mineral-rich nature of the samples and the absence of significant volatile or moisture-bearing phases.

Electromagnetic signals recorded during the field campaign exhibited distinct and reproducible waveform structures. The primary category of signals ranged between 330–430 kHz with amplitudes of 200–314 mV and durations of 3–5 μs (Fig. 8). Their repeatable shape—characterized by sharp onset peaks followed by resonant decay—suggests discharge processes likely driven by triboelectric mechanisms under moderate wind stress. Fast Fourier Transform (FFT) analyses of these signals confirmed dominant spectral peaks at 333 and 365 kHz, with signal-to-noise ratios (SNR) of 17.4 dB and 15.5 dB, and signal-to-background ratios of 7.5 and 5.9, respectively. These values confirm moderate to strong detectability within the EMA's operating band.

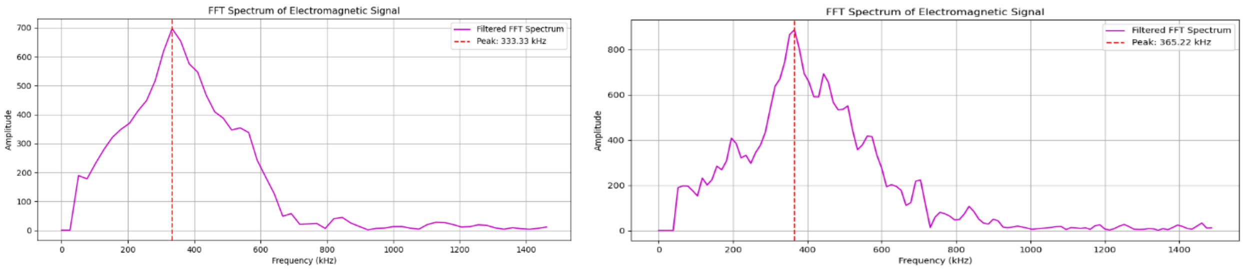
Secondary signals exhibited broader variability in amplitude (40–150 mV) and frequency (200–300 kHz), often with complex, non-repeating waveforms. These may be attributed to transient discharges influenced by localized turbulence, shifting electrostatic gradients, or even anthropogenic sources such as high-voltage infrastructure. Despite lower SNR (~9.3 dB) and signal-to-background ratios (~2.9), their frequency overlap with natural discharge signatures justifies further examination in future campaigns.



(a)



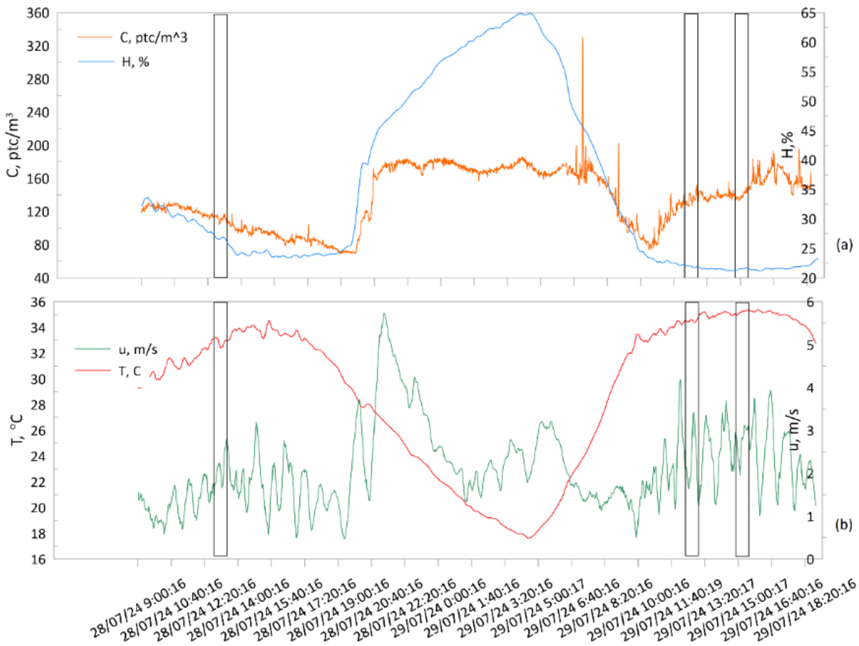
(b)



(c)

Fig. 8. Sample of the registered Electromagnetic signals in the field, (a) Raw data, with ADC counts on the y-axis, and time in µs on the x-axis. (b) Processed signal data, with amplitude in mV on the y-axis and time on the x-axis. (c) the Fast Fourier transform spectrum for the processed signals.

Notably, the most intense electromagnetic activity—up to 20 events per 30-second interval—occurred during low wind speeds (<4 m/s) and at relative humidity levels around 20% (Fig. 9). This finding aligns with prior work showing that under dry, sunlit conditions, triboelectric and balloelectric effects are amplified. Daytime humidity drops below 40% correlated with peaks in discharge events, particularly when accompanied by rising temperatures (18–34°C) and increased solar irradiance (~620–640 W/m²). This highlights the pivotal role of solar heating and evaporation in modulating dust electrization, whereby evaporation releases oppositely charged microdroplets and contributes to charge separation in the lower atmosphere.



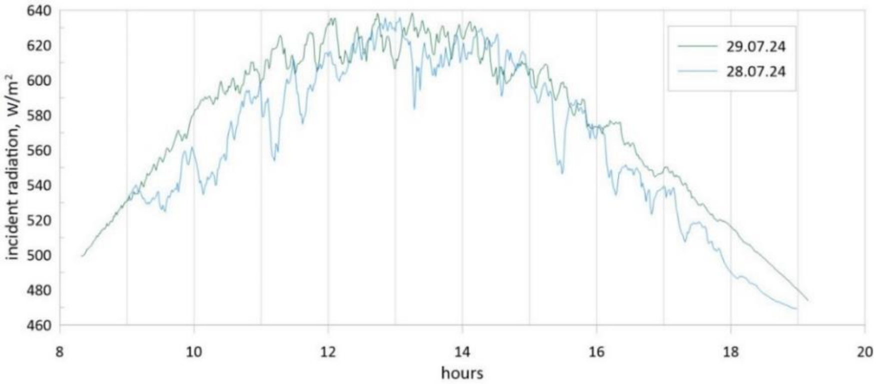


Fig. 9. Temporal variations in (a) relative humidity and dust aerosol particle number concentration (particles/cm^3) measured by LAS, (b) wind velocity and temperature, and (c) incident solar radiation over the measurement period.

Finally, time-domain, RMS, and spectral analyses collectively demonstrate the coherence between microphysical particle interactions and macroscale environmental drivers. These results reinforce the conclusion that moderate wind conditions, low humidity, and solar heating create an optimal regime for electrostatic discharge generation in desert environments. The experimental methodologies and signal analysis protocols developed here can be adapted for both terrestrial monitoring and extraplanetary applications, particularly in the design of instruments aimed at characterizing dust-related electrical phenomena on Mars.

Conclusions

This dissertation has systematically investigated the electromagnetic phenomena arising from charged dust particle interactions in planetary environments, focusing on Martian, and terrestrial conditions. Through a multidisciplinary methodology combining laboratory simulations, theoretical modeling, high-voltage discharge testing, and in situ field measurements, the work confirms that triboelectric and tunneling charge transfer mechanisms can generate detectable electromagnetic emissions across a broad frequency spectrum. Under low-pressure CO_2 atmospheres analogous to Mars, fine mineral particles were shown to reach discharge thresholds consistent with Paschen breakdown, producing transient discharges with characteristic spectral signatures. The adapted Electromagnetic Analyzer (EMA) instrument proved effective in detecting and classifying these emissions under both controlled and natural conditions, offering a validated diagnostic tool for future planetary missions.

The findings also highlight the importance of environmental parameters such as humidity, particle composition, and wind speed in modulating electrostatic activity. Field experiments in arid regions demonstrated that moderate wind and low humidity significantly enhance discharge occurrence, with emissions peaking above 300 kHz. Variability in signal amplitudes and frequency was found to correlate with dust mineralogy and grain size, supporting material-specific discharge behavior observed in laboratory conditions. These results offer critical insights into the electrodynamics of planetary dust layers, with direct implications for atmospheric chemistry, mission hazard assessment, and sensor development. Collectively, this research establishes a foundational framework for understanding and monitoring dust-induced electromagnetic activity in planetary boundary layers, providing both theoretical advancement and practical pathways for space exploration.

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