Planetary Wave-Dust Coupling During Regional Dust Storms: Implications for Solar-Powered Mars Missions

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Abstract

Martian dust storms represent among the most dynamic atmospheric phenomena governing planetary climate systems, with their influence extending beyond fundamental atmospheric science to pose critical operational challenges for contemporary Mars exploration missions. Solar-powered robotic systems face particular vulnerability to dust-induced power fluctuations, creating urgent needs for understanding dust storm impacts on surface infrastructure performance.

China's Zhurong rover, following its successful deployment in southern Utopia Planitia on May 15, 2021 (L_s ~45°, coordinates: 109.925°E, 25.066°N, elevation: -4099.4 m), provided an exceptional opportunity to investigate the early-season regional dust storm dynamics during Martian Year 36 (L_s ~150°-170°). This investigation integrated comprehensive datasets from multi-rover in-situ meteorological observations, climatological databases of Martian atmospheric dust optical depth, InSight's array current measurements and Mars Planetary Climate Model (Mars PCM) simulations to characterize the regional dust event's impact on the landing vicinity.

Our analysis reveals that this regional dust storm triggered surface wind enhancement across two distinct geographical domains. The primary affected zone encompasses the topographically heterogeneous landscape surrounding Olympus Mons, Tharsis Montes, and Valles Marineris, where complex orographic interactions intensify wind velocity fluctuations. The secondary region extends across Isidis Planitia, Elysium Planitia, and southern Utopia Planitia —encompassing Zhurong's operational theater. During the L_s ~150°-160° interval, Zhurong documented pronounced perturbations in wind velocity, temperature, and atmospheric pressure, accompanied by accelerated dust deposition rates. Critically, atmospheric dust concentrations exhibited systematic oscillations with characteristic periods of 10-20 sols. Coordinated meteorological observations from Perseverance, Zhurong, and InSight rovers demonstrated that these periodic variations result from eastward-propagating traveling planetary waves (TPW), which simultaneously induced coherent fluctuations in InSight's photovoltaic array current output.

Our findings indicate that enhanced atmospheric dust loading amplifies the visibility of planetary wave modulation in solar array performance, revealing a previously unrecognized coupling between large-scale atmospheric dynamics and surface power systems. This wave-dust interaction mechanism represents a critical pathway through which planetary-scale meteorological processes directly influence technological infrastructure, establishing fundamental connections between atmospheric science and Mars mission engineering.

This investigation provides crucial insights for Mars exploration sustainability, particularly relevant for China's upcoming Tianwen-3 sample return mission scheduled for the late 2020s. The identified amplification mechanism offers a predictive framework for anticipating power system fluctuations during dust events, enabling more robust mission planning and autonomous systems design. The multi-rover observational approach demonstrates the scientific value of international coordination in Mars exploration, establishing methodological precedents for future collaborative planetary investigations. These findings directly inform engineering requirements for advanced Mars missions, including sample return operations and eventual human exploration infrastructure, by quantifying atmospheric-technological interactions that could impact mission success and operational safety.