

Dust in the Atmosphere of Mars and Its Impact on Human Exploration

Houston, Texas
June 13–15, 2017

Institutional Support

Lunar and Planetary Institute
Universities Space Research Association
NASA Engineering and Safety Center (NESC)
NASA Jet Propulsion Laboratory
The College of William and Mary

Conveners

Joel S. Levine, Ph.D.
The College of William and Mary
Daniel Winterhalter, Ph.D.
NASA Jet Propulsion Laboratory

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The College of William and Mary
Daniel Winterhalter, Ph.D.
NASA Jet Propulsion Laboratory
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NASA Ames Research Center (Retired)

Abstracts for this meeting are available via the meeting website at
www.hou.usra.edu/meetings/marsdust2017/

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Guide to Sessions

Tuesday, June 13, 2017

9:00 a.m.	Lecture Hall	Welcome and Invited Presentations
12:00 p.m.		LUNCH
2:00 p.m.	Lecture Hall	Plenary Session
4:00 p.m.	Berkners D-F	Mars Dust: Characteristics, Composition and Electrification
4:00 p.m.	Berkners A-C	Mars Dust: Human Health
4:00 p.m.	Hess Room	Mars Dust: Mechanical Systems and Surface Operations

Wednesday, June 14, 2017

9:00 a.m.	Berkners/Hess	Breakout Panels
11:30 a.m.		LUNCH
1:30 p.m.	Berkners/Hess	Breakout Panels
4:00 p.m.	Lecture Hall	Plenary Session
5:30 p.m.	Great Room	Poster Session

Thursday, June 15, 2017

9:00 a.m.	Lecture Hall	Plenary Session
12:00 p.m.		LUNCH
2:00 p.m.	Berkners/Hess	Breakout Panels
4:00 p.m.	Lecture Hall	Plenary Session
5:00 p.m.		WORKSHOP ADJOURNS

* *Coffee Breaks will be daily at 10:30 a.m. and 3:30 p.m.*

Program

Tuesday, June 13, 2017
WELCOME AND INVITED PRESENTATIONS
9:00 a.m. Lecture Hall

Levine J. S. * Winterhalter D. *

Welcome and Logistics

Goals and Objectives of the Workshop

Introduction of Breakout Panel Moderators and Recorders

Zurek R. W. *

The Spatial and Temporal Distribution of Dust in the Atmosphere of Mars [#6019]

Dust is widely spread in the Mars atmosphere, but it varies spatially, seasonally, and from year-to-year. This presentation gives an overview of the dust distribution, with emphasis on the roles of local, regional and planet-encircling dust storms.

Ming D. W. * Morris R. V.

Chemical, Mineralogical, and Physical Properties of Martian Dust and Soil [#6027]

Chemical, mineralogical, and physical properties of martian dust and soil are reviewed from data returned by robotic landers and rovers.

McCoy J. T. * Ryder V. E. Lam C. W. Scully R. R. Romoser A. A.

Martian Dust Toxicity: Should We Believe the Headlines? [#6004]

Martian dust has received significant attention, and with good reason. However, it is important to keep toxicity in proper context, and to avoid overstating crew health risks. Are perchlorates and other stressors really martian show-stoppers?

Farrell W. M. *

Regarding Electrified Martian Dust Storms [#6020]

We examine the dynamic competition between dust devil/storm charging currents and dissipating atmospheric currents. A question: Can high-current lightning be a dissipation product of this competition? Most likely not but there are exceptions.

Darquenne C. * Prisk G. K.

Reduced Gravity and Aerosol Deposition in the Human Lung [#6008]

Studies during parabolic flights showed a significant effect of gravity on the amount and site of aerosol deposition in the lung, which may affect subsequent clearance and greatly increase the toxicological impact of inhaled lunar or martian dust.

Rucker M. A. *

Dust Storm Impacts on Human Mars Mission Equipment and Operations [#6013]

NASA has accumulated a wealth of experience between the Apollo program and robotic Mars rover programs, but key differences between those missions and a human Mars mission that will require unique approaches to mitigate potential dust storm concerns.

Hoffman S. J. *

Human Mars Mission Overview and Dust Storm Impacts on Site Selection [#6031]

This presentation briefly reviews NASA's current approach to human exploration of Mars and key features placed on locations (referred to as Exploration Zones) for these activities. Impacts of dust and dust storms on selecting an EZ are discussed.

Hecht M. H. * McClean J. B. Pike W. T. Smith P. H. Madsen M. B. Rapp D. MOXIE Team

MOXIE, ISRU, and the History of In Situ Studies of the Hazards of Dust in Human Exploration of Mars [#6036]

The upcoming MOXIE experiment will be the first to ingest large volumes of dust-laden martian atmosphere for processing, and will serve as a test case for translating our understanding into mitigation practices.

Tuesday, June 13, 2017

MARS DUST: CHARACTERISTICS, COMPOSITION AND ELECTRIFICATION
Berkner D–F

All participants, regardless of their assigned method of presentation, are encouraged to contribute during the breakout sessions, as all community input is essential to a positive outcome.

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David W. Beaty
Recorder: **Brandi Carrier**

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Mars Climate Sounder (MCS) Observations of Martian Dust — A Decade-Long Record [#6030]

We describe the Mars Climate Sounder (MCS) observations of atmospheric dust. The instrument acquires infrared observations to produce a 5.75 Mars Year (>10 Earth year) climatology global of dust, including its vertical distribution.

Bell J. F. III * Wellington D. F.

Local, Regional, and Global Albedo Variations on Mars From Recent Space-Based Observations: Implications for Future Human Explorers [#6023]

We describe recent as well as historic albedo variations on Mars as observed by space-based telescopes, orbiters, and surface missions, and speculate that some regions might offer fewer dust-related problems for future human explorers than others.

Edgett K. S. * Newsom H. E.

Dust Deposited from Eolian Suspension on Natural and Spaceflight Hardware Surfaces in Gale Crater as Observed Using Curiosity's Mars Hand Lens Imager (MAHLI) [#6017]

MSL MAHLI images and other observations regarding particles deposited from eolian suspension and potential local dust sources (wind-eroded mudstone) at the Curiosity field site in Gale Crater, Mars.

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Regionality of Dust Haze Transport in the Mars Atmosphere Revealed by Ensemble Simulations [#6014]

Regionality of dust haze transport in the Mars atmosphere is investigated by ensemble simulations using a GCM. It is turned out that processes of dust haze dispersion by advection are categorized into a few cases.

Vincendon M. *

Observation of Interannual Variability of Dust Surface/Atmosphere Exchange on Mars [#6029]

Transfer of Mars dust between surface and atmosphere occurs on Mars with various timescales. Orbital observations of surface albedo change by OMEGA onboard Mars Express are used to assess the timing and extent of dust deposition and removal events.

Morozhenko A. V. Vidmachenko A. P. *

Optical parameters of Martian Dust and Its Influence on the Exploration of Mars [#6010]

Flight to Mars is dangerous because of large amount of toxic dust. During dust storm particle size was 1–20 µm; at its highest activity ~8–10 µm, at the end ~1 µm; real part of refractive index was 1.59, which corresponded to their silicate nature.

Montabone L. * Forget F.

Forecasting Dust Storms on Mars: A Short Review [#6032]

In this article we provide a short review focusing on the current and future capabilities of forecasting martian dust storms for robotic and human missions.

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Electrochemical Reaction at Surface Induced by Electrostatic Discharge During Mars Dust Storm and Dust Devils [#6012]

We present the instantaneous formations and high yield of NaClO₃ and NaClO₄ from NaCl through atmosphere-surface electrochemistry stimulated by Electrostatic Discharge (ESD) that could occur during martian dust storm and dust devils.

Kuroda T. * Kadouaki M.

Simulation of the Small-Scale Dust Activities and Their Mutual Interactions on the Atmospheric Dynamics Using a High-Resolution Mars General Circulation Model [#6015]

We show the simulation results of our high-resolution Mars general circulation model including the dust lifting processes for the investigations of the meteorological features which invoke dust storms and subsequent enhancement of small-scale waves.

Spry J. A. * Rummel J. D. Race M. S. Conley C. A.

Three Faces of Martian Dust: Dust for Cover, Dust to Breathe, and Dust Everywhere [#6035]

While detailed approaches are mature for robotic missions, only guidelines are available for how planetary protection might be implemented on human missions. More dust-related data is needed before adequate mitigations can be identified and deployed.

Levine J. S. *

Dust in the Atmosphere of Mars and Its Impact on Human Exploration: A Review of Earlier Studies [#6007]

The impact of Mars atmospheric dust on human exploration has been a concern for many years, e.g., NRC (2002) and MEPAG (2005). The impact of Mars atmospheric dust on human exploration is a multi-faceted problem and will be reviewed in this paper.

Wadhwa M. * Leshin L. Clark B. Jones S. Jurewicz A. McLennan S. Mischna M. Ruff S.

Squyres S. Westphal A.

A Low-Cost, Low-Risk Mission Concept for the Return of Martian Atmospheric Dust: Relevance to Human Exploration of Mars [#6028]

We present a low-cost, low-risk mission concept for return of martian atmospheric dust. Such a mission would serve as a scientific, technological and operational pathfinder for future surface sample return and human exploration to Mars.

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The Potential Value of Returning Samples of Martian Dust and Other Granular Materials for Analysis in Earth Laboratories to Preparing for the Human Exploration of Mars [#6037]

In order to construct quantitative models for the behavior of dust on Mars, we need to understand the geological processes by which dust is created, transported, and deposited.

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MARS DUST: HUMAN HEALTH
Berkners A-C

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Moderator: Russ Kerschmann

Recorder: Pamela Sparks

Kerschmann R. L. *

What Questions Should We ask About the Health Effect of Mars Dust? Lessons from the Lunar Dust Experience [**#6034**]

The toxicology of lunar dust has been studied over the last decade and standards set by NASA for exposure. This summary reviews that data and proposes to reapply the strategy employed there to future research on the health effects of Mars dust.

Darquenne C. * Prisk G. K.

Reduced Gravity and Aerosol Deposition in the Human Lung [**#6008**]

Studies during parabolic flights showed a significant effect of gravity on the amount and site of aerosol deposition in the lung, which may affect subsequent clearance and greatly increase the toxicological impact of inhaled lunar or martian dust.

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The Current MEPAG Representation of Potential Dust-related Hazards as They May Relate to the Human Exploration of Mars [**#6022**]

The MEPAG Goals Document presents investigations that may correlate with dust risk to humans and human operations in potential future Mars missions. We list these here, together with their respective priority rankings, and invite community input.

Sim P. A. *

Martian Dust and Its Interaction with Human Physiology: An Emergency Physician's Perspective [**#6009**]

Martian dust has known physical and chemical characteristics which portend adverse effects when humans are exposed. An emergency physician briefly summarizes the potentially harmful components and offers some mitigating and treatment measures.

Kamakolanu U. G. *

The Impact of Mars Atmospheric Dust on Human Health [**#6033**]

The martian dust impact can be considered as an exposure to ultra fine particles of martian dust. Direct nose to brain pathway of particulate matter can affect the fine motor skills and gross motor skills, cognition may be affected.

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Geochemical and toxicological evaluations performed on six meteorite samples of mixed origin allow for toxicological risk assessments of celestial materials and clarification of important correlations between geochemistry and health.

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MARS DUST: MECHANICAL SYSTEMS AND SURFACE OPERATIONS
Hess Room

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Yun P. Y. *

Martian Dust Impact on Human Exploration [#6018]

Understanding martian atmospheric electricity, and dust impact on human health, surface mechanical systems and surface operations are critical to reduce the risks of the human exploration on Mars.

O'Hara W. J. IV *

Summary of Martian Dust Filtering Challenges and Current Filter Development [#6016]

Precursor and manned mission ISRU systems, habitat and rover ECLS systems, and airlock systems will include dust filtering in their design. This paper summarizes the challenges of filter development, and the status of the progress made in this area.

Baker M. M. * Lewis K. W. Bridges N. Newman C. Van Beek J. Lapotre M.

Aeolian Transport of Coarse Sediment in the Modern Martian Environment [#6021]

We use Mastcam images from Curiosity's change detection campaigns to trace surface winds and examine seasonal variability of aeolian sediment transport.

Guzewich S. D. * Bleacher J. E. Smith M. D. Khayat A. Conrad P.

Astronaut-Deployable Geophysical and Environmental Monitoring Stations [#6011]

Geophysical and environmental monitoring stations could be deployed by astronauts exploring Mars to create a broad network that would collect high-value scientific information while also enhancing astronaut safety.

McClean J. B. * Pike W. T.

Estimation of the Saltated Particle Flux at the Mars 2020 In-Situ Resource Utilization Experiment (MOXIE) Inlet [#6025]

Dust is a challenge for filtration prior to Mars atmospheric *in-situ* resource utilization. Previously, wind tunnel tests simulated suspended dust loading on the Mars 2020 ISRU demonstrator. Initial analysis of the saltated dust loading is presented.

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Introduction: Planning successful human exploration of Mars will require the thorough identification and characterization of all acceptable and unacceptable risks to human health and mission operations. Suspended atmospheric (aerosol) dust and dust on the Martian surface could pose hazards to crews and/or surface assets of potential future Mars missions.

The Mars Exploration Program Analysis Group (MEPAG) Goals Document [1] presents as Goal IV - *Prepare for Human Exploration*. Objectives A and B within Goal IV provide a framework for addressing open questions regarding risks related to dust on Mars. Specifically, Objective A directs that we "*Obtain knowledge of Mars sufficient to design and implement a human mission to Mars orbit with acceptable cost, risk, and performance;*" and Objective B stipulates that we "*Obtain knowledge of Mars sufficient to design and implement a human mission to the Martian surface with acceptable cost, risk, and performance.*" The following list of Goal IV Investigations presents our current understanding of each possible dust-related risk and its respective priorities (parenthesized). High-priority listings are likely to associate with unacceptable risks. Investigations are categorized by risks related to 1) atmospheric modeling for weather-forecasting and EDL simulations, and 2) understanding the impact of dust on humans and human operations. Additional information on the rationale for priority rankings is available in the Goals Document.

We are interested in receiving input from the science and engineering communities on the content and priority ranking of each Investigation, and also whether additional Investigations addressing these or other risks should be outlined in future drafts of the Goals Document.

Atmospheric Modeling Investigations

Goal IV Investigation #A1-2; (High): At all local times, make long-term (> 5 Martian year) global measurements of the vertical profile of aerosols (dust and water ice) between the surface and > 60 km with a vertical resolution \leq 5 km. These observations should include the optical properties, particle sizes and number densities.

Goal IV Investigation #B1-1; (High): Globally monitor the dust and aerosol activity, especially large

dust events, to create a long-term dust activity climatology (> 10 Martian years) capturing the frequency of all events (including small ones) and defining the duration, horizontal extent and evolution of extreme events.

Goal IV Investigation #B1-2 (High): Make temperature and aerosol profile observations under dusty conditions (most importantly within the core of a global dust storm) from the surface to ~40 km with a vertical resolution of < 5 km.

Goal IV Investigation #A1-3; (Medium): Make long-term (> 5 Martian year) observations of global winds and wind direction with a precision \leq 5 m/s at all local times from 15 km to an altitude > 60 km. The global coverage would need observations with a vertical resolution of \leq 5 km and a horizontal resolution \leq 300 km. The record needs to include a planetary scale dust event.

Humans/Human Operation Investigations

Goal IV Investigation #B2-1 (High): Determine if extant life is widely present in the Martian near-surface regolith, and if the air-borne dust is a mechanism for its transport. If life is present, assess whether it is a biohazard.

Goal IV Investigation #B4-1 (High): Test ISRU atmospheric processing system to measure resilience with respect to dust and other environmental challenge performance parameters that are critical to the design of a full-scale system.

Goal IV Investigation #B1-6 (Low): Combine the characterization of atmospheric electricity with surface meteorological and dust measurements to correlate electric forces and their causative meteorological source for more than 1 Martian year, both in dust devils and large dust storms.

Goal IV Investigation #B6-3 (Low): Assay for chemicals with known toxic effect on humans, particularly oxidizing species (e.g., Cr(VI)), in samples containing dust-sized particles that could be ingested. Of particular interest is a returned sample of surface regolith that contains airfall dust, and a returned sample of regolith from as great a depth as might be affected by surface operations associated with human activity (EVA, driving, mining, etc.).

Goal IV Investigation #B6-5 (Low): Analyze the shapes of Martian dust grains with a grain size distri-

bution (1 to 500 microns) sufficient to assess their possible impact on human soft tissue (especially eyes and lungs).

Goal IV Investigation #B7-1 (Low): Analyze regolith and surface aeolian fines (dust), with a priority placed on the characterization of the electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of regolith from a depth as large as might be affected by human surface operations.

Goal IV Investigation #B7-2 (Low): Determine the charge on individual dust grains.

Goal IV Investigation #B7-3 (Low): Determine the column abundance and size-frequency distribution, resolved at less than scale height, of dust particles in the Martian atmosphere.

About the MEPAG Goals Document: The MEPAG Goals Document [1] is a living document that is revised regularly (~every 2 yrs) in light of new results from Mars and changes in NASA's strategic direction. It is organized into a hierarchy of goals, objectives, and investigations. The four Goals are not prioritized and are organized around major areas of scientific knowledge: "Life", "Climate", "Geology", and "Preparation for Human Exploration".

References: [1] MEPAG (2015) *Mars Scientific Goals, Objectives, Investigations, and Priorities: 2015*, 74 p., <http://mepag.nasa.gov/reports.cfm>.

AEOLIAN TRANSPORT OF COARSE SEDIMENT IN THE MODERN MARTIAN ENVIRONMENT. M. Baker¹, K. W. Lewis¹, N. Bridges², C. Newman³, J. Van Beek⁴, M. Lapotre⁵, ¹The Johns Hopkins University Morton K. Blaustein Department of Earth and Planetary Sciences (mmbaker@jhu.edu), ²Applied Physics Laboratory, Johns Hopkins University, ³Ashima Research Corporation, ⁴Malin Space Science Systems, ⁵Division of Geological and Planetary Sciences, California Institute of Technology.

Introduction: Evidence of aeolian sandstone outcrops, migrating sand dunes, and changes in surface albedo changes caused by redistribution of surface dust on Mars demonstrate that aeolian processes have been and continue to be a dominant agent of surface modification [3] [7] [9]. It is known that strong wind events on Mars can be responsible for lifting large amounts of sediment into the atmosphere. Entrained dust can significantly decrease optical visibility and saltation of sand can cause large amounts of particle splash due to Mars' low gravity. For these reasons, and many more, the effects of surface wind need to be carefully considered for any mission to Mars. Ensuring that instruments remain operational in these conditions requires a full understanding of the modern-day aeolian processes. Yet, transport within Mars' low atmospheric pressure environment is still not fully understood and requires a combination of modeling, experiments, and ground truth observations [1] [4] [6]. Here we present results from a series of systematic change detection campaigns conducted by Curiosity over three Martian years (site locations shown on basemap in Figure 1).

These results include the first-ever observations of coarse-grained (1-3mm) sediment transport in the modern Martian environment. These unforeseen results are particularly noteworthy -and potentially enigmatic- given the frequency with which grain motion occurs and the overall wind strength implied by standard saltation models. For this reason, the motion of coarse sediment likely requires an alternate explanation, such as strong but infrequent wind gusts or impact-driven creep by smaller, saltating particles.

Identifying how wind transports coarse sand grains in the modern Martian environment is important for understanding the danger that sediment-lifting events pose for robotic instruments as well as for future human exploration. Our results confirm that winds are most active during Southern Summer on Mars, and ongoing work is focused on classifying diurnal variations in wind activity. Direct imaging of surface sediments changes is useful for collecting information on the strength, frequency and duration of individual wind events, all of which can be used to keep future explorers safe. These results can also be used to test and improve general circulation models.

Methods:

Change detection. The primary component of this research study was visual inspection of Mastcam images (M100 camera) taken along the Curiosity traverse (between Sol 176 and Sol 1498). At each site in question, the rover was stopped for an extended

period of time to conduct various in situ rock analyses or for solar conjunction events. At each site, we acquired a set of images right after ingress and right before egress; the "before" and "after" images are separated by anywhere from 8 to 100 sols, depending on the site.

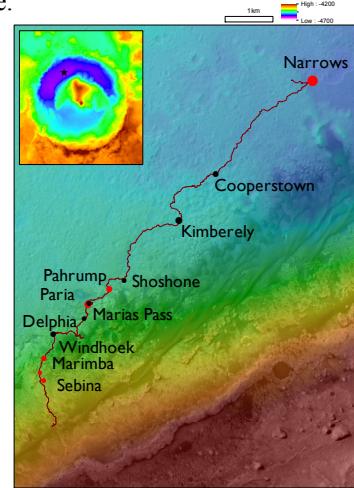


Figure 1: Basemap of Curiosity traverse through Gale Crater. Site marker size is scaled to the length of each campaign. Red marker = motion observed, black marker = no motion observed.

An example of our Mastcam images is shown in Figure 2. Coarse grains that we see moving between the first and second images are highlighted with black arrows. The M100 camera's high spatial resolution (0.22mm/pixel at a typical distance of 3 meters) allowed us to accurately resolve coarse sand grains and observe precise grain movement up to several meters away from the rover. Our study is most sensitive to the creep population, which is both large enough, and moves slowly enough, to detect by eye. We are not able to resolve the movement of saltating sand, but this does not eliminate the possibility that fine sands are undergoing saltation during these campaigns.



Figure 2: Example of a Mastcam image taken on Sol 872 at Pahrump. Black arrows indicate coarse sand grains that move between the two imaged sols.

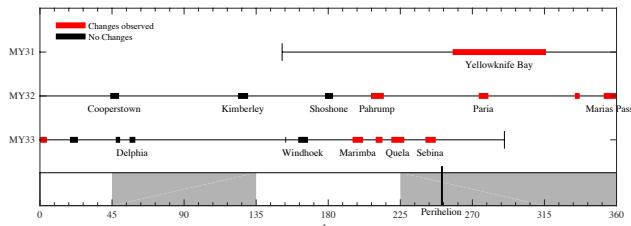


Figure 3: Timeline of the seven traverse stops made over the course of Mars Years 31-33. The three sites where grain movement was detected (marked in red) all occur close to or during southern summer.

Grain motion. A large number of these small-scale grain paths were then combined to reconstruct the average local wind directions and speeds. Grain motion was identified manually in Matlab and geometrically projected to determine the 2D geographic motion vectors. Individual motion vectors were combined and mapped as a tracer of surface wind direction. Obtaining images from many sites over a long period of time helped us discern the effects of regional topographic feedback and seasonal variations in wind. The winds inferred by observations at each site are also compared to the wind speeds and directions predicted by a mesoscale model nested within a MarsWRF GCM (as shown in Figure 5).

Results: Overall, we observed that each site demonstrated either significant grain movement or virtually no grain movement; this distinction allowed for binary classification of wind dominated sites. All positive detections occurred near $L_s \sim 270^\circ$ (close to perihelion and southern summer solstice). Figure 2 shows a full timeline of this study over three Martian years.

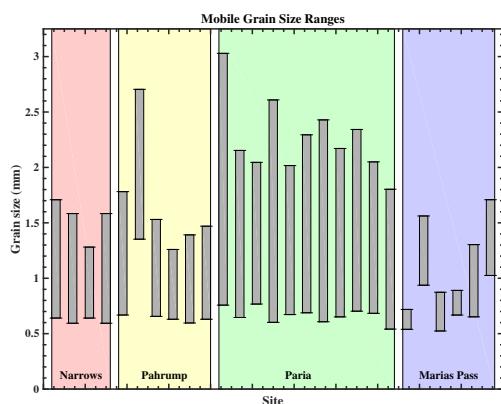


Figure 4: Size ranges for observed mobile sediment in each image. Low-end sizes are calculated using 3 pixels as the minimum threshold for visual grain resolution; maximum values are calculated from the largest mobile grain identified in each image.

Contrary to expectations, we find that coarse grains are frequently transported on the Martian surface today. At all of the active sites, a significant fraction of the mobile population consisted of very coarse sand grains $>1\text{mm}$ in diameter (using the Wentworth 1922 classification scheme). These results are surprising due to the fact that wind speeds needed to detach particles of this size from the surface are much higher than ever recorded or predicted to occur on Mars [2] [5]. It is possible that coarse grain motion is being caused by impact-driven creep, where the impacting populations are too small and transient for us to observe by eye. Such impacts could cause slow accumulation of surface changes over time [11]. Our observations show surface changes occurring on ~daily timescales, requiring that a sufficient amount of sediment is saltating with high enough kinetic energies during those days. The likelihood of this remains to be resolved. The size ranges for mobile grain populations can be seen in Figure 4.

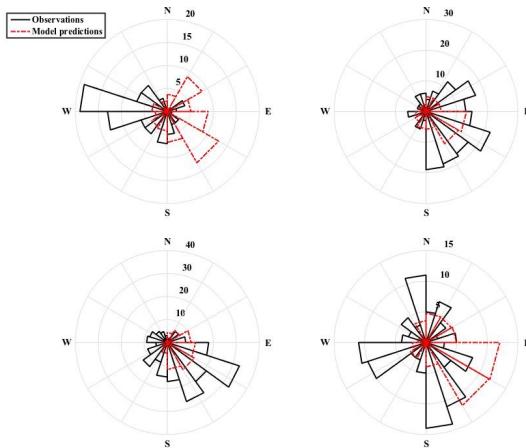


Figure 5: Polar histograms (direction wind is coming from) of sediment transport at Narrows, Pahrump, Paria and Marias Pass (from top left to bottom right). Red dashed lines indicate MarsWRF predictions.

The individual 2D grain motions at each site were combined to assess local wind directions. Three of the four sites revealed consistent net transport directions, which we infer to be induced by consistent wind patterns. The fourth (Marias Pass) seemed to demonstrate more randomized motion. These discrepancies could be caused by local topographic interactions or by diurnal/seasonal changes in wind direction, both of which will be examined in greater detail. These wind tracers were compared directly to nested MarsWRF predictions (Figure 5).

The largest disagreement between observations and predictions occurs at the Narrows site, which could be caused by its relative proximity to the rim of Gale crater. Winds at this site could be subjected to the strong night-time winds flowing down the crater rim. Furthermore, since Narrows is further from large topographic features (e.g. Mount Sharp), the surface winds at Narrows could be influenced more by small-scale topography that is not resolved in models. Pahrump and Paria are much closer to Mount Sharp than Narrows and thus the wind at these locations is likely dominated by the strong down-slope morning winds coming off the mound.

Discussion: Here we present the first ongoing analysis of surface images obtained during Curiosity's change detection campaigns. We find that wind activity follows a clear annual trend, validating previous theories of seasonally variable wind. Yet, wind speeds predicted for even the peak windy season are far lower than the speeds needed to move coarse sand following the classic saltation model. It is possible that strong, intermittent gusts are responsible or that impacts from smaller saltators cause the motion we observe.

Now that seasonal variations have been well-chronicled in sediment flux measurements, global wind models, and in the in-situ observations presented here, future work will aim to constrain diurnal variations in the strength and direction of wind. These results can be shed light on the accuracy of wind models and improve our understanding of surface-atmosphere interactions as a whole. Ultimately, we found that models are inconsistent in their ability to predict net transport direction on the surface, possibly due to unresolved topographic feedback. But the potential effects of diurnal variations have not been well-constrained and are thus not used to analyze the data presented here.

Observing modern aeolian transport in images taken by Curiosity could aid in deciphering the deposition and preservation of cemented aeolian sandstones in Gale Crater, especially those containing dispersed coarse grains [5] [9]. The apparent ability of the modern atmosphere to transport coarse sand, even in creep, can help constrain the environmental conditions present during deposition. Furthermore, characterizing modern-day wind behavior (strength of wind, frequency of dust-lifting events etc.) is of critical importance for assessing hazards for future rovers and human explorers.

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LOCAL, REGIONAL, AND GLOBAL ALBEDO VARIATIONS ON MARS FROM RECENT SPACE-BASED OBSERVATIONS: IMPLICATIONS FOR FUTURE HUMAN EXPLORERS. J.F. Bell III¹ and D.F. Wellington¹, ¹Arizona State Univ., School of Earth & Space Exploration, Tempe AZ (Jim.Bell@asu.edu).

Introduction: The surface of Mars has gone through dramatic changes in albedo over the last ~40 years of modern space-based observations. These variations have been monitored and quantified by telescopic [e.g., 1-3], orbital [e.g., 4-10], and surface-based [e.g., 11-12] observations spanning nearly 20 Mars years. Detailed characterization of the spatial and temporal variability of these changes has helped to elucidate the causes of seasonal and secular variations in the distribution of mobile surface materials (dust, sand) in the planet's current climate regime. These changes also provide important observational inputs for global and mesoscale climate models [e.g., 13-15]. Here we summarize the recent historic record of surface changes on Mars, characterize the nature of these changes in terms of various hypothesized surface/atmospheric interaction processes, and qualitatively conjecture on the implications of these processes for future human explorers and eventual inhabitants of the Red Planet.

Observations: Much of the modern record of dust storm and albedo change activity on Mars comes from synoptic-scale global imaging studies based on data taken from the Viking Orbiter, Mars Global Surveyor (MGS) orbiter, Hubble Space Telescope (HST), and Mars Reconnaissance Orbiter (MRO) missions, as well as local-scale time series observations from long-lived surface platforms like the Mars Exploration Rovers (MERs) Spirit and Opportunity.

In this presentation we review the history of modern space-based observations of albedo changes and related atmospheric dust activity on Mars, but focus mostly on the substantial time history of the most recent global-scale images acquired from the MRO Mars Color Imager (MARCI) investigation [e.g., 16]. MARCI is a wide-angle multi-spectral imager capable of acquiring almost daily coverage of large portions of the martian surface at up to 1 km/pixel near the centerline of each image swath. MARCI has been in orbit around Mars since 2006, providing nearly six Mars years of continuous surface and atmospheric observations. MARCI data build on the nearly five previous Mars years of global-scale imaging from the MGS Mars Orbiter Camera Wide Angle (MOC/WA) imager [e.g., 9,17], which operated from 1997 to 2006.

MARCI time-series observations (e.g., Figure 1), like MOC/WA observations before them, show that, while many of the most significant changes in the surface albedo are the result of large dust storms, other regions experience seasonal darkening events that repeat with different degrees of regularity from one Mars

year to the next [18]. Some of these are associated with local dust storm activity, while for others, frequent surface changes take place with no associated evidence for dust storms, suggesting action by seasonally-variable winds and/or small-scale storms/dust devils too small to resolve from orbit. Discrete areas of dramatic surface changes located across widely separated regions of Tharsis (including the slopes of some of the large volcanoes) and in portions of Solis Lacus and Syrtis Major are among the regions where surface changes have been observed without a direct association to specific detectable dust storm events [19].

Deposition following the annual southern summer dusty season (when insolation increases by up to ~40% relative to southern winter due to the relative high eccentricity of the Martian orbit) plays a significant role in maintaining the cyclic nature of these changes. These and other historical observations also show that major regional or global-scale dust storms produce unique changes that may require several Mars years to reverse.

Here we show regional time-lapse MARCI mosaics for much of the Martian surface that minimize surface obscuration by atmospheric dust and clouds while clearly showing the wide variety of seasonal patterns of surface changes on Mars.

Implications: Future human explorers, tourists, and eventually colonists will relatively quickly learn that Mars is not only a dusty place, but that the frequency of dust deposition and dust-clearing events is generally quite repeatable (and thus predictable [e.g., 9]) from place to place during the Mars year. Thus, locations for semi-permanent or permanent stations or structures that could be most susceptible to contamination or mechanical fouling by typically micron-sized airfall dust particles might best be established in regions with the longest time history of consistently low surface albedo, if other environmental constraints on site selection are otherwise roughly equal. Examples of such regions, discussed here, include northern Syrtis Major, Sinus Sabaeus, and a number of other persistently low albedo northern mid-latitude regions.

A caveat to the above, however, might be that many of the lowest albedo locations on the planet are also sites of active or recently-active sand transport (not coincidentally, as saltation helps to keep a surface clean of dust). Thus, a balance between the need for dust mitigation/minimization and the potentially-erosive long-term effects of sandblasting will need to be struck by future Martian astronauts and, eventually, civil engineers.

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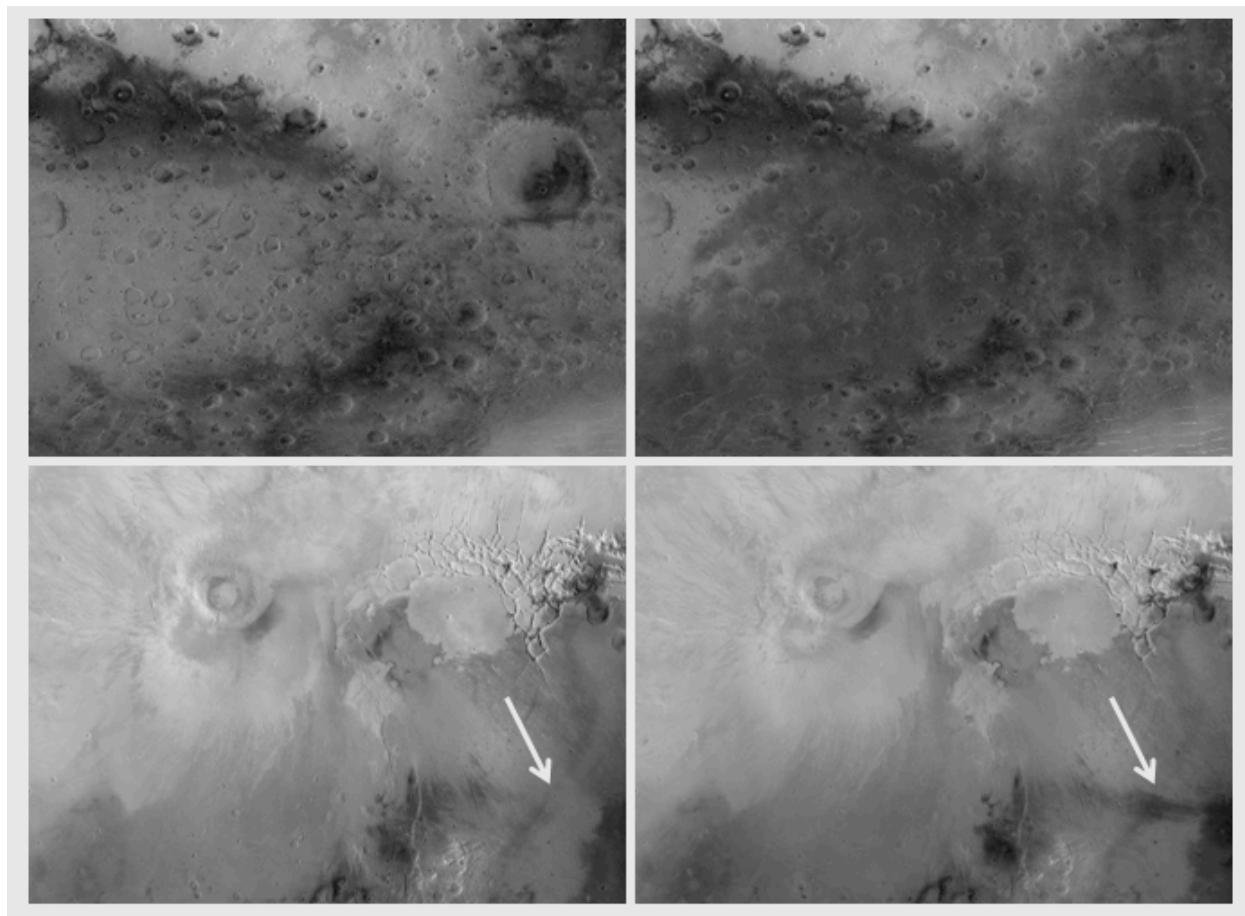


Figure 1. These four images are map-projected MRO/MARCI Band 5 (720 nm) mosaics showing before (left) and after (right) views of surface darkening (dust removal) on Mars. For scale, each image is approximately 2500 km across. TOP: Extensive darkening in Noachis and Sabae Terra following a large cross-equatorial storm in Mars Year 31. The 450-km crater just above center at right is Huygens. BOTTOM: Southern hemisphere low latitude mosaic including Arsia Mons and portions of Daedalia, Syria, Sinai, and Solis Planum. The dark streak in lower right (arrow) formed gradually over $L_s = 200^\circ$ - 320° of Mars Year 29, with no obvious associated dust storm clouds.

THE POTENTIAL VALUE OF RETURNING SAMPLES OF MARTIAN DUST AND OTHER GRANULAR MATERIALS FOR ANALYSIS IN EARTH LABORATORIES TO PREPARING FOR THE HUMAN EXPLORATION OF MARS. B. L. Carrier¹, D. W. Beaty¹, M. H. Hecht². ¹Jet Propulsion Laboratory, California Institute of Technology (Brandi.L.Carrier@jpl.nasa.gov), ²MIT Haystack Observatory

Introduction: By means of numerous robotic missions to Mars over the past four decades, we have learned a lot about the dust on Mars, both in the atmosphere and on the ground. However, there are some aspects of the dust that cannot effectively be measured at Mars, and for which the analysis of returned samples would be required.

Dust is one dimension of a broader set of geological components which we encompass with the general term “granular materials.” Although granular materials are present everywhere on the martian surface, they are not equally hazardous either to humans or to the hardware that would be necessary to keep them alive and productive.

In order to construct quantitative models for the behavior of dust on Mars, we need to understand the geological processes by which dust is created, transported, and deposited. How do these processes cause the size distribution and chemistry of the dust to change with time? How does the dust that falls out of the atmosphere get admixed into the regolith? Knowledge of these processes would help us to understand and predict the chemical, mechanical, electrical, and biological effects of martian dust as it interacts with future human exploration systems.

It would also be valuable to determine the nature and concentrations of commodities of potential interest, such as water, in martian dust and other types of granular materials, which could possibly be used for in-situ resource utilization (ISRU). MEPAG Goal IV-D is centered around characterization of potentially extractable water resources to support ISRU [1]. Hydrated minerals present in granular materials have been identified as one potential source from which water for human activities might be captured. To advance this objective it will be necessary to better constrain the chemical composition and concentrations of hydrated minerals in martian granular materials. Knowledge of the physical and mechanical properties of these materials will also aid in the advancement of the technologies needed to capture this potential resource.

In order to fully address these knowledge gaps we will need a mixture of information from in-situ missions and from samples returned from Mars [1-3]. The in-situ data, from both orbiters and landers, are necessary to understand the context of how the atmosphere interacts with the surface to create, lift, and transport dust. Data from sample studies are needed to narrow

the focus in order to understand the specific roles of mineralogy, geochemistry and, potentially, biology.

In order to advance this planning, and to decide what kinds of samples should be prioritized by the Mars 2020 sample-collecting rover, we need community discussion on the relative value and priority of various types of martian granular material to advancing our various objectives related to future human exploration. The purpose of this analysis is to encourage community discussion and feedback on the following issues:

1. What are the specific reasons (and their priority) for collecting and analyzing samples of granular materials?
2. How do those reasons translate to potential sampling priorities?
3. If we were to collect samples of martian dust and/or other granular materials, in what condition would they be expected to be received on Earth?
4. What is our best projection of the approach by which these samples would be divided, prepared, and analyzed to achieve our various objectives?

Terminology: In order to distinguish between various types of granular material, we are using a working taxonomy that includes the following end member categories: 1) globally sourced airfall dust (dust); 2) saltation-sized particles moved either by aeolian or fluvial processes, including dune material (sand); 3) locally sourced decomposed rock (regolith); 4) crater ejecta, which may contain exotic lithologies (ejecta); and, 5) other. Since granular materials, unlike solid rocks, can commingle, granular materials encountered on Mars will likely represent some combination of these end members.

For the purposes of this workshop, we find it most appropriate to focus on categories 1-3, as these are the types of material likely to be ubiquitous on Mars and therefore most likely to interact continuously with both humans and hardware.

Prior Work: Previous studies have identified outstanding knowledge gaps and scientific objectives that could be advanced through the return of martian dust and other granular materials [1-3]. Of particular importance for potential human exploration are questions relating to planetary protection, possible astronaut health, and possible mechanical, chemical, and electrical effects on engineered systems. Martian dust and

other granular materials have also been proposed as possible sources of water and other resources for ISRU, but the concentrations and availability of these resources is currently poorly constrained.

A major part of the reason that Mars is interesting is that it has the potential for life, both past or present. This means that any current life would have the potential to be transmitted to Earth if and when samples are returned or astronauts come home. In order to understand any related risks, we have to know if such life could be transported by the globally circulating dust, because the astronauts would certainly come into contact with it, and there would be no way to completely leave it behind. Because the martian atmosphere is well circulated, the case has been made that one sample of this material from any location would be representative of Martian dust overall [2]. Analysis of this material would therefore test the hypothesis that airborne dust could serve as a vector for potential replicating biohazards, a critical planetary protection issue. Secondary objectives would include evaluation of its physical and chemical properties. As this dust is ubiquitous in the atmosphere and is thus inevitably going to interact with any systems placed on the martian surface this analysis has been considered to be of high priority for sample return.

Another likely target for sample return might be the saltation-sized particles that were found to dominate the landscape at the Phoenix landing site [4]. This is another instance where analysis of one sample might provide information about a much larger area. Samples of other types of martian granular material have also been identified as candidates for sample return in regards to both their relevance to human exploration as well as to advancing other more general knowledge gaps, but their relative importance and priority have not been fully explored by the community.

Goals/Objectives: We seek community feedback on the prioritization of the specific objectives relevant to the collection and possible subsequent analysis of martian granular material. We have identified six preliminary objectives that would be advanced via the return and analysis of martian granular material:

- 1) Address the possibility of extant life for both potential replicating biohazards and planetary protection
- 2) Identification of potential health hazards posed by the martian surface material and airborne dust
- 3) Identification of hazards to hardware and technological assets (including spacesuits)
- 4) Creation of a high-fidelity simulant for testing resources and technology
- 5) Assessment of resources for ISRU
- 6) Assessment of resources for civil engineering or other possible uses

We seek to prioritize these objectives and identify the types of granular materials which would best advance each objective in order to inform possible sampling strategies for Mars 2020. It will also be important to identify the types of analyses that would be necessary to best achieve the stated objectives in order to constrain the masses required and the appropriate handling, preparation, and division of any returned samples.

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REDUCED GRAVITY AND AEROSOL DEPOSITION IN THE HUMAN LUNG. Chantal Darquenne and G. Kim Prisk. Dept. of Medicine, University of California, San Diego, USA (9500 Gilman Dr., MC 0623A, La Jolla CA, 92093-0623, cdarquenne@ucsd.edu).

Introduction: The deposition of aerosol in the human lung occurs through a combination of inertial impaction, gravitational sedimentation and diffusion. For 0.5 to 5 μm -diameter particles and resting breathing conditions, the primary mechanism of deposition in the intrathoracic airways is sedimentation, and therefore the fate of these particles is markedly affected by gravity. Besides one experimental study performed in the 1970s [1], our laboratory has performed all of the experimental studies of aerosol deposition in the lung in altered gravity to date [2-12]. These studies have mostly been performed in humans during parabolic flights both in microgravity (μG) and hypergravity ($\sim 1.6\text{G}$). This abstract provides an overview of those studies as a basis for the consideration of aerosol deposition in the reduced gravity of Mars.

Overall deposition: We first performed total deposition studies of 0.5-3 μm -diameter particles in normal gravity (1G), microgravity (μG) and hypergravity ($\sim 1.6\text{G}$) using the NASA Microgravity Research Aircraft [2]. Subjects continuously breathed aerosol from a reservoir at a constant flow rate ($\sim 0.45 \text{ l/s}$) and breathing frequency ($\sim 15 \text{ breaths/min}$). Data showed that deposition increased with increasing G level. However, in μG , deposition of the small particles ($\sim 1\mu\text{m}$) was higher than predicted by the numerical models. As inertia is negligible for these small particles and sedimentation is absent in μG , the higher deposition was explained by a larger deposition by enhanced diffusion resulting from previously unaccounted for mixing effects. While the overall change in total deposition caused by this process in 1G might be small, the effect may be disproportionately large if deposition occurs in the sensitive alveolar region of the lung, a region where the subsequent clearance of deposited particles is significantly slower than in the central airways [13].

Regional deposition: In order to probe the details of aerosol deposition, we undertook a series of bolus deposition (DE) and dispersion (H) studies in altered G levels [3-5]. A small bolus containing 0.5, 1.0 or 2.0 μm aerosol particles was introduced at predetermined points in an inspiration from residual volume to 1 liter above functional residual capacity. Penetration volumes (V_p) of the bolus ranged from 150 to 1500 ml, and in doing so directly probed deposition in the central airways ($V_p = 150 \text{ ml}$), moving towards the periphery as penetration volume was increased. For

each particle size, the data showed that, at shallow V_p ($<200\text{ml}$), DE and H were not different between gravity levels. In contrast, at larger V_p , when the aerosol bolus reached the alveolar regions of the lung, DE and H were strongly dependent on the G level. The steady increase in dispersion with increasing V_p suggests a continued presence of mixing processes in the early generations of the acinar region. This mixing may facilitate particles entering the alveolar cavities and eventually depositing.

Understanding “enhanced diffusion”: We performed a series of bolus studies with a protocol designed to induce complex folding patterns within the lung [7]. Small flow reversals were imposed during a 10-sec breath-hold that followed the inspiration of 0.5 and 1 μm aerosol bolus. This protocol was based on the suggestion that irreversibility of alveolar flow combined with a stretched and folded pattern of streamlines can lead to a sudden increase in mixing and therefore deposition in the lung [14, 15]. Contrary to our expectations, the data showed that increasing the number of flow reversals had almost no effect on aerosol dispersion and deposition. We concluded that the mechanism of stretch and fold likely occurred during the one breathing cycle included in the basic maneuver. This conclusion is consistent with the complex mixing patterns observed by Tsuda et al. [14] in rat lungs after only one breathing cycle. This conclusion is important as it provides a mechanistic basis to explain what we previously described as “enhanced diffusion resulting from unaccounted mixing effects” that was found in our total deposition studies [2].

Retention of deposited particles in reduced gravity: The other important aspect of understanding aerosol effects in the lung is the residence time of the particles following deposition. Depending upon the lung region where particle deposit (airways versus alveolar region), these residence times differ by several orders of magnitude. The spatial distribution of coarse particles ($\text{MMAD} \approx 5 \mu\text{m}$) deposited in the human lung was assessed using planar gamma scintigraphy [9]. Radiolabeled particles ($\text{Tc}^{99\text{m}}$) were inhaled in a controlled fashion (0.5 l/s, 15 breaths/min) during multiple periods of μG aboard the NASA Microgravity Research Aircraft and in 1G. In both cases, deposition scans were obtained immediately post inhalation and at 1h30 min, 4h, and 22h post inhalation. Relative distribution of deposition between the airways and the

alveolar region was derived from data acquired at the various time points. Data showed that the absence of gravity caused a smaller portion of 5 μm particles to deposit in the lung periphery than in the central region where deposition occurred mainly in the more central airways. This is consistent with the absence of gravitational sedimentation, which is normally dominant in the smaller peripheral airways.

Because this study utilized only coarse particles, the question of the site of deposition of fine particles (i.e., 0.5–2 μm -diameter particles) in a reduced gravity environment remained unanswered. While there are no human data available to date, some insight may be gained from recent data we obtained in animals [12]. Using postmortem magnetic resonance imaging techniques developed in our laboratory [16], we measured aerosol deposition in lungs of rats that were exposed to aerosolized 0.9- μm -diameter particles both in μG and 1G. Deposition in the lung periphery of these animals was similar between G levels, although overall deposition tended to be less in μG than in 1G, consistent with the results in humans [2]. This suggests that potential toxicological effects of aerosol exposure in a low gravity environment, such as the surface of the Moon or Mars, are likely not reduced compared with 1G. Because these data were obtained in rodents, one should be cautious in extrapolating these results to humans as there are major differences both in terms of airway tree structure and ventilation distribution between dependent and non-dependent regions of the human and rat lungs. However these are the only available data to date on the site of deposition of small particles in reduced gravity.

Implications for Mars exploration: While there is no doubt that the inhalation and deposition of small particles in the lungs is a health concern here on Earth, long-term spaceflight represents a situation in which aerosol deposition may also be an important health consideration. In a spacecraft environment such as the International Space Station (ISS) or a future Lunar or Martian habitat, the potential for significant airborne particle loads is high as the environment is closed and sedimentation is either absent (as on the ISS) or greatly reduced (as in the case of a Lunar or Martian habitat). Furthermore, Lunar and/or Martian habitats will likely operate at an absolute pressure significantly less than sea-level. Studies in 1G of aerosol bolus transport while breathing low-density gas (80:20 Heliox, ~about one third of sea level air density) showed a reduction in deposition in the upper respiratory tract and large airways, and an increase in deposition in the peripheral lung [17, 18]. The combination of reduced gravity and reduced gas density on aerosol deposition that was representative of a lunar habitat (~390 mm Hg, 32%

O₂, i.e. gas density of ~53% of that of sea level air) was investigated with the hypothesis that such combination would increase the deposition of aerosol particles in the peripheral lung in a synergistic manner [10]. Data showed that, while minimally affected by gas density, deposition was significantly less in reduced gravity than in 1G for both gases, with a larger portion of particles depositing in the lung periphery under lunar conditions than Earth conditions. Thus, our data strongly suggest that reduced gravity rather than reduced gas density is the major factor affecting deposition in the lungs of astronauts exposed to airborne particulates.

Conclusions: Studies of aerosol deposition in altered gravity have shown a significant effect of gravity on the amount and sites of aerosol deposition in the lung, which may affect subsequent clearance, and may significantly increase the toxicological impact of inhaled Lunar or Martian dust.

A significant gap in knowledge still exists regarding the spatial distribution of fine particulates in the human lung in reduced gravity even though studies in animals suggest a trend for a shift from central to peripheral deposition for these particles, the same particles known to have the greatest toxicological potential. Filling this gap would help establishing safe exposure levels to extraterrestrial dust. This may ultimately aid in mitigation strategies by developing appropriate crew systems against dust inhalation that are neither under-designed and unsafe, nor over-designed and costly.

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DUST DEPOSITED FROM EOLIAN SUSPENSION ON NATURAL AND SPACEFLIGHT HARDWARE SURFACES IN GALE CRATER AS OBSERVED USING CURIOSITY'S MARS HAND LENS IMAGER (MAHLI). K. S. Edgett¹ and H. E. Newsom², ¹Malin Space Science Systems, San Diego, CA USA, ²Institute of Meteoritics, University of New Mexico, Albuquerque, NM USA.

Introduction: This report describes observations of Mars Hand Lens Imager (MAHLI) data regarding particles deposited from eolian suspension at the Mars Science Laboratory (MSL) rover, Curiosity, field site in Gale crater, Mars. This summary was produced, in part, to consider future use of MAHLI and its build-to-print counterpart for NASA's Mars 2020 rover mission, WATSON (Wide Angle Topographic Sensor for Operations and eNgineering)—part of the SHERLOC (Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals) investigation [1]—to obtain new images of value to understanding the properties of eolian dust and dust deposits in support of future robotic and human missions to Mars.

Background: Previous high spatial resolution imaging studies of Martian eolian dust deposited on natural and hardware surfaces was performed on the Mars Exploration Rover (MER) Spirit and Opportunity missions using the fixed-focus, panchromatic Microscopic Imager (MI; 31 $\mu\text{m}/\text{pixel}$) [2, 3]. Experiments designed to use images of magnets to characterize dust were performed on the Viking, Mars Pathfinder, MER, and the Phoenix missions [4, 5]. Further, the Phoenix microscopy investigation examined sand-, silt- and clay-sized particles scooped from near-surface high-latitude regolith, some of which could be representative of dust deposited from suspension [5, 6]. In this context, too, Sullivan *et al.* [7] discussed the threshold wind friction speed (u_{*t}) for mobilization of dust and dust aggregates, given the morphological characteristics of dust deposits observed by the MER MI and Pancam systems; they also discussed the issue of whether dust can aggregate in suspension and thus hasten settling.

Purpose: The focus, here, is on MAHLI observations that add to or expand upon the preceding landed mission results, particularly (1) the nature of the MSL field site with regard to dust-coated and dust-free surfaces; (2) the sizes of the largest and smallest grains interpretable as having been deposited from suspension that can be identified in MAHLI data; (3) images obtained at higher resolution than MER MI of dust-coated and dust-free surfaces; (4) observations of dust coatings disrupted by natural and anthropogenic events; and (5) the observation that Mars has local dust sources, such as wind-eroded, fine-grained bedrock.

MAHLI: MAHLI (**Fig 1**) is a robotic arm-mounted color camera that can focus on subjects at working distances of 21 mm to infinity [8]. The high-

est resolution images are 13.9 $\mu\text{m}/\text{pixel}$ but, owing to arm positioning uncertainties, the highest resolution views are usually 16–17 μm per pixel [9]. MAHLI was designed to be robust to challenging environments (e.g., dust, temperature, vibration) and yet work within a scientific, engineering, and data downlink trade-space that (1) permits distinction of very fine sand from silt, (2) facilitates identification of rock, regolith, and sediment properties as good as or better than a geologist's hand lens, (3) acquires images, mosaics, focus stacks, and stereo/multiple images for three-dimensional views, and (4) all while having a sufficient field of view and ability to focus at a range of distances so that the camera can provide high resolution images, context images, sample extraction documentation, and hardware inspections.

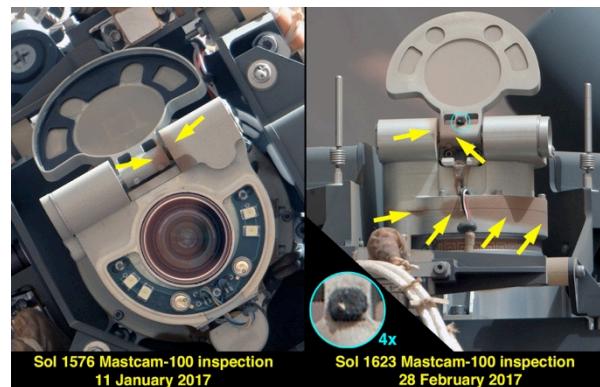


Fig 1. The observer as the observed. Dust on the MSL MAHLI camera head after >2.3 Mars years of surface operations. Although used to observe geologic materials, the hardware also accumulated geologic materials on its exterior; yellow arrows indicate patches of brownish-orange dust adhering to the camera head; blue circle (and 4x magnification) indicates a sand grain or aggregate of smaller grains attracted to a Hall effect sensor magnet. A thin film of very fine dust coats most of the camera head, including the dust cover exterior; the film was initially deposited during the rover's terminal descent to the Martian surface in August 2012.

Dust: Technically, “dust” is not a particle size term [10]. The Wentworth [11] scheme bins particle sizes as follows: clay (used independent of mineralogy; grains $\leq 3.9 \mu\text{m}$), silt (3.9–62.5 μm), sand (62.5–2000 μm), granules (2–4 mm), and pebbles (4–64 mm). On both Earth and Mars, these bins correspond to typical sediment transport and depositional conditions in water and air, with clay- and silt-sized particles traveling in and settling from suspension, sand traveling in saltation, and coarse sands, granules, and pebbles in reptation and traction. The finest particles transported in the atmospheres of Earth and Mars can undergo “long-

term suspension” and coarser silt can be transported in “short-term suspension” [11] under typical conditions. On Mars, very fine and fine sand could, perhaps, also experience short-term suspension [12]. Grains in long-term suspension on Mars are considered to be $< 10 \mu\text{m}$ and, in most cases, $< 2 \mu\text{m}$ in size [13, 14].

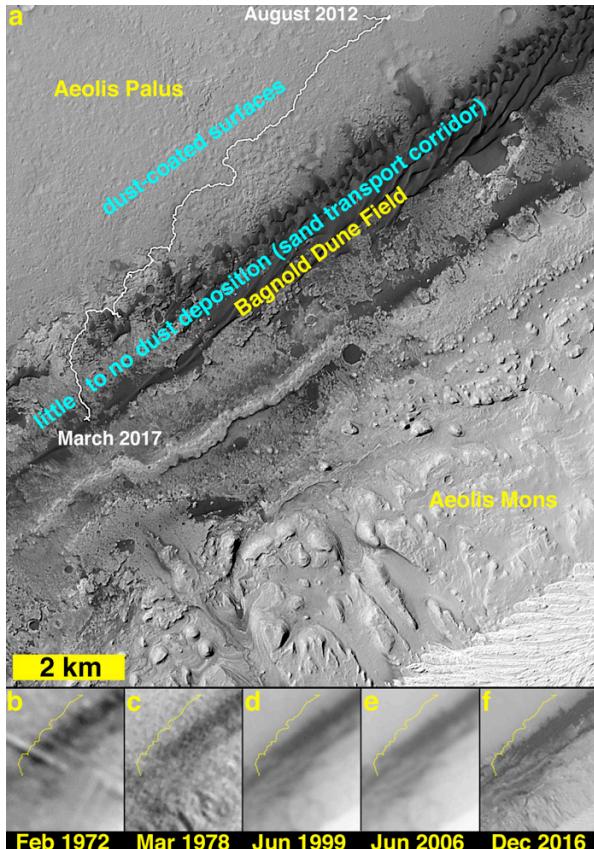


Fig 2. (a) MSL Curiosity rover traverse (white trace) in northern Gale crater through mid-March 2017. Most surfaces encountered were covered by a thin coating of dust, except in the sand transport corridor (eolian dunes and bare, dust-free bedrock). (b-f) Time series showing examples indicating that the albedo pattern in the study region might have remained largely unchanged since 1972; that is, the dust coatings on rock, regolith, and eolian sand surfaces observed by MAHLI might have been present for > 20 Mars years. Yellow trace indicates rover traverse; each figure is a portion of the following images: (b) Mariner 9 DAS 7650478 (caution: data artifacts), (c) Viking 1 631A05 (caution: data artifacts), (d) Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) M02-01392, (e) MGS MOC S19-0120, (f) Mars Reconnaissance Orbiter Context Camera J10_048774_1751_XN_04S222W.

Field Site: Curiosity landed in Aeolis Palus, the low-elevation (about -4.5 km) terrain [16] located between the north wall of the 155-km-diameter Gale crater and Aeolis Mons, a mountain that occupies part of the crater interior. Located $\sim 5^\circ$ south of the equator, Aeolis Mons rises 5 km above Aeolis Palus and consists of a complex, three-dimensional geologic record of environmental change through time [e.g., 17]. Everywhere that the Curiosity rover has traversed (**Fig 2**), wind-eroded sedimentary bedrock occurs at or very near the surface. These rocks have been interpreted to

include fluvial conglomerates [18]; fluvial, deltaic, and eolian sandstones [19, 20], and lacustrine mudstones [19, 21]. Modern eolian deposits include active, dark gray sand deposits (dunes, ripples) [22], inactive, dust-coated sands [e.g., 23]; and dust deposited on natural and spacecraft surfaces (this report).

Eolian Dust at the MSL Field Site: Observations made via Curiosity’s cameras show that much of the terrain over which the rover traversed (**Fig 2**) consisted of bedrock exposures; very little regolith is present.

Natural Dust Coatings. Over most of the traverse, except within the Bagnold Dune Field (a sand transport corridor banked against a break in slope along the lower north flank of Aeolis Mons [22]), the bedrock, loose stones, regolith, and eolian sand deposits were coated with dust (**Figs 2, 3a**). Typically, the dust coatings were $< 1 \text{ mm}$ thick but spatially variable in both thickness and surface texture (e.g., **Fig 4**).

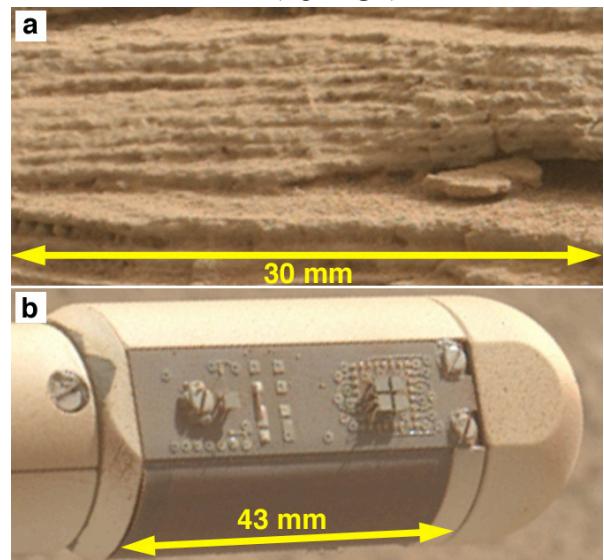


Fig 3. Example constraints on eolian dust deposit thickness on natural and hardware surfaces at Curiosity’s field site. (a) Dark gray sandstone target named Coachella, coated with dust. Each lamina in this rock face is $\sim 750 \mu\text{m}$ thick; the dust coating the outcrop is thinner than these laminae (i.e., $<< 1 \text{ mm}$); the image is a portion of MAHLI focus merge product 0833MH0002270000301900R00. (b) REMS meteorology boom #1 [24]; the white and gray boom is coated with a thin, spatially variable coating of dust. This was its condition on Sol 526; this is a portion of MAHLI 0526MH0003430000201119C00.

Long-term Dust Coating Configuration. Although there are temporal gaps in coverage, examination of orbiter images suggests that the albedo patterns present at the field site—indicative, in part, of the distribution of dust-coated and dust-free surfaces—have been largely unchanged since February 1972, more than 20 Mars years ago (**Fig 2**).

Active Eolian Sand Transport Observed. Within the Bagnold sand transport corridor (**Fig 2**), wind mobilization of sand and dust has been observed; this includes changes in sand grain configuration (via saltat-

tion or reptation) during the few minutes that MAHLI has been deployed to observe these sands (**Fig 5**).

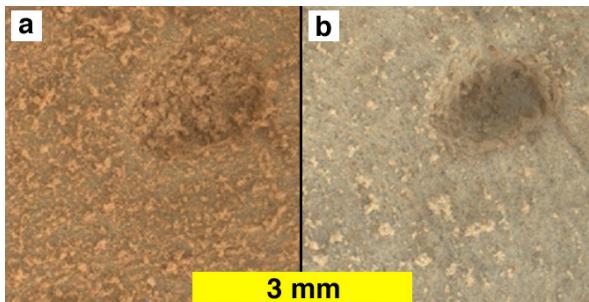


Fig 4. Ekwir mudstone target (a) before and (b) after brushing with Curiosity's Dust Removal Tool (DRT), both in full shadow and at the same scale (~16.4 $\mu\text{m}/\text{pixel}$). (a) Surface with natural coating of eolian dust; the coating morphology is spatially variable and dust grains locally form sand-sized aggregates; image 0149MH0001690010101341C00. (b) Rock surface after brushing; aggregates of dust created by brushing (perhaps a mix of fine grains scraped from the rock plus the preceding dust) are present; MAHLI image 0150MH0001690010101421C00.

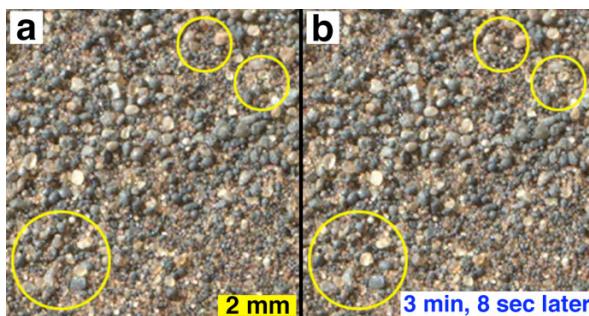


Fig 5. Example of eolian sand motion detection on a wind ripple during MAHLI imaging on Sol 1603 (8 February 2017). Changes occurred within the circled areas within a 3-minute, 8-second period. Sunlight illuminates the scene from the upper left. MAHLI images (a) 1603MH-0005490010602027C00 and (b) 1603MH-0005490010602038C00.

Dust-Free Surfaces. Naturally-occurring dust-free surfaces are also observed at the MSL field site. In regions mantled with dust, windward rock faces were sought so as to provide relatively dust-free surfaces for MAHLI and APXS observing; **Fig 6** shows an example. In some cases, the undersides of protruding grains were coated with dust while the upward-facing surfaces were not (**Fig 6**); this might indicate removal of a previous dust coating by the impact of saltating grains. Another form of dust-free surface was encountered in the Bagnold sand transport corridor, wherein bedrock and eolian sand surfaces are often dust-free (**Fig 7**).

Particles Deposited from Suspension: While MAHLI images cannot be used to resolve the finest grains of dust, they can provide insights regarding grains deposited from eolian suspension on Mars.

Smallest grains. In the highest resolution MAHLI images (13.9–17 $\mu\text{m}/\text{pixel}$), when a grain contrasts with its surroundings, or casts a shadow, it is possible to constrain its size even to within 2x2 pixels. The smallest such grains were observed in dust adhering to the US cent on the MAHLI calibration target (**Fig 8**);

these grains are 28–42 μm in size (medium to coarse silt). Of course, smaller grains exist and MAHLI images show them as coatings or films of clay- and/or fine-silt-size materials and dust aggregates on natural and flight hardware surfaces (**Figs 3, 6**). Indeed, a film of dust coated the transparent MAHLI dust cover during the rover's terminal descent on Sol 0 [25]; this film of very fine particles remained in-place > 1650 sols later.

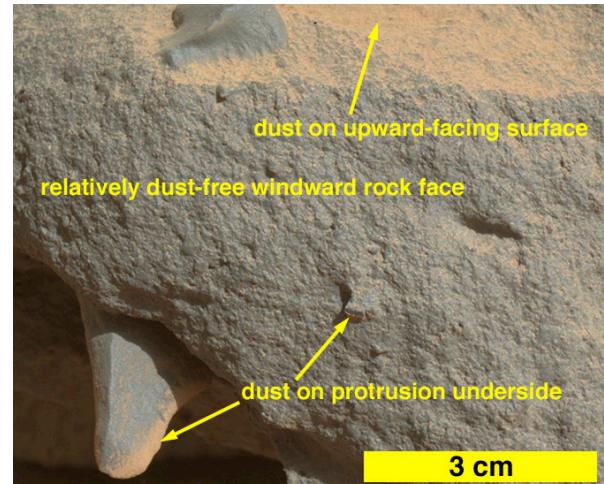


Fig 6. Eolian dust distribution on a dark gray sandstone with protruding granule and pebble clasts. MAHLI target Rensselaer; MAHLI image 0442MH0001900010200110C00.



Fig 7. Example of a dust-free surface examined by MAHLI (rock target named Pogy). Windy corridors of active eolian sand transport prevent dust deposition or remove dust. A small dark cobble, lithic fragments of reddish mudstone, and dark gray eolian sand are all evident in this portion of MAHLI image 1606MH0001900010602220C00.

Largest grains. The largest grains inferred to have been deposited from suspension—perhaps transported via short-term suspension—are fine sand grains superimposed on dust-coated surfaces (**Fig 9**) for which there is no indication of arrival by saltation impact—i.e., the dust coating was not disrupted by grain arrival. Of course, whether the evidence for a disruptive arrival is preserved, over time, is uncertain.

Aggregates. The best MAHLI image evidence for dust aggregates is the coarse sand-sized feature seen on the MAHLI calibration target US cent on Sol 411 (**Fig 8**). This aggregate was not present when the cent was imaged on Sol 322. Whether dust aggregation occurred during atmospheric transport, or whether it occurred on

the ground and the object was lifted and transported to the US cent from the Martian surface, is not known.

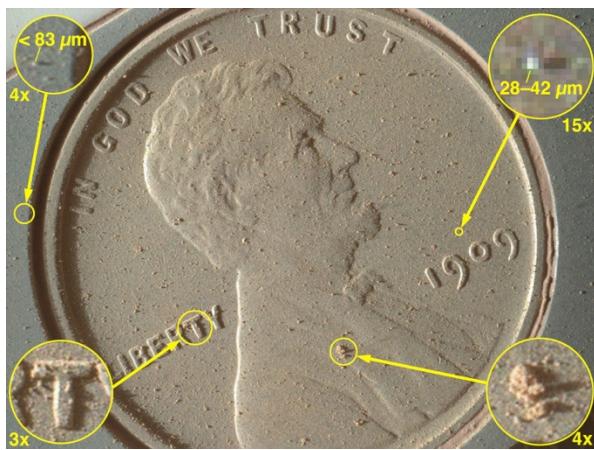


Fig 8. Dust on US cent (19 mm diameter) on MAHLI calibration target at 13.9 $\mu\text{m}/\text{pixel}$ on Sol 411. Smallest grains, identified by pixel coverage and shadow length, are 28–42 μm in size (upper right inset); smaller grains are inferred to be present because there is a thin film of dust (some of which was deposited during Sol 0 terminal descent) coating the entire surface. Inset at upper left shows grains or aggregates $< 83 \mu\text{m}$ in size on the Ti housing surrounding the cent target. Inset at lower left shows letter, T, in actual orientation (vertical) as it is mounted on the rover, showing dust accumulation on vertical and horizontal surfaces. Lower right inset shows a coarse sand-sized aggregate of dust grains that was deposited between Sol 322 and 411.

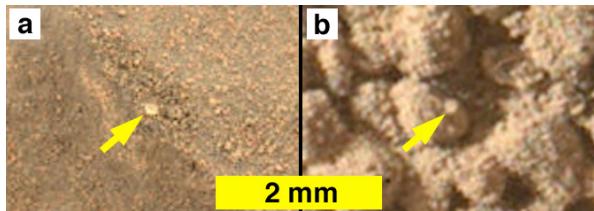


Fig 9. Examples of the largest singular grains that might have been deposited, with dust, from suspension. In both cases, the grains (yellow arrows) are angular, possibly clear to milky, translucent, and $\sim 170 \mu\text{m}$ (fine sand) in size. (a) Example on dust-coated dark gray rock, Bathurst Inlet, in MAHLI focus merge product 0054MH0000200000100370R00. (b) Example occurring with coating of dust on coarse sand grains at the Rocknest eolian sample extraction site, MAHLI focus merge product 0058MH000320000100495R00.

Disruption of Dust Coatings: Scooping of dust-coated sand during the Rocknest campaign [e.g., 23] showed these coatings to be somewhat indurated (**Fig 10a**). However, not all dust coatings are indurated; **Fig 10b** shows a natural slump, a micro-landslide, that occurred in the dust coating on a nearby rock at the Rocknest site. ChemCam laser-induced breakdown spectroscopy (LIBS [26]) action on dust-coated surfaces typically moves dust away from the targeted areas (**Fig 11**); this agitation results in dust coating morphologies similar to those sometimes seen on natural surfaces (e.g., **Fig 4a**), suggesting that some natural surfaces might also have been agitated (e.g., by wind).

Dust on Spaceflight Hardware: Dust coatings on rover hardware surfaces (**Figs 1, 3, 8**) are ephemeral and accumulate even on surfaces that are vertical most of the time (**Fig 8**). Dust coatings on the rover's obser-

vation tray and APXS calibration target have also been studied [27, 28]. Understanding the processes by which dust coatings are removed is challenged by the fact that Curiosity is a mobile and robotic platform; in addition to wind events which can remove dust, variations in vibration and tilt occur as a result of rover activities. The rover also carries ring-shaped magnets on the Mastcam calibration target [29] and on the REMS ultraviolet sensor [24]; their purpose is to maintain dust-free surfaces at the ring centers. These are sometimes observed by MAHLI but no analysis has been performed. As was observed of the magnets on the MER rovers [3], MAHLI images show that sometimes magnetic grains on the REMS UV sensor have been removed, presumably by wind (however, the relative role of the impact of saltating sand grains is not known).

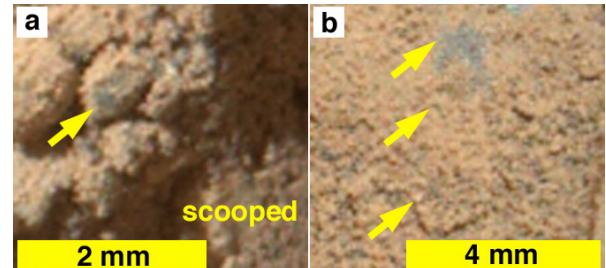


Fig 10. Example disruptions of dust coatings. (a) Coating on dark gray sand grain (arrow) broken by rover scooping activity at Rocknest; portion of MAHLI image 0066MH0000760020100608C00. (b) Slump (micro-landslide; arrows) in dust on dark gray rock called Burwash; portion of MAHLI focus merge product 0082MH0000900000100876R00.

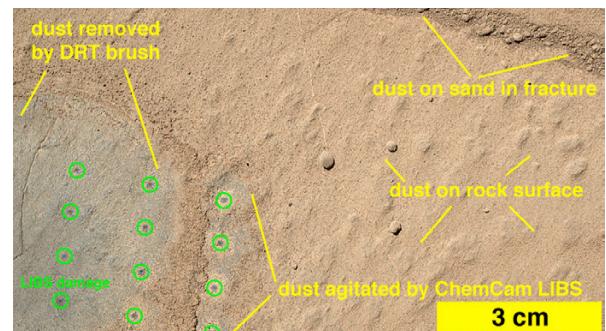


Fig 11. Examples of natural dust deposits on rock and sand surfaces and two forms of anthropogenic disruption of dust coatings in support of MSL rover investigations. ChemCam LIBS agitation of dust might resemble effect of wind agitation and aggregation. Sub-frame of MAHLI image 0615MH0003880010203452C00 of the Windjana drill site.

Local Dust Source Observations: A key question regarding grains transported and deposited from eolian suspension in the present Martian environment centers on whether the planet has local sources of dust that differ in particle properties and composition from the canonical “global dust” population. The dust thought to be transported and mixed globally is considered to be very fine grained ($< 10 \mu\text{m}$) [14, 15] and of an orange-brown or butterscotch color [30]. Before Curiosity landed, there were a few local dust storms observed that might have been dark-toned (gray) [31], and a case

was made for dark-toned (mafic) silt and very fine sand, transported in short-term suspension, to have formed some of the dark wind streaks which emanate from craters, including Gale and particularly the craters of western Arabia Terra [32].

The dust coatings on natural surfaces observed by the cameras aboard Curiosity are generally of the “red Mars” variety; that is, visually indistinct from “global dust.” However, MAHLI and other MSL instruments have provided three critical new observations about Mars: (1) that rocks formed of silt- and/or clay-sized particles (e.g., mudstones) actually exist on Mars, (2) that these fine-grained rocks are eroded by wind (**Fig 12a**), and (3) that sand-sized lithic fragments of these fine-grained rocks also exist and are transported by wind (**Fig 12b**). The on-going eolian erosion of—and creation of lithic clasts from—very fine-grained sedimentary rocks implies that they have to be sources for at least some of the particulates transported in eolian suspension on present-day Mars.

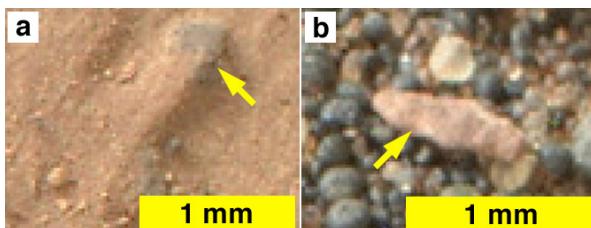


Fig 12. Mudstones as local eolian sediment sources. **(a)** Dust-free mudstone surface. Wind erosion removes clay- and silt-sized grains and releases them into eolian suspension after, in this case, >3 billion years of storage. The yellow arrow indicates a gray sand grain or concretion emergent from within a reddish mudstone. This is from MAHLI focus merge product 1610MH0001710000602362R00, target Spurwink. **(b)** Elongated reddish grain (arrow) is a mudstone lithic fragment eroded from local bedrock and incorporated into an eolian dune at MAHLI target Flume Ridge. This is a portion of MAHLI focus merge product 1604MH0004580000602124R00.

Conclusions: Over the course of the MAHLI investigation, dust has usually been something to be ignored, to (literally) be brushed aside and for which windward rock faces are sought so as to obtain dust-free lithologic observations. However, many MAHLI images include dust deposited from eolian suspension on rocks, eolian sands, regolith, and hardware surfaces. Wind and saltating sand prevent or remove dust; this observation is extendable to orbiting spectrometer observations interpreted as mineral occurrences—these are also indicators of wind conditions. The dust coatings on natural surfaces examined along Curiosity’s traverse were thin (<1 mm), suggesting the period of net deposition has not been long (decades? centuries?). Dust deposit surface textures range from smooth to clumpy at millimeter- to sub-millimeter scale; the clumping might be, in part, a product of agitation by wind and/or a result of deposition of aggregates from suspension. The smallest dust grains are too small for

MAHLI to resolve but it can, where a grain contrasts with surroundings, detect 28–42 µm-sized silt. MAHLI images also show sand-sized dust aggregates and show that some very fine and fine sand-sized grains might undergo short-term suspension and be co-deposited with dust. The occurrence of very fine grained sedimentary rocks (e.g., mudstones) on Mars has been confirmed by the MSL investigation, these rocks are eroded by wind, and can therefore provide local contributions of dust for suspension in the Martian atmosphere.

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REGARDING ELECTRIFIED MARTIAN DUST STORMS. W. M. Farrell, NASA/Goddard Space Flight Center, Greenbelt, MD 20771 (William.M.Farrell@nasa.gov)

Introduction. Impulsive lightning discharges have been detected from the atmosphere of many planets – obviously Earth - but also Jupiter, Saturn, Uranus, and possibly Neptune (see reviews by Farrell et al. [1], Aplin et al. [2] and references therein). It has long been speculated that Mars' atmosphere may also generate electricity through the vigorous tribo-electric interaction of particulates in dust devils and dust storms like that in **Figure 1** [3, 4]. However, the exact nature of the discharge associated with such features on Mars still remains a question of fundamental study, which connects directly to both science and exploration.



Figure 1. HiRISE image of a 20 km high dust devil

In the area of science, new reactive chemistry may be created depending upon the nature of the discharge. Under the influence of moderately large E-fields (> 10 kV/m), the low pressure (~5 Torr) CO₂ dominant Martian atmosphere will breakdown to create an enhanced population of energetic (2-20 eV) electrons, referred to as an electron avalanche, that exponentially grows. These electrons, in turn, are expected to chemically modify the neutral gas to create CO₂⁺, CO, and O⁻ from CO₂ (and create OH and H⁺ from any water in the atmosphere) [5]. Recombination of these products is also predicted to create new reactive species like hydrogen peroxide [6]. Methane may be destroyed [7] and/or created [8] under the influence of these E-field-induced energetic electron flows. However, the degree of new plasma chemistry being formed is a function of the intensity of the discharge-related electron flow and varies widely depending on the yet-to-be-identified saturation mechanisms that limits the current generation & chemical production [9].

From an exploration perspective, the nature of the discharge is directly associated with environmental ESD hazards that any explorer may encounter on the dusty surface. Under the MEPAG Goal 4, an outstanding question is lightning generation on Mars, and how

it might affect take-off and ascent. In 2009, there was a provocative report of lightning detected from a Mars dust storm as observed from one of the DSN ground-based radio telescopes in the GHz emission band [10]. These emissions were inferred to originate from a discharge with 10⁵ times more current than a nominal terrestrial lightning stroke. However, subsequent Earth-based observations near the same frequencies failed to reproduce the result [11]. Gurnett et al. [12] also reported on the lack of any RF emission from lightning in the 4-5.5 MHz band of the MEx/MARSIS radio receiver in proximity about Mars. They used data collected over a 5-year period that included multiple close passes over two major dust storm events.

From an exploration viewpoint, **the primary question remains: Can the atmosphere generate, on rare occasions, large discharge events that possibly pose a threat to human systems?**

System Perspective. From a system perspective, the rate of E-field generation within a storm generator, $\partial E / \partial t$, is a direct function of particulate charging currents, J_C, and intensity of the offsetting atmospheric dissipation currents, J_D, that acts ‘short-out’ or shunt the growth of the E-field [13, 14]:

$$-\epsilon_0 \frac{\partial E}{\partial t} = J_C - J_D \quad (1)$$

For low or moderate E-fields, the dissipation current is J_D = σE, where σ is the atmospheric conductivity. Under stronger E-fields, the gas conductivity can increase exponentially under the influence of increasing electron impact ionizations. In this case, σ varies as n_o exp(αd)eμ, n_o being the ambient electron density, μ the electron mobility, α= α(E) Townsend's primary ionization coefficient and d the anode/cathode distance. Townsend's primary coefficient represents the inverse of the scale length between electron impacts with gas molecules. As E increases, any free electrons will undergo increased acceleration along their free path and thus have a greater likelihood of ionizing an ambient gas molecule upon collision. As such, α= α(E) will itself exponentially increase in cascade with the driving E (See Townsend analysis for Mars atmosphere by Delory et al. [5]).

As illustrative examples of Equation (1), consider the very simply case of a continuously charging at J_C = J_o in an ideal non-dissipating (σ = 0) medium between the charging anode and cathode. In this ideal case, E would increase as ∼ J_o T where T is the time over which J_o is applied. If we placed a solid dielectric medium between the anode and cathode then E would

rise until it reaches a dielectric breakdown threshold, and then the dissipation current would manifest itself in the form of a fast (lightning-like) discharge from anode to cathode cutting through the dielectric.

High-pressure gases behave somewhat similar to solids, although substantial dissipation currents can form in response to the driving E-field. Volland [13] presented a model of a nominal 16 km x 16 km terrestrial lightning storm, and derived a total storm-wide charging current of $J_C \sim 5\text{A}$ and a storm-wide dissipation current of $J_D \sim 2\text{A}$. The latter is acting (unsuccessfully) to neutralize the charging centers that form at the cloud top and bottom. Since $J_C > J_D$, the E-field grows. In about 1000 seconds, E reaches breakdown levels near 1 MV/m (see Curve B in Figure 1). At this breakdown point, the ‘dissipation current’ is temporarily in the form of the lightning discharge – which is acting to neutralize the cloud dipolar charging centers in a highly impulsive way.

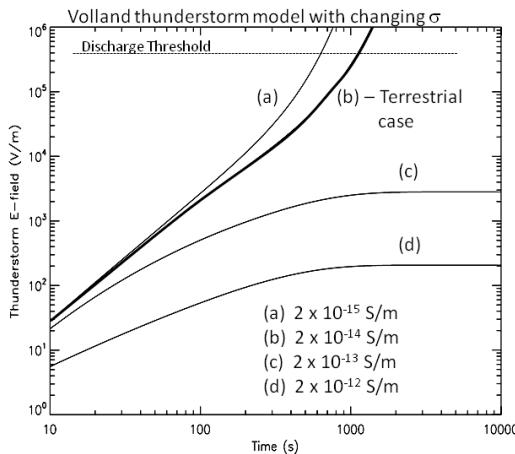


Figure 2. The Volland [13] terrestrial storm charging model with varying atmosphere conductivity.

However, we note for the Volland storm model that J_C is just slightly above J_D , and that if J_D were slightly larger, we might expect $\partial E / \partial t$ to become 0. **Figure 2** shows an exercise where we coded the Volland electrical storm generator model (Eq. 5.1 to 5.7, Volland [13]) using the constants applied therein. Once coded, we adjusted the atmospheric conductivity to 4 cases. For the terrestrial case, Curve B, we reproduce the Volland lightning storm charging scenario. For atmospheric conductivity a factor of 10 lower, the storm charges slightly faster than the terrestrial case. However, for atmospheric conductivities of 10 and 100 times greater than the terrestrial case (Curves C and D), the storm electrical system levels off at an equilibrium value where $J_C = J_D$. In this case, the dissipation currents are large enough to shunt the growth rate, $\partial E / \partial t$, and the storm E-field levels off to an equilibrium E-field value. Since dissipation currents now keep

pace with the charging currents, a lightning discharge that normally develops in an attempt to impulsively neutralize the ever-growing charge centers is not generated – it is not necessary since the system is quasi-stable. The charge centers themselves reach equilibrium with charge collected at the storm top and bottom being offset by the charge dissipated.

With this system perspective, we can now formulate the question we have for Mars storms: **In a Mars convective dust feature, do dust tribo-electric charging currents, J_C , exceed the atmospheric dissipation currents, J_D ?** If they do, the charge centers may grow until they impulsively discharge (i.e., lightning). However, if J_C is comparable to J_D , then the discharge may be only in the form of a low-level ‘leaky’ dissipation current, in which case the storm would have reduced electrical potency – there would be less stored electrical energy (which varies as E^2) in the capacitive system.

Figure 3 shows a model of E-field growth for a given (constant) dust devil charging current, J_C , and range of values of atmospheric conductivity (or range of J_D) [15]. Note that the system-level charging, as manifested by the growth of the E-field in 10 seconds ($\Delta E / \Delta t$) is decreasing with increasing conductivity. For an Earth-like conductivity near 10^{-14} S/m , J_C dominates. However, for conductivities above 10^{-12} S/m , the dissipation currents, J_D , become comparable to J_C , reducing $\Delta E / \Delta t$. Much like the terrestrial lightning storm example in Figure 2, the atmospheric conductivity at values $> 10^{-13} \text{ S/m}$ gives rise to substantial competing dissipation currents that act to stabilize the growth of the E-field.

We now discuss in greater detail the charging and dissipation currents.

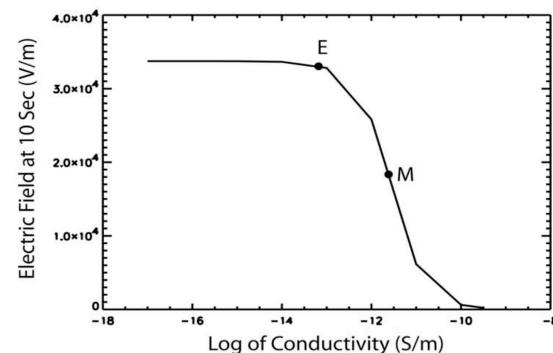


Figure 3. $\Delta E / \Delta t$ vs. atmospheric conductivity for a given charging current (from [15]).

Dust Devil Charging Currents, J_C : In order to create an effective charging current, two elements are required: (1) A mass-preferential charging process and (2) a mass-preferential spatial separation process that acts to spatially displace the various charges. In terrestrial storms, upward-blown light ice collides with polarized heavy pellets/graupe to charge positive. Vertical winds then vertically separate light (+) ice from the downward-moving heavy (-) material to create the charge separation. The result is a continual build-up of a negative charge center at a storm base and positive charge center at the storm top (see more details in Saunders [16]). Thus, an electric dipole forms in the cloud, and its image is formed in the ground.

In the case of dust devils, within their saltation layers, micron-sized dust and millimeter-sized sand grains come into vigorous contact. There is charge exchange via contact electrification between these particles, especially in low humidity conditions [17, 18]. The contact electrification or ‘tribo-electrification’ of metal-metal contacts is understood [17], with surface charge developing to bring the Fermi energy of each grain to a common potential. Ironically, the situation is not as clear for insulator-insulator contacts, or contacts between grains of similar semiconductor material [17, 19].

The model presented in Forward et al. [19] involves the exchange of electrons trapped on defect-created energy levels between the semi-conductor valence and conductive bands. These trapped electrons do not have the energy to jump up to the conductive band or cannot lose energy to drop to the filled valence band. However, they can jump to the low energy defect-created levels on other grains that are brought into contact. Over many contacts between large and small grains, the heavily collided larger grains will tend to transfer electrons to the smaller grains making smaller grains tending in a statistical sense to charge negative and larger grains tending to charge positive.

Vertical winds from a vertical pressure gradient will the separate the small negative dust grains from the heavy positive sand grains and positive surface, creating an electric dipole in the dust feature. In terrestrial dust devils, such dipole fields were initially reported by Freier [20], Crozier, [21], and examined more recently via a large number of desert field studies by numerous investigators (see review by Harrison [18]). The formation of a dipole dust storm electrical system has also been modeled by numerous authors (see most recent discussion in Barth et al., [22] and references therein). The tribo-charging vertical currents in moderate sized terrestrial dust devils are estimated to be as large as $\sim -5 \mu\text{A}/\text{m}^2$ [23] which is larger than the current density generated within the Volcanic-class terrestrial storm.

Atmosphere-Responsive Dissipation Currents, J_D : Given the above-described charging current and associated increasing E-field, the low pressure atmosphere at Mars will respond under the influence of this increasing electrostatic stress. Previous laboratory studies have found that mixing dust and sand under low-pressure Mars-like atmospheres will create small sparks, glows, and detectable RF discharges in the gas [3, 4, 24, 25] suggesting the development of intense dissipation currents. Farrell et al. [23] recently examined in detail the response of a 5 Torr CO₂ gas under increasing electrical stress via lab study.

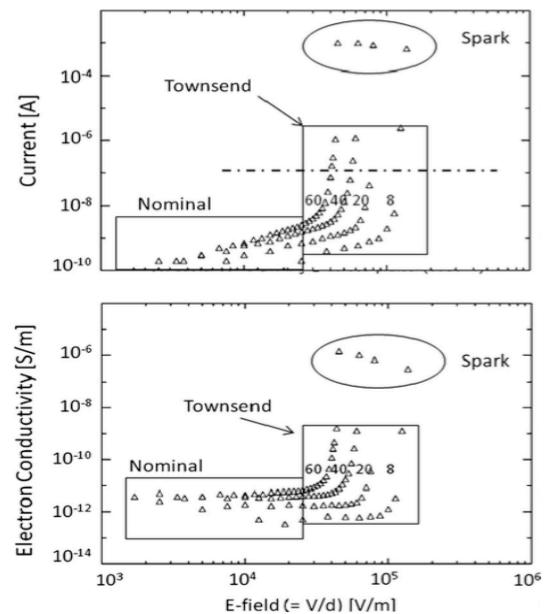


Figure 4. Lab experiments on the pre-breakdown regime of a 5 Torr, CO₂ gas. The current vs. driving E curves are shown for anode-cathode separations of 60, 40, 20 and 8 mm (from [23]).

Figure 4 from these lab studies clearly shows that the gas has three electrical regimes for E-fields below about 200 kV/m. Specifically, for low E-fields, the gas conductivity is quasi-constant, and the dissipation current, J_D , varies as σE (nominal case). However, as E grows, there is an increase in electron impact ionizations, and the conductivity effectively grows exponentially as $\exp(\alpha d)$. This pre-spark regime is called the Townsend ‘dark’ discharge (TDD) because there is not an obvious visual manifestation - no obvious glow - but yet there is exponentially increasing atmospheric current in the direction of E under the stress of E . The TDD and associated electron avalanche was modeled previously by Delory et al. [5]. Finally, at a threshold E-field, the gas will have a more intense discharge- the dissipation current will jump by a factor of 10^3 - into the ‘spark’ regime. We note that the spark regime is not a 100% ionized lightning-like discharge. The

measured spark currents, at milliAmpere levels, indicate that the ‘spark’ is still a very weakly ionized gas with electron densities below 1 part per 100 billion of the neutral gas. Once initiated, the spark will remain ‘on’ for the period the E-field is above the threshold (unlike an impulsive lightning discharge). We consider both the TDD and spark discharge low energy dissipation currents.

J_C & J_D Current Comparisons: Given the relatively mild charging current and the atmospheric response in the low pressure gas, we conclude that, on the large scale, that charging and dissipation currents in Mars dust features are able to come into equilibrium in the low pressure gas. The dashed line in Figure 4A shows the charge current for a dust devil having a large value of $J_C \sim 5 \mu\text{A/m}^2$ [23]. In our laboratory gas breakdown environment, this driving charging current is expected to be offset by a mild Townsend dark discharge (and not a more-intense spark discharge).

If we make the assumption that the dissipation currents, at least on the large scale, keep pace with the charging currents, we can express Eq. (1) in terms of the current density balance between the fluid lifting of the negatively charged dust ($n_{\text{dust}} q_{\text{dust}} v_{\text{dust}}$) and dissipating Townsend dark discharge as

$$-\epsilon_0 \partial E / \partial t = -n_{\text{dust}} q_{\text{dust}} v_{\text{dust}} + n_e(E) e \mu E \sim 0 \quad (2)$$

with $n_e(E) = n_o \exp(\alpha(E)d)$ where α is the Townsend’s primary coefficient defining the number of electron impact ionizations per unit length and d is an assumed length between charge centers in the system. The exponential growth of electrons in the second term describes the Townsend regime observed in lab experiments (Figure 4A). Townsend’s primary coefficient is found to be a function of the E-field, varying as $\alpha = \alpha_o \exp(-E_o/E)$ where $\alpha_o = C_1 p$ and $E_o = C_2 p$, with p being pressure (in Torr), and C_1 & C_2 having unique values depending upon the gas species [26]. Rearranging the terms and assuming operation in the Townsend regime, $\exp(\alpha d) > 1$, we then have:

$$\ln(n_{\text{dust}} q_{\text{dust}} v_{\text{dust}} / n_o e \mu) \sim \alpha d \exp(-E_o/E) \quad (3)$$

Rearranging, we thus can arrive at an expression for the equilibrium ($J_C \sim J_D$) large scale E-field in the convective dust feature as

$$E = -E_o / \ln(A) \quad (4)$$

where $A = (\alpha_o d)^{-1} \ln(J_C/\sigma_o)$, the conduction current is $J_C = n_{\text{dust}} q_{\text{dust}} v_{\text{dust}}$ and the intrinsic atmospheric conductivity is $\sigma_o = n_{e0} e \mu$ ($\sim 10^{-12} \text{ S/m}$ from Figure 4B). From past CO₂ breakdown studies, the values of $C_1 = 2000/\text{m-Torr}$ and $C_2 = 46.6 \text{ kV/m-Torr}$ [26]. For a 5

Torr atmosphere, this corresponds to $\alpha_o = 10000$ ionizations/m and $E_o = 233 \text{ kV/m}$.

As an illustrative example, consider a tribo-charged dust devil vertical current density of $J_C = 1 \mu\text{A/m}^2$. For a dust devil of height $d = 0.01, 0.1$, and 1 km, the equilibrium E-field from Eq. (4) is then $E = 26.2, 20.8$ and 17.2 kV/m , respectively. The reduction in equilibrium E-field with increasing d is consistent with a greater path length for ionization (greater electron avalanche) corresponding to increased system-level TDD dissipation currents.

The Inhomogeneous Townsend Dark Discharge. While Eq. (4) represented a system-level condition, typically the TDD and other corona-type phenomena are characteristically inhomogeneous, with local regions in disequilibrium (where $\partial E / \partial t$ is locally not zero). In this case, there may be the initiation of a visible local spark discharge (and a factor of 1000 times current increase) to achieve equilibrium.

One of the most studied phenomena is the electron corona that forms around high voltage power lines [27, 28]. The phenomena include the creation of an electron-rich avalanche region about the line and the generation of RF and audible crackles or noise [28] where steady-state equilibrium has failed locally. The RF and audible impulsive events represent very local imbalances that lead to faster breakdown than that at the overall equilibrium level.

Analyzing dust and sand mixing in a low-pressure Martian-like atmosphere, Eden and Vonnegut [3] reported on the presence of a steady glow, which is likely the ‘spark’ discharge. However, they also report on impulsive filamentary type discharges to the system wall, consistent with the influence of secondary electron phenomena that created local disequilibrium.

Consequently, the macroscopic E-field value from Eq. (4) has large variations about the mean, depending upon proximity to surrounding metal/capacitive structures, secondary electron sources (UV light on surrounding materials), and the influx of external charged particles like cosmic rays. As suggested in Figure 4, small variations in E in the Townsend regime can give rise to triggered spark discharges, given the steep slope of dI/dE in this regime. We thus expect local disequilibria creating temporary sparks and glows.

Undercharged Dust and Enhanced Electrostatic Energy. We have so far treated the driving dust charging current, J_C , as independent of the atmospheric responding Townsend discharge current, J_D . We have implicitly assumed the Townsend discharge is occurring in a clean, uncontaminated gas. However, J_D also has a dependence on dust density, n_{dust} [29, 30]. Specifically, the population of lofted dust has a statistical distribution of charged states, with some fraction being undercharged or charge-neutral. These initially under-

charged dust grains will start to charge negative as they come into equilibrium with the TDD's electron avalanche current [23]. These undercharged dust grains will gain electrons by absorbing those flowing in the TDD - reducing the effectiveness of the dissipating currents. The undercharged grains are 'moderators' suppressing the avalanche process.

We can incorporate this effect by applying a modified Townsend's primary ionizing coefficient, $\alpha' = \alpha - \eta$, with $\eta = \eta(n_{dust})$ representing the loss of electrons from the avalanche via dust absorption [29]. Examining Equation (4), this effect would act to reduce α_o from its 'unobstructed' value at 10^4 ionizations/m to a lower value depending upon the electron-obstructing undercharged dust density.

For example, if we use Eq. (4) with $d = 1$ km, $J_C = 1 \mu\text{A}/\text{m}^2$, $\sigma = 10^{-12} \text{ S}/\text{m}$ for values of $\alpha_o = 10^4$ (unobstructed), 10^2 , and 1 ionizations/m, then the equilibrium E-field increases as $E = 17, 26$, and 54 kV/m respectively. The system-level electrostatic energy ($\sim E^2$) increases as the TDD is systematically suppressed. In essence, the same population of charged dust, having a statistical spread in charged states, both creates the charging currents, J_C , responsible for the growth of E but also suppresses dissipation current, J_D , thereby self-fortifying the charging centers and increasing the retention of system-level electrostatic energy.

A remaining question: **Could a strongly self-fortified dusty system (like the $E \sim 54 \text{ kV/m}$ case) give rise to another form of impulsive dissipation, like a lightning event, in an attempt to reduce the anomalous charge buildup?** If dissipation currents become too suppressed, equilibrium could even be lost. In this case, $J_C > J_D$, leading to the development of anomalously large E-fields and an impulsive discharge.

Preliminary Recommendations. (1) Obtain in-situ (landed) measurements of the Martian DC E-field, RF activity, and atmospheric conductivity. Such a package has been proposed (and even awarded) for US missions [31]. The ill-fated Schiaparelli lander had such a package as well [18]. This measurement needs to be made at least once to assess the discharge hazard.

(2) Make the outer skin of space suits conductive. The surface conductivity is $< 2 \text{ nS/cm}$ [32] and may be comparable to or lower than the atmospheric conductivity. An astronaut may be 'electrically grounded' to the atmosphere as opposed to the regolith. As an astronaut roves, they will accumulate tribocharge from the boot-regolith interaction, and a conductive space suit will increase the area of dissipating return currents from the atmosphere, driven by σE , where E is now the E-field from the tribo-charged astronaut. If the boot-regolith interaction is vigorous, one can imagine the return currents moving into a TDD or occasional 'spark' discharge. A conducting space suit

ensures a large return current collecting area to offset charge build-up and limit the growth of the astronaut E field.

(3) Obtain atmospheric and near-surface chemical measurements in dust storms to determine if new reactive species are created. This includes a determination on if the species are harmful to humans.

(4) Continuously measure the E-field in the first 2-3 centimeters above the surface. Schmidt et al [33] reported that $E \sim 160 \text{ kV/m}$ can be generated in near-surface windblown sand. As such, new electrochemical species may not be limited strictly to dust devils and storms but may also include any windblown saltation event. In effect, any time the wind blows, new harsh species may be created near the surface.

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ASTRONAUT-DEPLOYABLE GEOPHYSICAL AND ENVIRONMENTAL MONITORING STATIONS.

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Introduction: When the Apollo astronauts landed on the Moon, they deployed a series of science experiments at their landing sites. Combined, these instruments formed the Apollo Lunar Science Experiments Package (ALSEP), which consisted of seismometers, magnetometers, and various instruments to measure the solar wind and charged particles [1]. We expect future astronauts exploring Mars will deploy similar, but more sophisticated autonomous instrument packages to study and monitor the environment and geophysical properties of the landing site region. Additionally, the longer expected duration of future human missions, relative to Apollo, present the opportunity for astronauts to build up a large *network* of instruments throughout a wide region, enhancing both the scientific return of the instruments and providing advance notice of potentially hazardous events (e.g., martian dust storms) approaching their location. This abstract presents conceptual ideas for future astronaut-deployable Geophysical and Environmental Monitoring Stations (GEMS).

GEMS Concept: Geophysical network science has been rated as high priority for both the Moon and Mars [2]. On Mars, a meteorological network could better study regional scale phenomena such as dust storms and water transport. Seismological networks on both worlds would help study their interiors and localize seismological sources such as quakes or recent impacts. Thus, network science is a driving element in the GEMS concept. Astronauts would be equipped with a substantial number of GEMS units that could be deployed at will during a traverse. Large-scale production of GEMS units would reduce per-unit cost. Over the lifetime of a landed mission (weeks to possibly 1 Mars year), a dense and broad network of GEMS units could be deployed. Such a network would be robust against loss or failure of individual units. Networked monitoring stations have wide applications terrestrial-ly: monitoring severe weather to protect life and property [3], seismic monitoring [4], and conducting targeted scientific studies [5]. A concept GEMS network is shown in Figure 1.

To simplify deployment, which would both foster a more dense network of GEMS units and be safer and simpler for the astronauts, the GEMS units could be carried on the exterior of the astronaut's rover in a "magazine". At set intervals along a traverse, the rover could briefly stop and deploy a GEMS unit with the rover's manipulator arm. After turning on the unit,

radioed commands would deploy the solar panels and instruments and perform a communications check. Then the astronauts could proceed upon their traverse and continue to deploy GEMS units without needing to don their suits and perform an extravehicular activity (EVA).

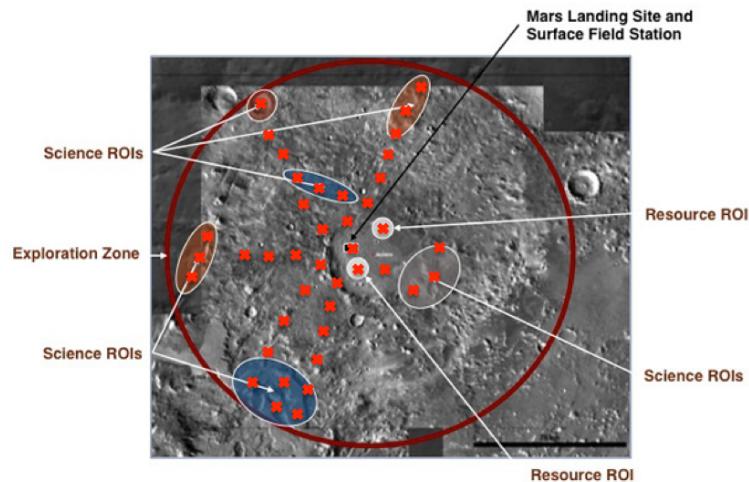
We present a concept drawing of a GEMS unit on Mars in Figure 2. The GEMS unit is box-shaped, with fold down solar panel "wings", a radio antenna, and possibly masts to extend or deploy instrumentation.

Instrumentation: GEMS instrumentation will be tailored to the world that the astronauts will land upon and the scientific goals of the mission. On Mars, meteorological sensors would be included on each GEMS unit. The Rover Environmental Monitoring Station (REMS) instrument [6] onboard the Mars Science Laboratory (Figure 3) represents a useful initial baseline for such a suite of air pressure, wind, and temperature (both ground and air) sensors and they will be largely reflown for both the InSight mission and Mars2020 rover [7]. Sensors to meaure atmospheric optical depth, as will be included on the Mars2020 Mars Environmental Dynamics Analyzer (MEDA) instrument, would also be valuable for scientific and astronaut-safety purposes by tracking the potential approach of a dust storm and understanding the reduced efficiency of solar power systems during periods of increased atmospheric dust. Geophysical instruments, such as seismometers and subsurface heat-flow, would be scientificaly valuable as well.

Conclusion: Human exploration will hopefully reach Mars in the next 20-30 years. To perform their scientific studies, a suite of instruments must be designed, built, and tested long before the first mission is launched. Astronaut-deployable GEMS networks would autonomously collect a wealth of data while also enhancing astronaut safety.

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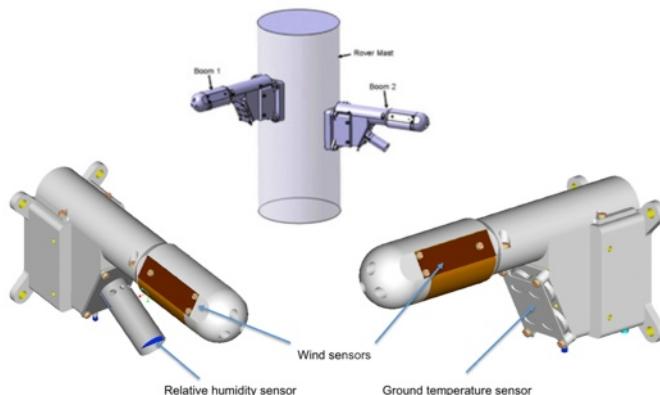
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1. GEMS units (red X's) are deployed along astronaut traverse routes to scientific regions of interest (ROIs) and create a wide network in this concept image of a Mars exploration zone (NASA First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars, 2015)



2. Concept image of a GEMS unit unfolding and deploying sensors on the martian surface.



3. The REMS sensor booms, containing temperature (air and ground), humidity, and wind sensors, are attached to the mast of the Curiosity rover [6].

ACUTE METEORITE DUST EXPOSURE AND PULMONARY INFLAMMATION - IMPLICATIONS FOR HUMAN SPACE EXPLORATION. A.D. Harrington^{1,2,3}, F.M. McCubbin¹, J. Kaur³, A. Smirnov^{3,4}, K. Galdanès², M.A.A. Schoonen^{3,5}, L.C. Chen², S.E. Tsirka⁶, and T. Gordon². ¹NASA Johnson Space Center, Mail Code XI2, Houston, TX 77058 (Andrea.D.Harrington@NASA.gov). ²Department of Environmental Medicine, New York University School of Medicine, Tuxedo, NY 10987. ³Department of Geosciences, Stony Brook University, Stony Brook, NY 11794. ⁴Geology Department, Lone Star College, Kingwood, TX 77339. ⁵Environmental Sciences Department, Brookhaven National Laboratory, Upton, NY 11973. ⁶Pharmacological Sciences, Stony Brook University, Stony Brook, NY 11794.

Introduction: The previous manned missions to the Moon represent milestones of human ingenuity, perseverance, and intellectual curiosity. However, one of the major ongoing concerns is the array of hazards associated with lunar surface dust. Not only did the dust cause mechanical and structural integrity issues with the suits, the dust ‘storm’ generated upon reentrance into the crew cabin caused “lunar hay fever” and “almost blindness [1-3]” (Figure 1). It was further reported that the allergic response to the dust worsened with each exposure [4]. The lack of gravity exacerbated the exposure, requiring the astronauts to wear their helmet within the module in order to avoid breathing the irritating particles [1]. Due to the prevalence of these high exposures, the Human Research Roadmap developed by NASA identifies the *Risk of Adverse Health and Performance Effects of Celestial Dust Exposure* as an area of concern [5]. Extended human exploration will further increase the probability of inadvertent and repeated exposures to celestial dusts. Going forward, hazard assessments of celestial dusts will be determined through sample return efforts prior to astronaut deployment.



Figure 1. Eugene Cernan after a spacewalk (Apollo 17)

Studies on the lunar highland regolith indicate that the dust is not only respirable but also reactive [2, 6-9], and previous studies concluded that it is moderately toxic; generating a greater response than titanium oxide but a lower response than quartz [6]. The presence of reactive oxygen species (ROS) on the surface of the dust has been implicated. However, there is actually little data related to physicochemical

characteristics of particulates and pulmonary toxicity, especially as it relates to celestial dust exposure.

As a direct response to this deficit, the present study evaluates the role of a particulate’s innate geochemical features (e.g., bulk chemistry, internal composition, morphology, size, and reactivity) in generating adverse toxicological responses *in vitro* and *in vivo*. This highly interdisciplinary study evaluates the relative toxicity of six meteorite samples representing either basalt or regolith breccia on the surfaces of the Moon, Mars, and Asteroid 4Vesta (Table 1); three potential candidates for future human exploration or colonization. Terrestrial mid-ocean ridge basalt (MORB) is also used for comparison as a control sample.

Table 1. Key Sample Information

	Sample	Class	Description
Martian	Tissint	IB	Representative of starting conditions of rocks on Mars
	NWA 7034	RB	First sample of lithified Martian soil for study on Earth
Lunar	NWA 4734	IB	Representative of Mare regions and the starting conditions of lunar rocks
	NWA 7611	RB	Mechanical mixture of all the different rock types on the lunar surface
Vestian	Berthoud	IB	Primarily represents minimally processed, basaltic igneous material
	NWA 2060	RB	Representative of multiple generations of secondary processing
MORB		IB	Minimal secondary processing
IB (Igneous Basalt); RB (Regolith Breccia); H (Howardite); MORB (Terrestrial Mid-Ocean Ridge Basalt)			

Experimental Details: The meteorite and terrestrial samples were first crushed using an agate mortar and pestle and then ground using an agate ball mill to a respirable size fraction (<10µm). The bulk chemistry and mineralogy were determined via x-ray fluorescence and x-ray diffraction, respectively. The geochemical reactivity of the dust was evaluated by quantifying iron solubility (FerroZine UV-Vis method) and *in situ* reactive oxygen species (ROS) generation (ISO-HPO-100 Microsensor for hydrogen peroxide). Both *in vitro* and *in vivo* toxicological techniques were used to determine the pulmonary inflammation caused by acute exposure (hereafter

referred to as acute pulmonary inflammation or API). The *in vitro* method utilized a technique first published in [10], where the inflammatory stress response (ISR) of the cells to the presence of the dust is quantified. *In vivo* dust exposure was administered via oropharyngeal aspiration of dust slurries. The neutrophil infiltration into the bronchoalveolar lung fluid (BALF) was quantified to evaluate the body's inflammatory pulmonary response to the presence of the particles.

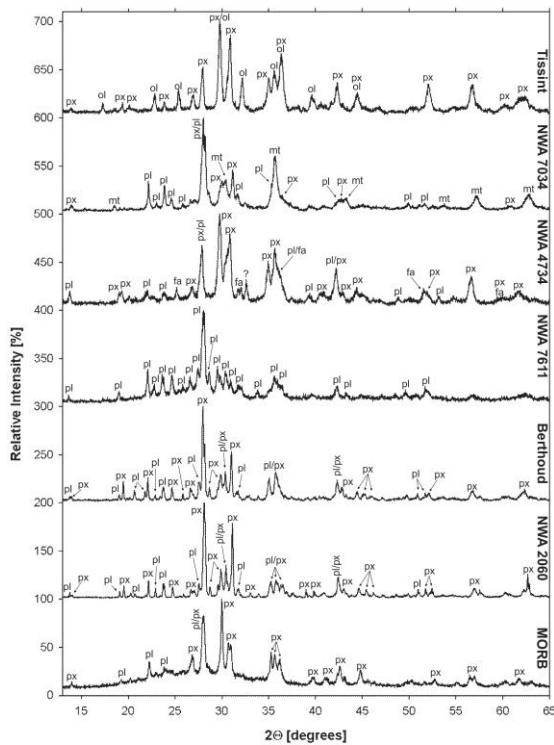


Figure 2. Mineralogical characterization of meteorite and MORB sample determined by XRD.

Geochemical Results: MORB, Tissint, and NWA 4734, all basalts, leached the most iron after eight days (Figure 2). NWA 7611, a lunar breccia, leached the least after eight days but based on the temporal trend, there was likely some iron precipitation from solution. Tissint and MORB also generated the greatest H₂O₂ in solution. Within the first five minutes both generated 5 μM H₂O₂, after which the two differentiated with H₂O₂ concentration 10 μM after 20 minutes in the Tissint slurry. At 4 μM, the NWA 4734 slurry generated the third highest concentration of H₂O₂ in solution after 20 minutes.

Biological Response Results: The MORB generated the lowest ISR after 24 hours; followed by the lunar breccia NWA 7611 (Figure 3). The ISR values generated by NWA 7611 and the vestian samples are similar to inert material; however the

temporal trends indicate biological reactivity. The lunar basalt, NWA 4734, was the first dust sample to

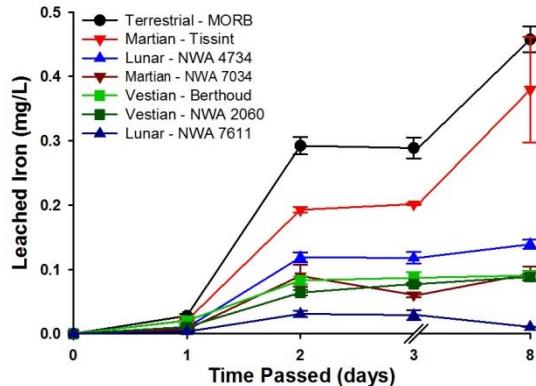


Figure 3. Iron leached from dust slurry (0.01 m²/mL) in simulated lung fluid. For some data points, the error bars (SEM) are obscured by the symbols.

generate an ISR definitively outside of the range of inert material. The only other meteorite dust sample to generate a more significant loss in cell viability is the martian basalt, Tissint. Tissint also generated the second highest cellular upregulation of ROS, which was the major determining factor in its high ISR. The highest ISR and cellular upregulation of ROS was generated by the martian regolith, NWA 7034. Unlike Tissint, NWA 7034 did not illicit significant cellular death. However, although driven solely by the upregulation of ROS, the ISR generated by the NWA 7034 is similar to terrestrial soil contaminated with high levels of trace elements (NIST 2710 [10]).

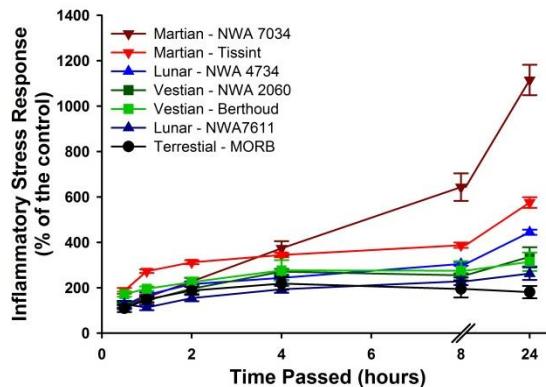


Figure 4. The ISR generated over time by the meteorite and terrestrial dust samples at a dose of 0.002 m²/mL. For some data points, the error bars (SEM) are obscured by the symbols.

The lunar basalt (NWA 4734) generated the greatest PMN infiltration into BALF followed by Tissint, the martian basalt. However, this difference was not statistically significant. The martian and lunar regolith dust samples generated the next greatest PMN infiltrations, respectively. These values are

statistically lower than Tissint but not from each other or from the NWA 2060 (Table S3). MORB generated the lowest PMN infiltration; statistically lower than all dust samples other than Berthoud.

Discussion: The MORB demonstrated higher geochemical reactivity than most of the meteorite samples but caused the lowest API (Table 2). Notably, the martian meteorites generated two of the three the highest API but only the basaltic sample is significantly reactive geochemically. Furthermore, while there is a correlation between a meteorite's soluble iron content and its ability to generate acellular ROS ($P=0.0442$), there is no direct correlation between a particle's ability to generate ROS acellularly and its ability to generate API. However, assorted *in vivo* API markers (data not shown) did demonstrate strong positive correlations with Fenton metal content and the ratio of Fenton metals to silicon.

Table 2. Sample Data Comparison to MORB

Sample	Iron ^a	H ₂ O ₂ ^b	ISR ^c % of MORB	PMNs ^d
Tissint	83	208	618	163
	20	4	318	132
NWA 4734	30	83	246	172
NWA 7611	2	28	145	128
Berthoud	20	11	180	106
NWA 2060	19	53	174	120

^a Iron leached from dust in simulated lung fluid after 8 days
^b H₂O₂ formed in water after 25 minutes
^c Cellular ISR at 24 hours post exposure only
^d Polymorphonuclear leukocytes (PMNs) infiltration in BALF

In summary, this comprehensive dataset allows for not only the toxicological evaluation of celestial materials but also clarifies important correlations between geochemistry and health. Furthermore, the utilization of an array of celestial samples from Moon, Mars, and asteroid 4Vesta enabled the development of a geochemical based toxicological hazard model that can be used for: 1) mission planning, 2) rapid risk assessment in cases of unexpected exposures, and 3) evaluation of the efficacy of various *in situ* techniques in gauging surface dust toxicity.

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MOXIE, ISRU, AND THE HISTORY OF IN SITU STUDIES OF THE HAZARDS OF DUST IN HUMAN EXPLORATION OF MARS. M. H. Hecht¹, J. B. McClean², W. T. Pike², P. H. Smith³, M.B. Madsen⁴, D. Rapp⁵, and the MOXIE Team; ¹MIT Haystack Observatory, 99 Millstone Rd., Westford, MA 10886, ²Imperial College, London, ³Space Exploration Instruments, Tucson, AZ, ⁴Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen, ⁵1445 Indiana Ave., South Pasadena, CA 91030

Dust as a hazard to human exploration: For nearly 20 years, the scientific exploration of Mars under NASA's Science Mission Directorate (SMD) has been augmented by experiments sponsored by the human exploration directorates, with the objective of paving the way for crewed missions. Four themes have consistently been featured: Hazards associated with radiation; safe landing of large payloads; *in-situ* resource utilization (ISRU); and hazards associated with dust and soil. This talk addresses the latter two concerns and, in particular, their confluence in the Mars Oxygen ISRU Experiment (MOXIE) under development for the upcoming Mars 2020 Lander [1].

The first significant investment in flight payloads was provided by what was then called the Human Exploration and Development of Space (HEDS) program, a collaboration among two NASA codes responsible for human space flight. Under this program, three *in situ* payloads were developed and delivered for the Mars 2001 Surveyor Lander, which was eventually cancelled in the wake of the loss of Mars Polar Lander. These were: The Mars Radiation Environment Experiment (MARIE) [2], which had a counterpart on the Mars Odyssey orbiter; The Mars Environmental Compatibility Assessment (MECA), a multi-technique exploration of dust and soil hazards [3]; and the Mars ISPP Precursor (MIP), a demonstration of what is was then called In Situ Propellant Production (ISPP) and is now captured under the umbrella of ISRU. Reflecting the intimate link between ISRU and dust hazards, MIP also carried a capable diagnostic payload that included the Dust Accumulation and Repulsion Test (DART) [4].

Concerns about dust are associated with abrasion, toxicity, inhalation, and corrosion, as well as triboelectricity and corresponding obscuration and clogging of surfaces that might result. Much of this concern stemmed from Apollo experience on the moon, where abrasion threatened the integrity of space suits and, despite the lack of atmosphere, clouds of dust coated visors and other surfaces during mobility activities. Dust on the moon was found to be starkly different from Earth dust, more like highly charged, finely ground glass than the generally benign, electrically neutral, weathered, and aqueously eroded material typically found on Earth. The closest terrestrial analogy might be the silica fines produced in coal mining and responsible for life-threatening silicosis. MECA in particular was

motivated by the question of whether dust on Mars would be more like that on Earth or the moon.

Mars 2001 HEDS payload objectives were eventually to be realized despite the cancellation of the mission. MECA flew under a different name but the same acronym on the 2007 Phoenix mission. MARIE scientific objectives were realized and extended by the RAD instrument on MSL [5]. The MOXIE instrument scheduled for Mars 2020 will capture the ISRU objective of MIP, producing ~200 times as much oxygen with comparable mass and volume, reflecting a much greater power allocation; some of the DART objectives will be realized by a dust experiment that is part of the MEDA meteorological investigation on Mars 2020 [6].

Phoenix 2007: The Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) on the 2007 Phoenix mission was the successor to the 2001 MECA experiment, featuring several minor improvements in its basic microscopy and wet chemistry systems while replacing a 2001 electrostatics experiment on the end of the robotic arm with a thermal and electrical conductivity probe (TECP) [7].

The microscopy experiment, with its fixed optical bench, returned the highest resolution images of surface martian dust and silt to date or planned (Fig. 1). The optical resolution was limited by the pixel size, $4 \mu\text{m}$, with an attached Atomic Force Microscope (AFM) extending that range to $\sim 0.1 \mu\text{m}$. The taxonomy of the particles [8] prominently features small, ill-formed reddish particles, presumably nanophase iron oxide, that dominate the overall color of the sample (and, presumably the planet!), and larger particles, of order $20\text{--}100 \mu\text{m}$, that appear polished and sub-rounded, presumably transported by saltation. Occasional white flakes are presumably salts, likely either carbonates or perchlorates. From a human exploration standpoint, it is reasonable to conclude that the iron oxide dust represents an airborne hazard, while the larger particles could represent chemical or toxic hazards and are likely to dominate (by mass) accumulation directly on the surface.

By individually identifying particles in optical and atomic force micrographs, it was possible to construct a particle size distribution (PSD), Fig. 2. [9]. The result strikingly demonstrated that the sampled soil was deficient in clay-sized particles compared either to Earth or the moon. On Earth, these particles are formed by aqueous alteration, suggesting that the martian soil has been

exposed to a negligible amount of water. On the moon, small particles can be formed by meteoritic gardening. On Mars, apparently, comminution alone is responsible for the distribution of fine particles.

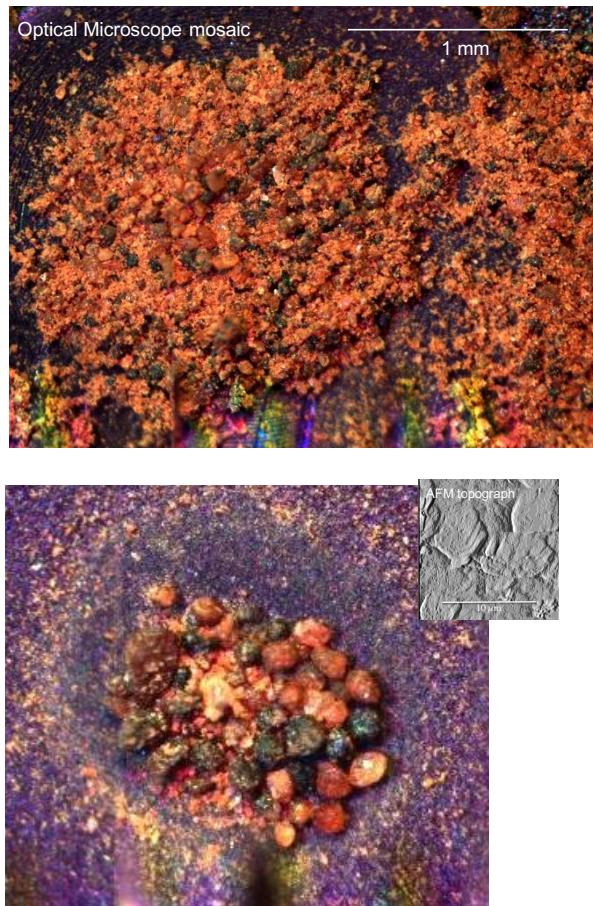


Fig. 1. Top, MECA microscope image of surface soil captured on a magnetic target, 4 μm per pixel. A mix of “ubiquitous red dust,” and larger particles (20–100 μm) are seen. Bottom, a later image where the larger particles had aggregated on the magnet. Upper right: AFM image with $\sim 0.1 \mu\text{m}$ resolution, possibly a phyllosilicate particle.

MECA also performed wet chemistry analysis on surface soil samples, with the notable finding that the dominant source of chlorine in the soil is perchlorate, not chloride [10]. Chemically, the soil was otherwise unremarkable, though the finding of a neutral pH, apparently due to a carbonate component, was surprising [11].

Adding to the microscopy and chemistry findings were results from the TECP, observations from the excavation and handling of the regolith, and conclusions from other Phoenix experiments. From the standpoint of dust hazards to human exploration, the key findings from Phoenix were:

- The bulk properties of the regolith pose no particular hazards; It is structurally competent, not

easily dispersed, and deficient in the finest particles that would pose inhalation hazards

- Perchlorate posed the only notable toxicity hazard. The primary adverse effect is suppression of thyroid function, which can be severe but is treatable and reversible.

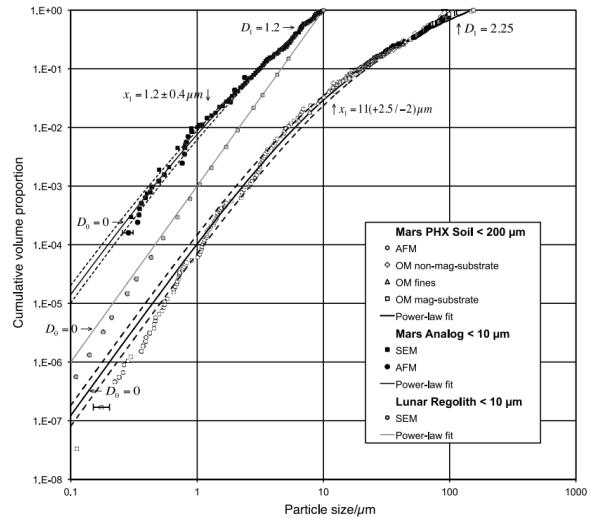


Figure 2. The PSD of Martian soil as measured by Phoenix suggests comminution-dominated physics deficient in the finest particles.

Magnet Experiments: Much of what we know about the interaction of airborne dust with surfaces on Mars comes from experiments with magnets placed on landers for that purpose. The Viking landers were the first to show that both airborne dust and surface soil have a magnetic susceptibility [12]. The soils were inferred to contain 1 – 7 wt.% of a strongly magnetic phase [13]. A “sweep magnet” experiment on the Mars Exploration Rovers subsequently showed that most airborne particles have an appreciable magnetic susceptibility [14]. Mössbauer spectra of the airborne dust showed that the magnetic susceptibility is caused by the mineral magnetite [15]. APXS spectra indicated that, apart from Si, Fe is the most abundant element in the dust. Ti and to a lesser extent Cr are associated with Fe in the most strongly magnetic phase, which points to a basaltic origin of this phase and therefore that the magnetic particles were not formed by precipitation in or primarily by interaction with water [16].

MOXIE: MOXIE is a technology demonstration on the Mars 2020 Lander (M2020) to demonstrate In Situ Resource Utilization (ISRU) in the form of converting atmospheric CO₂ into O₂ [1]. On a future human mission, such a process will be used to autonomously provide up to 30 metric tons of liquid oxygen (LOx) for ascent vehicle propellant in the 16 months preceding launch of a human crew to Mars.

Fig. 3 describes the major MOXIE subsystems and shows how they are arranged in the body of the M2020 rover. The CO₂ Acquisition and Compression (CAC) system collects Martian atmosphere, filters it, and pressurizes it to ~1 atmosphere using a mechanical scroll compressor under development by Air Squared, Inc.; the Solid OXide Electrolyzer (SOXE), developed by Ceramatec, Inc., electrochemically converts the compressed CO₂ into the product O₂ and waste CO at ~800°C. The process monitor and control (PMC) subsystem provides the means to optimize and evaluate the efficacy of operation.

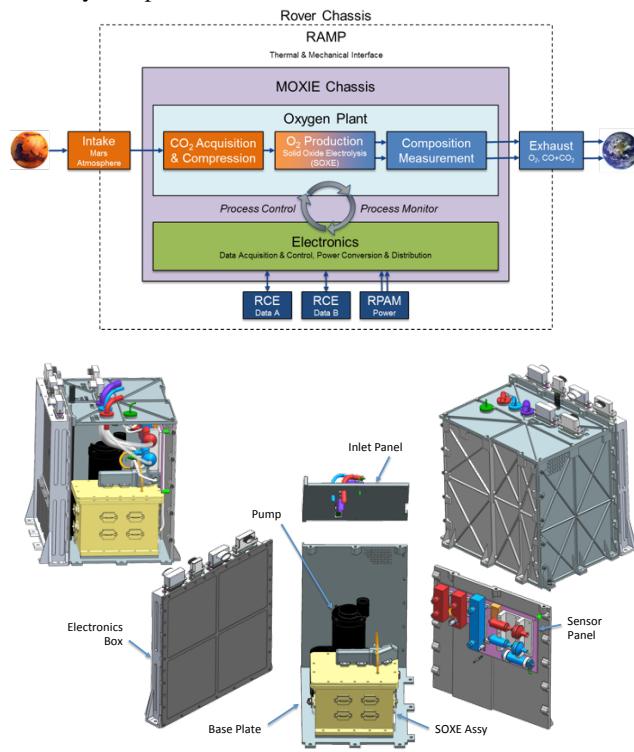


Fig. 3. (top) as the thin Mars atmosphere (orange) passes through MOXIE, it becomes progressively Earth-like (blue), producing oxygen at approximately 1 bar atmosphere while discharging approximately equal parts CO and CO₂ as waste products. Dark blue boxes at the bottom indicate electronic interfaces with the Mars 2020 Rover. (bottom) MOXIE is packaged in a 24x24x31 cm volume that contains the compressor/pump (black) to collect CO₂, the SOXE (gold) to convert it to oxygen, sensors (red/blue) to characterize the effluent, an electronics box, and a gas manifold.

MOXIE dust mitigation: While martian dust could conceivably compromise the CAC mechanical pump, it is primarily a hazard for the SOXE. Sulfates, which are common in Martian soil, can poison the cathode. Other constituents of dust might act more subtly, by coating surfaces with glassy materials or by obstructing the gas flow fields.

For MOXIE, filtering occurs both upstream (HEPA) and downstream (sintered metal) of the mechanical compressor. While the latter protects the more critical components, it is the former that poses the greater challenge. That is because, following Darcy's law, pressure drop ΔP across a filter scales with gas velocity but not with total pressure (with the exception of the slip correction discussed below). As a result, ΔP of a few millibar that would barely be noticeable on the high-pressure outlet of the compressor could effectively throttle the low-pressure flow at the compressor intake. Moreover, the lower the ambient pressure, the faster the flow velocity must be to maintain a particular mass flow, exacerbating ΔP .

Studies of HEPA filter performance are typically performed at a flow rate of a few cm/s on particles of order 0.1–0.3 μm , a range that defines HEPA performance but is poorly characterized for Mars. Laboratory experiments in this range consistently find that pressure drops of a few mbar (a few hundred Pa) begin to appear at dust coverages as small as 1 g/m² of filter media area (e.g. Fig. 4).

The principal means to increase filtering capacity is to increase the filter surface area, often by making deep pleats within a given face area. For MOXIE, the *face* area of the filter is 264 cm², but the pleats increase that area by a factor of 19.2.

The optical depth in the martian atmosphere scales primarily with particle cross section, and the cross-section weighted mean radius has been reported to be in the 1.5 μm range [17], though it should be noted that optical measurements become increasingly unreliable as particle sizes become significantly smaller than 1 micron. Optical depth studies also don't discriminate well between particles close to the ground and those far above the surface.

There is little data to determine how to translate filter dust loading to exposure to larger particles likely to be experienced on Mars, but it would be a reasonable assumption that, like the optical depth, the obstruction should be cross-section weighted. Following this logic, the critical dust mass loading might be expected to scale inversely with particle diameter, such that the threshold of ~1 g/m² for 0.15 μm particles in Fig. 4 might be expected to increase to ~10 g/m² for the 1.5 μm particles expected on Mars.

For the planned MOXIE operation for ~100 hrs on Mars, with air being drawn through the filter at a few cm/s, MOXIE is expected to accumulate ~50 mg dust, which corresponds to ~2 g/m² of *face* area but less than 0.1 g/m² per unit filter area. However, the MOXIE filter is exposed to incident dust even when it is not operating, and the incident velocity (i.e. the ambient Mars wind) is

of order a few m/s, ~ 100 x more than the velocity imparted by the compressor. Over 10,000 hours of the primary M2020 mission, at an estimated arrival rate of $10^6 \text{ g/m}^2\text{-s}$ (derived from Mars Global Climate Models), the filter would be expected to accumulate $\sim 2 \text{ g/m}^2$ of filter area in the pleated configuration. This level might be expected to be measurable, but without causing significant impairment of MOXIE operation. Moreover, the MOXIE filter is baffled to prevent pebble strikes and saltation exposure, which may further limit the exposure to ambient dust. For comparison, a full scale system producing oxygen at a rate of 2 kg/hr might be expected to accumulate $\sim 500\text{g}$ of dust over 10,000 hours.

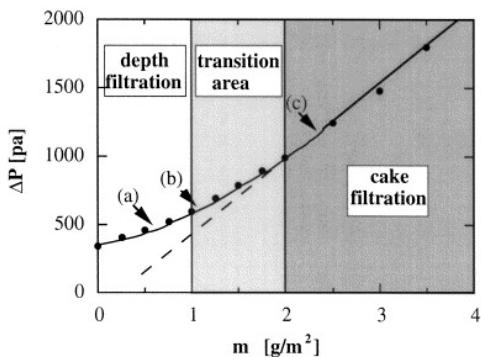


Fig. 4: Laboratory measurements of pressure resistance across a HEPA filter for incident particle velocity $v_0=5 \text{ cm/s}$ and particle diameter $d_p=0.15 \mu\text{m}$. [21]

An additional mitigating factor for operation in the Mars environment is the fact that the mean free path of gas molecules is comparable to the HEPA pore filter size (i.e. the Knudsen number is of order 1). In this circumstance, a “slip correction” needs to be applied because of the non-zero fluid velocity at the fiber surface. This is illustrated qualitatively in Fig. 5; an accurate analysis depends on improved knowledge of both the atmospheric conditions and the filter construction.

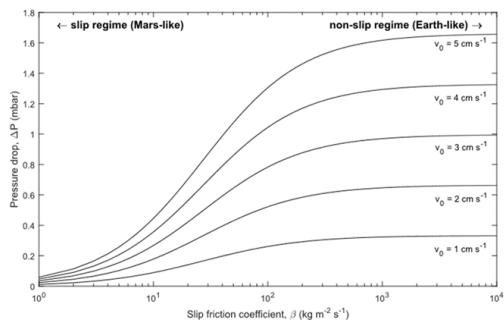


Fig. 5: Pressure drop of fluid with a viscosity $1.1 \times 10^{-5} \text{ Pa}\cdot\text{s}$, typical of martian CO_2 , through a 0.4 mm long, $1 \mu\text{m}$ radius tube typical of a HEPA filter, using slip friction coefficients from 1 to 10^4 and inlet velocities of $0\text{-}5 \text{ cm/s}$, comparable to the MOXIE compressor.

Wind tunnel testing: A prototype MOXIE filter and scroll compressor were tested under ambient Mars conditions in the Aarhus Wind Tunnel Simulator II (AWTSII) in the Mars Simulation Laboratory at the University of Aarhus, Denmark [18] for five days in 2016 [19]. Sections of filter media were connected via a feedthrough to a scroll pump (Air Squared V10T016A-01) and the pressure drop across the filter, ΔP , was monitored by a differential pressure sensor. The inlet face velocity was determined with a Laser Doppler Anemometer, which measured the vertical component of the velocity of dust particles $\sim 1 \text{ cm}$ below the filter inlet. To monitor passive dust accumulation, a second filter media section was mounted adjacent to the first but without any connection to the pump. By varying the compressor speed, it was verified that the expected pressure drop was seen to scale with inlet velocity (Fig. 6) even at Mars ambient pressure.

Salten Skov dust simulant [20] was then injected into the tunnel. In an accelerated simulation of the MOXIE mission, three one-hour runs used average dust particle number densities of $n_0 = 40, 400$, and 800 cm^{-3} , compared to the expected background of $\sim 4 \text{ cm}^{-3}$ on Mars. After the runs were completed, dust loading m was determined by weighing the filter media.

After all three dust exposure runs, the mass of the filter media increased to $65.600(5) \text{ g}$, corresponding to a dust loading $m = 0.03(2) \text{ g m}^{-2}$. Dust accumulation was evident in the color change of the exposed filters (Fig. 7). However, neither a measurable increase in pressure drop ΔP nor a decrease in inlet face velocity v_0 , was seen after the three dust exposure runs. Microscopic analysis of filter loading is underway. An incidental conclusion of this analysis is that *in situ* color monitoring of the filters is likely to be the most sensitive way to detect filter degradation. Nothing in these results, however, suggest that dust loading is likely to pose a problem for MOXIE.

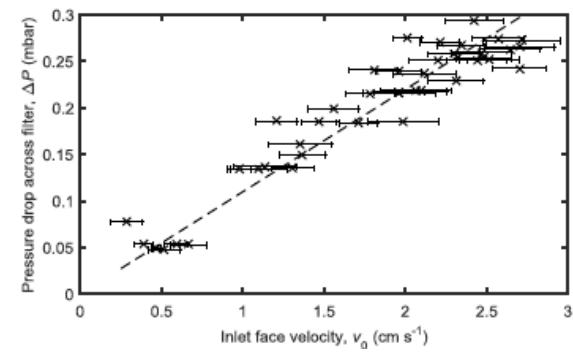


Figure 6. Pressure drop, ΔP , across the HEPA filter as a function of inlet face velocity, v_0 .

Further testing has been proposed that will focus on basic dust-filter interactions. Emphasis will be on understanding:

- Pressure drop vs. dust loading at Mars-like conditions for particles of different (sieved) sizes ranging from 0.1 micron to 100 microns
- Pressure drop vs. dust loading as a function of chamber pressure from 1-1000 mbar to understand slip factors.
- Differences in the above properties among commercially available HEPA materials.
- Filter uptake rates for sieved particles of particular sizes, 0.1 micron to 100 microns
- Active (i.e. drawn on by pump) and passive dust uptake in different orientations relative to the air flow, in pleated vs. flat filters, and in baffled vs. open filter configurations.



Figure 7. Clean (left), passive (center) and active (right) filter after dust exposure runs.

Future solutions: HEPA filters are designed to trap and retain particles, particularly at the low coverages that we have seen can cause significant pressure drops on Mars. For this reason, attempts to clean or backflush filters are likely to be futile, and the only improvement possible over massive, heavily pleated, consumable filter assemblies will be to use other methods of dust mitigation. Efforts both within and outside NASA have focused on electrostatic methods that trap particles before they get to an inlet. Cyclonic mitigation is also possible.

For MOXIE and similar systems that actively collect martian atmosphere, another possible approach will be to filter dust at the high-pressure outlet of a compressor where small pressure drops can be tolerated. While this would require a dust-tolerant first pumping stage, it is conceivable that even the MOXIE scroll pump, if preceded by a commercial 25 μm mesh screen, would be insensitive to smaller particles. Such an assessment may be undertaken as part of the ground support aspect of the MOXIE investigation on Mars.

Conclusions: A great deal has been learned in the 20 years since NASA's Human Exploration programs

undertook the exploration of dust hazards on Mars. MER rovers completed much of the basic characterization of surface soils beginning in 2004, and the Phoenix mission specifically addressed both physical and chemical properties of the soil that could impact human exploration. MSL has further increased our understanding of mineralogical properties of the soil, and both experimental and theoretical progress has been made with respect to the airborne component. The upcoming MOXIE experiment will be the first to ingest large volumes of dust-laden martian atmosphere for processing, and will serve as a test case for translating our understanding into mitigation practices.

Acknowledgments: We gratefully acknowledge the support of NASA's HEOMD, STMD, and SMD in sending MOXIE to Mars. We are also particularly grateful: to Juan Agui of NASA GRC for educating us about filters and drawing our attention to slip factors at low pressure; to Jon Merrison and the crew at the Mars wind tunnel at Aarhus; and to the MOXIE development team led by the Jet Propulsion Laboratory.

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HUMAN MARS MISSION OVERVIEW AND DUST STORM IMPACTS ON SITE SELECTION. S. J. Hoffman¹, Aerospace Corporation, NASA Johnson Space Center, 2101 NASA Parkway, Houston, Texas 77058, stephen.j.hoffman@nasa.gov.

Introduction: NASA has begun a process to identify and discuss candidate locations where humans could land, live and work on the martian surface. This process is being carried out as a cooperative effort by NASA's Human Exploration and Operations Mission Directorate (HEOMD), responsible for future human mission preparations, and the Science Mission Directorate (SMD), responsible for the on-going Mars Exploration Program of robotic vehicles in orbit and on the surface of Mars. Both of these Directorates have a significant interest in this process, as these candidate locations will be used by NASA as part of a multi-year effort to determine where and how humans could explore Mars. In the near term this process includes: (a) identifying locations that would maximize the potential science return from future human exploration missions, (b) identifying locations with the potential for resources required to support humans, (c) developing concepts and engineering systems needed by future human crews to conduct operations within a candidate location, and (d) identifying key characteristics of the proposed candidate locations that cannot be evaluated using existing data sets, thus helping to define precursor measurements needed in advance of human missions.

At present NASA is assessing different options for conducting these future human missions to Mars by means of coordinated studies, the results of which are assembled into an end-to-end mission description collectively known as the Evolvable Mars Campaign (EMC) [1]. To guide studies associated with the EMC over the past several years, a set of ground-rules and assumptions were established to examine one particular approach to the human exploration of Mars. Principle among these ground-rules and assumptions that are relevant to EMC activities was a choice to concentrate all of the surface assets needed to support human exploration at a single location and then send future crews to this site for subsequent missions. This contrasts with the scenario considered in Design Reference Architecture 5.0 (DRA 5.0) [2] in which a campaign of three missions would send crews to different locations on Mars. One outcome of the choice to concentrate all surface assets at a single location is the concept of an Exploration Zone (EZ), describing the features of a surface location where the activities of the human crews will take place (Figure 1) [3]. An EZ is a collection of Regions of Interest (ROIs) that are located within approximately 100 kilometers of a centralized land-

ing area. ROIs are areas that are relevant for scientific investigation and/or development/maturation of capabilities and resources necessary for a sustainable human presence. The EZ also contains multiple landing sites within the centralized landing area, as well as a habitation area that will be used by multiple human crews during missions to explore and utilize the ROIs within the EZ. The "First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars," held on 27-30 October 2015, discussed 47 proposals for EZs and ROIs based on a set of criteria developed for our current understanding of both scientific and operational objectives for human missions [2]. Figure 2 shows the locations of these 47 proposed EZs.

Dust as a site selection factor: Dust will be one of several important factors considered when choosing from among proposed EZs: both the dust that is resident at the centralized landing sites and habitation zone when surface facilities are first established, and the potential for dust storms to originate or move through the site over time.

Each crew sent to the selected EZ will require several large landers to support their surface mission. Current EMC studies estimate three to four landers for each crew, depending on length of stay and equipment delivered [4]. Based on modeling of rocket plume interaction with surface materials (personal communication P. Metzger 2015), dust and other small, loose debris will be lofted by the terminal descent rocket engines of these landers, creating a surface hazard for other nearby assets. Depending on a number of factors, this surface material can achieve very high velocities and can be thrown several hundred meters from the lander. Consequently, it will be necessary to separate landing sites for all of the landers supporting a crew by a significant distance. Until better data is available, the working assumption for this separation distance is 1000 meters; yet it is also desirable to have all of these landers as close together as possible at the centralized landing site. Figure 3 illustrates how several potential landing sites could be arrayed around a specific surface location, taking this separation distance into account. Some of these landing sites will be used one time (e.g., delivering a surface habitat) and some can be reused once all useful material has been removed from a preceding lander. Figure 4 illustrates how the landing sites portrayed in Figure 3 could be transformed into a multi-use surface field station [4].

In addition to dust already resident at the site, site selection consideration must also be given to dust storms that could originate at or pass over the EZ. Dust storms over the centralized landing sites could delay the arrival of landers or the departure of the crew at the end of their surface mission. In addition, dust storms during the surface mission could impact the operation of surface equipment (discussed later by M. Rucker) or surface operations, such as EVAs or rover operations by the crew away from the central habitation zone. The lower portion of Figure 5 shows the frequency and duration of regional dust storms for several martian years [5]. The central portion of Figure 5 shows the duration of three different surface mission opportunities for two different propulsion types (a “hybrid” propulsion system and a “split” propulsion system). The message of this chart is that the orbit mechanics of getting to and from Mars will cause some crews to spend most or all of their surface mission on the ground during the most active dust storm season of a martian year. Figure 6 shows the pathways taken by the majority of these regional dust storms as they grow and/or move across the surface [5]. Figure 7 indicates where individual dust storms, regardless of size, have formed without necessarily moving away from these formation locations [5]. Overlaying Figures 6 or 7 with Figure 2 provides an initial indication of the dust storm potential at any one of these proposed EZs.

Conclusion: NASA is in the process of defining where and how human crews sent to Mars will land, live and work on the martian surface. Current assumptions presume a single site to which multiple crews will

be sent during the course of an exploration campaign. Many factors will go into selecting this single site, but a significant factor will be the dust that either resides at or is brought to this site by local environmental conditions. Understanding dust and dust storms will inform how to incorporate dust into site selection criteria.

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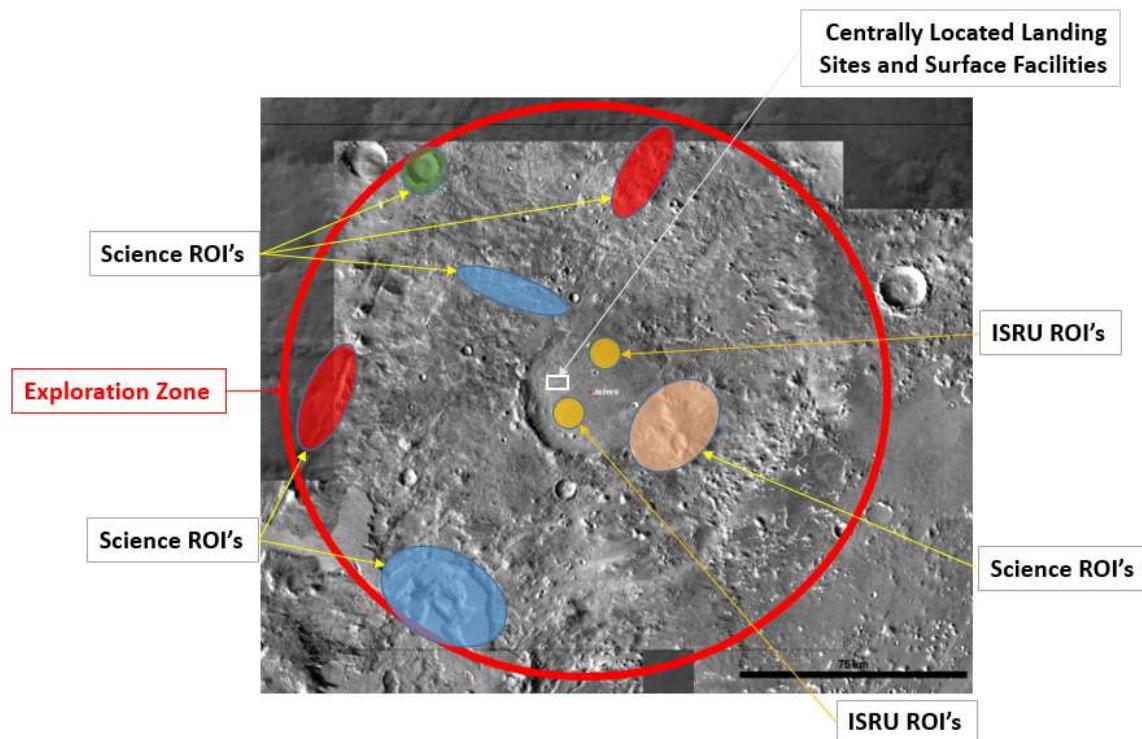


Figure 1. Example Mars Exploration Zone Containing Several Regions of Interest (ROI's) [3]

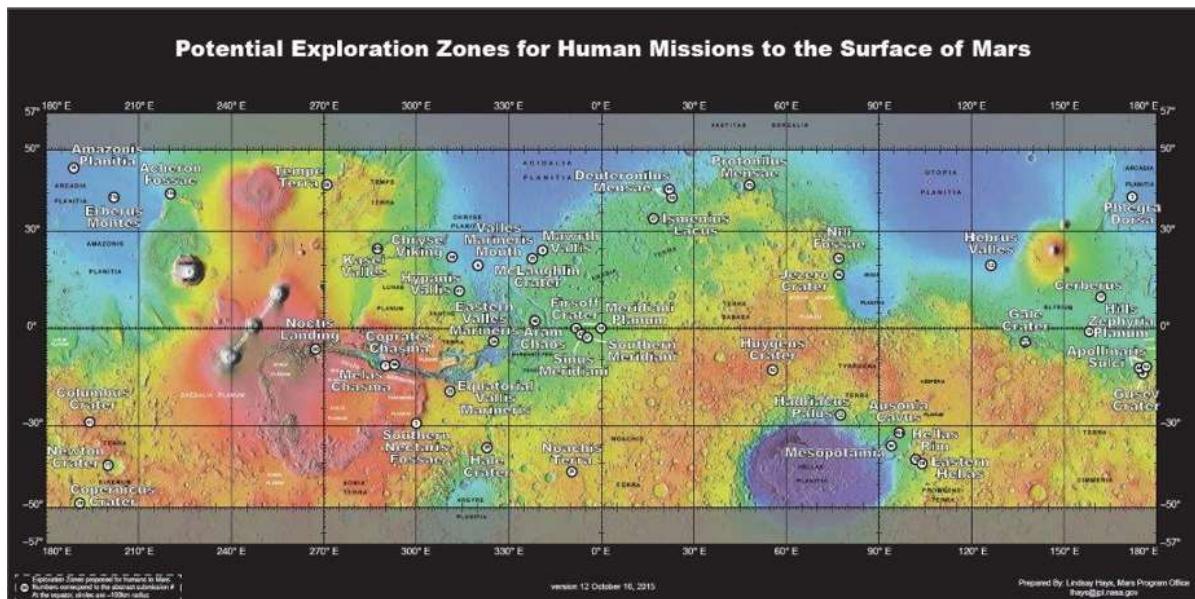


Figure 2. Exploration Zones Proposed at First EZ Workshop [3]

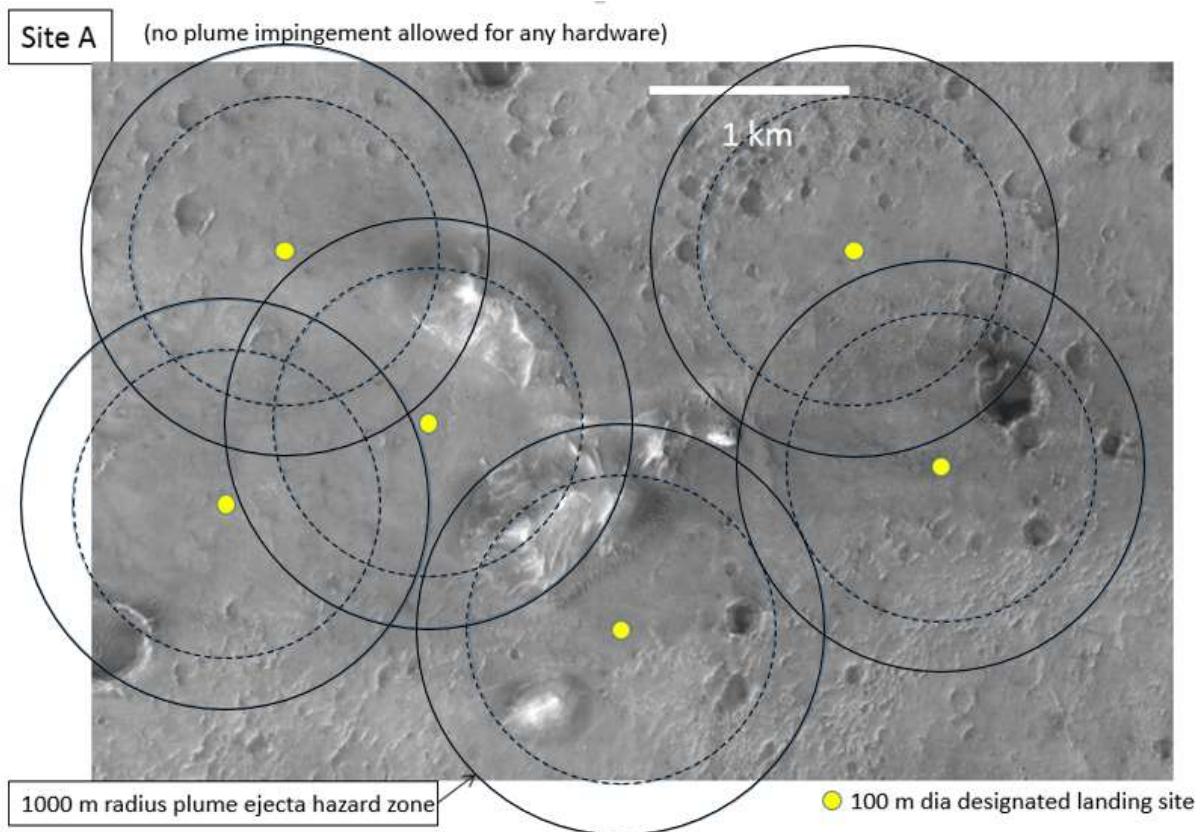


Figure 3. Example of Non-Interfering Landing Zones [4]

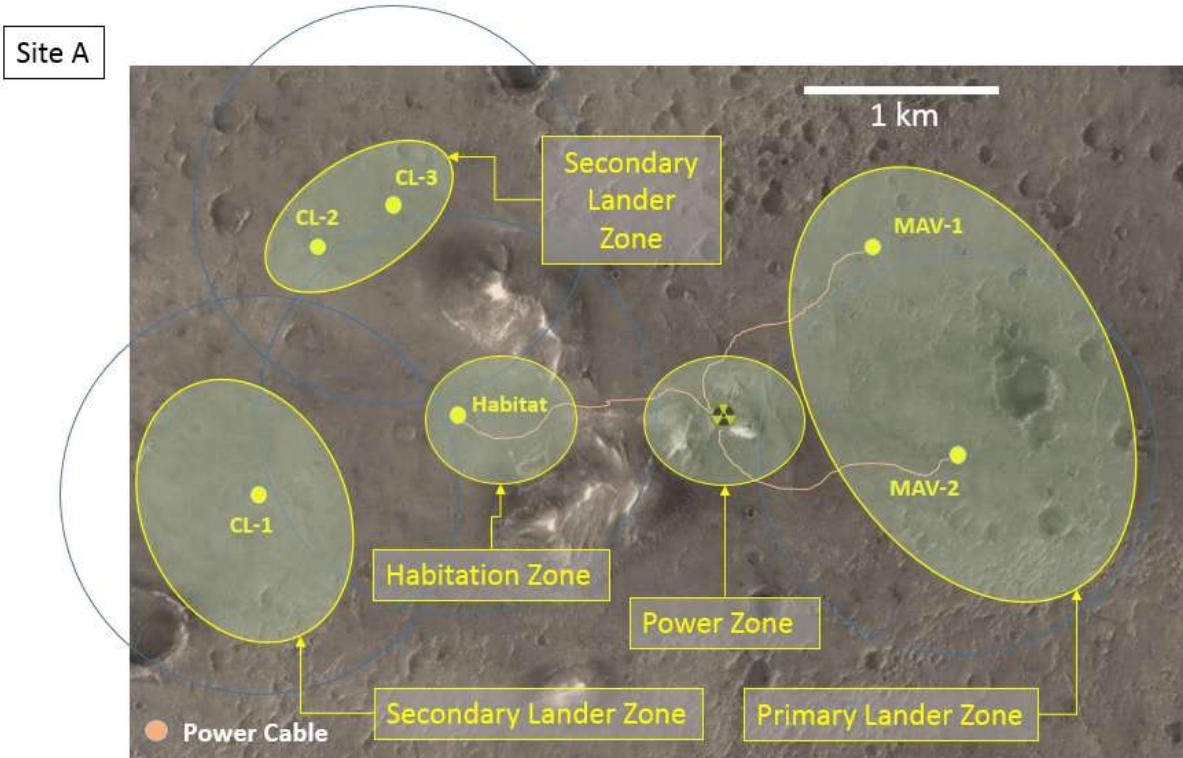
(plume impingement *allowed* for any "dead" hardware)

Figure 4. Example of Field Station Layout with Specific Utilization Zones Identified [4]

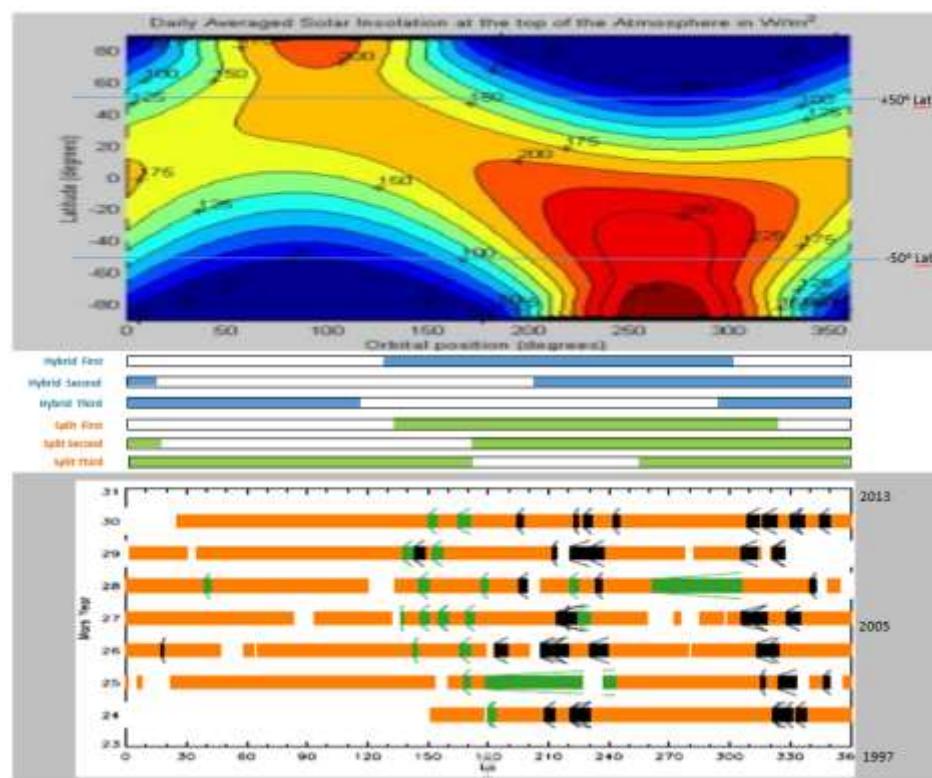


Figure 5. Relative Timing of Mars Surface Missions and Regional Dust Storm History [5,6]

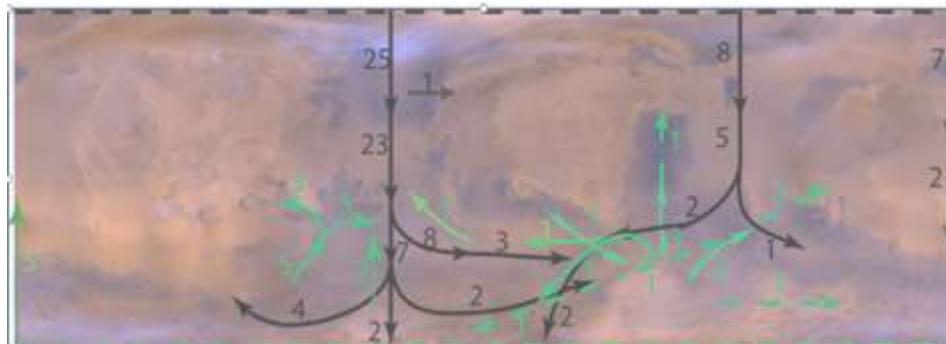


Figure 6. Pathways Followed by Regional Dust Storms [5]

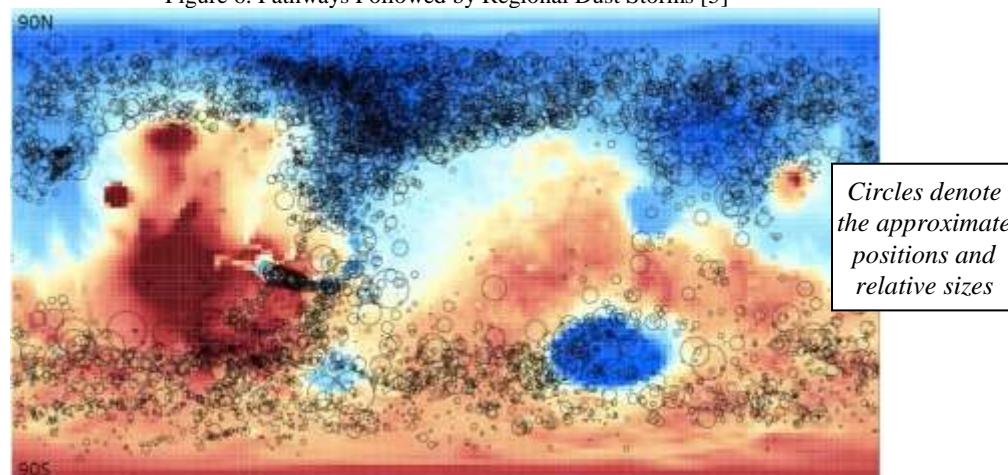


Figure 7. Spatial Distribution of Dust Storms Derived from 4 Mars Years of MARCI MDGMs [5]

MARS CLIMATE SOUNDER (MCS) OBSERVATIONS OF MARTIAN DUST—A DECADE-LONG RECORD. D. M. Kass¹, D. J. McCleese¹, A. Kleinböhl¹, J. T. Schofield¹ and N. G. Heavens², ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA (David.M.Kass@jpl.nasa.gov), ²Department of Atmospheric and Planetary Sciences, Hampton University, Hampton, VA, USA.

Introduction: Dust in the Martian atmosphere is ubiquitous. It is always present in some amount, at least in the lowest ~30 km of the atmosphere. However, it is not uniformly distributed in time or space. The dust plays a key role in the weather and climate of Mars (in some ways similar to water in the terrestrial atmosphere) [1]. Dust storms are the most noticeable expression of the atmospheric dust. They range in size from small, short lived local ones to global storms that envelop the entire planet.

Here we describe the Mars Climate Sounder (MCS) observations of atmospheric dust. The instrument has used infrared observations to produce an extensive climatology global of dust, including its vertical distribution. This provides a complementary dataset to visible imagery of dust storms.

Mars Climate Sounder (MCS): MCS is a passive 9-channel radiometer on the Mars Reconnaissance Orbiter (MRO) that is optimized for atmospheric observations [2]. It uses limb staring to obtain atmospheric profiles from the surface to ~80 km. The instrument consists of two telescopes that are slewed in azimuth and elevation to view the martian atmosphere in limb, nadir, and on-planet geometries (Figure 1). Each channel consists of 21 detectors, which observe the atmosphere simultaneously. Their angular separation provides an altitude resolution of ~5 km (half a scale height) at the Mars limb.



Figure 1: Mars Climate Sounder Flight Instrument

MCS has 8 mid- and far-infrared (IR) channels and one visible/near-IR channel, ranging from 0.3 to 45 μm . Three channels cover frequencies around the 15 μm CO_2 absorption band (A1, A2 and A3) and are used for pressure and temperature sounding. A channel centered around 22 μm (A5) gives information about dust opacity while a channel centered at 12 μm (A4)

covers an absorption feature of water ice. In the far-IR three channels (B1, B2, and B3) are designed to give information about surface temperature, water vapor abundance and dust and condensate opacities. IR observations have a significant advantage when looking at the dust. It allows observations of the dust to occur in both the daytime and the nighttime. Dust is also significantly less opaque at these wavelengths than at visible wavelengths. This is particularly important for the very long path lengths used in limb views.

MRO is in a sun-synchronous polar orbit [3] and provides global observations at 3 AM and 3 PM. In addition, MCS uses azimuth scanning to observe at four additional local times: 1:30 AM, 4:30 AM, 1:30 PM and 4:30 PM [4]. The polar MRO orbit covers all longitudes in 13 orbits (each separated by ~27°) over 24 hours 20 minutes. Each day, the ground track "walks" ~5° to the east.

The MCS retrieval algorithm [5, 6, 7] produces vertical profiles of temperature, dust and water ice extinction versus pressure (Figure 2). It also produces surface brightness temperatures. The retrievals are based on a modified Chahine method [8]. This is an iterative technique that simultaneously solves for all fields by minimizing the radiance residuals. The algorithm uses both limb observations and (where available) nearby on-planet or nadir observations. The on-planet observations are used for the surface temperature retrieval and to retrieve the temperature in the lower atmosphere when the limb is too opaque due to aerosols.

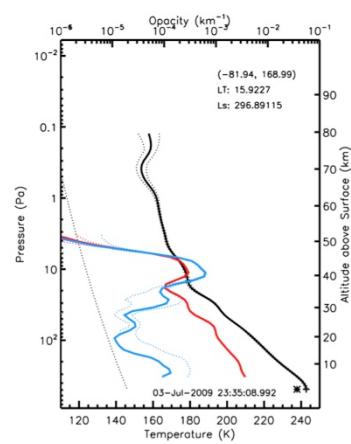


Figure 2: MCS retrieved profile of temperature (black), dust (red), water ice (blue) and surface temperature (*).

Aerosol radiative transfer is performed using both absorption and single scattering. The dust and water ice properties are determined with Mie calculations using a gamma distribution with an $r_{\text{eff}} = 1.06 \mu\text{m}$ for dust and an $r_{\text{eff}} = 1.4 \mu\text{m}$ for water ice.

All MCS profiles are publicly archived on PDS (http://atmos.nmsu.edu/data_and_services/atmospheres_data/MARS/aerosols.html).

Seasonal & Spatial Behavior of Dust: The MCS observations cover ~5.75 complete Mars Years (Figure 3). MCS has been collecting data since Ls 110° of MY 28 (September, 2006). The extended record provides a continuous and self-consistent climatology of temperature and dust (Figures 3 & 4). The dataset also provides the ability to investigate interannual similarities and differences.

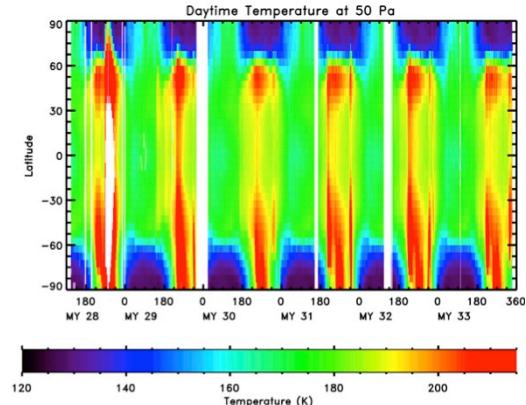


Figure 3: MCS zonal mean daytime temperature climatology at 50 Pa (~25 km) for the full MCS mission to date.

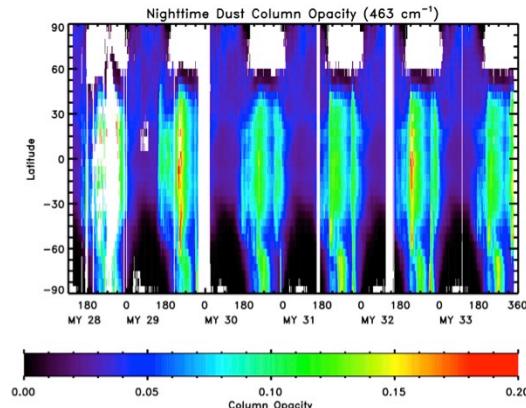


Figure 4: MCS zonal mean dust column at 22 μm (nighttime) for the full MCS mission to date.

Annual Dust and Temperature Trends. The Martian atmosphere exhibits two major seasons with regards to dust [1]. The first is northern spring and summer when the atmosphere is relatively clear and cold (Ls 0° to 180°). While there is less dust in the atmosphere, there is always some suspended dust. The other is the dusty or dust-storm season during southern spring and summer (Ls 180° to 360°) where the atmosphere is much warmer and all of the largest of dust storms occur.

The MCS observations clearly show the significant differences between the seasons in the temperature

structure (Figure 5) as well as the dust (Figure 6). The two are linked due to the dust heating the atmosphere, although the temperatures also respond to the eccentricity of the orbit and distance to the sun. The winter polar regions, with their extremely cold temperatures and extremely low dust amounts are apparent in both the temperature and dust fields.

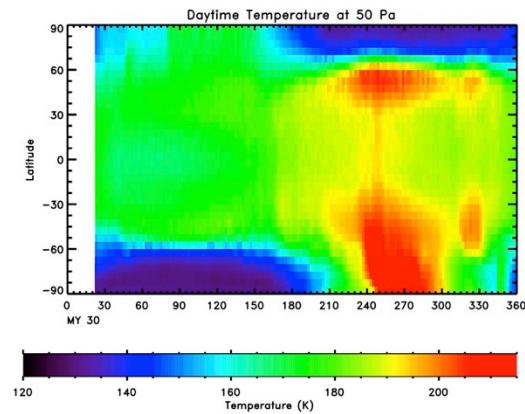


Figure 5: MCS zonal mean daytime temperature structure at 50 Pa (~25 km) for MY 30 (October 2009 to September 2011).

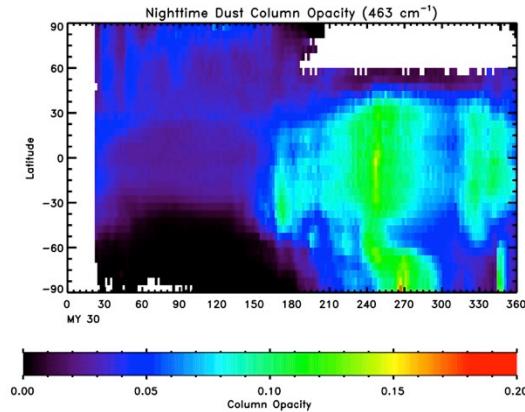


Figure 6: MCS zonal mean dust column at 22 μm for MY 30.

Large Dust Storms in MCS Data. Large regional and global dust storms show up in the MCS data in several ways. They produce a warming of the middle atmosphere as dust is lofted from the boundary layer (< 10 km) upwards [9]. The dust then absorbs sunlight and rapidly warms the relatively cool middle atmosphere. In addition to the direct warming from the dust, the atmosphere usually globally responds to the change in heating resulting in a modified global circulation. This results in changes to the temperature structure. MCS also directly observes the dust, either as a column amount [10] or at specific pressure levels/altitudes [9].

Figure 7 [9] shows a pattern of three large-scale regional dust events that the MCS data have revealed occur every Mars Year without a global dust storm during the dusty season. They are called the A storm, B storm and the C storm. The starting and ending dates, specific regions and peak heating of the storms vary somewhat from year to year. However, they always occur in the same order and at similar seasons. The dust field indicates that the southern hemisphere warming is due to direct dust heating while the warming in the northern hemisphere high latitudes associated with the A and C storms is not due to dust, but instead is a primarily a dynamical response to the southern hemisphere dust heating. The onset of these types of events is very rapid (often a few days) and the initial growth can be spectacular.

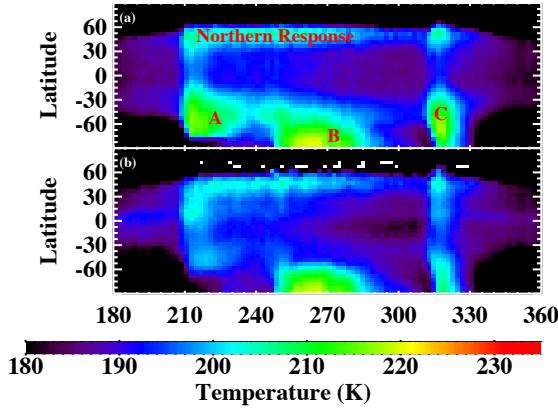


Figure 7: MCS zonal mean temperature structure at 50 Pa of the dusty season of MY 31. (a) Daytime and (b) Nighttime. The three large-scale regional dust storms are labeled along with the northern response.

In MY 29, but not in other years seen by MCS, a large-scale regional dust event also occurred starting around Ls 146° , although there are some earlier perturbations in the southern hemisphere. The strongest warming was in the northern hemisphere (the summer hemisphere), with peak temperatures of below those in the dusty season, although the increase is of a similar magnitude. The duration, $\sim 25^\circ$ of Ls, is similar to other large-scale regional events. The difference in temperature is probably due to the reduced insolation. Likewise, the stronger northern hemisphere warming is due to the season, with the sub-solar point in the northern hemisphere.

Global Dust Storms in MCS Observations. During the MCS observations, there is one example of a global dust storm, the most extreme of dust storm phenomena on Mars. The global dust storm of Mars Year 28 started in the second half of June 2007. Dust was lifted into the middle atmosphere and the atmospheric dust load-

ing increased on a planet encircling scale. By mid-July 2007 the dust storm was in full force, although dust was still not distributed homogeneously around the planet.

The Figure 8 shows a transect of retrievals of temperature (top) and dust extinction (bottom) along the dayside part of an orbit on July 12, 2007. Retrievals in high-dust conditions are possible between altitudes of 30-40 km, below which the atmosphere is nearly opaque in the limb, and ~ 80 km, which corresponds to the top of the MCS detector array. High dust opacities are found from the south pole to the northern mid-latitudes. Only beyond $\sim 50^\circ$ N the dust opacity decreases significantly.

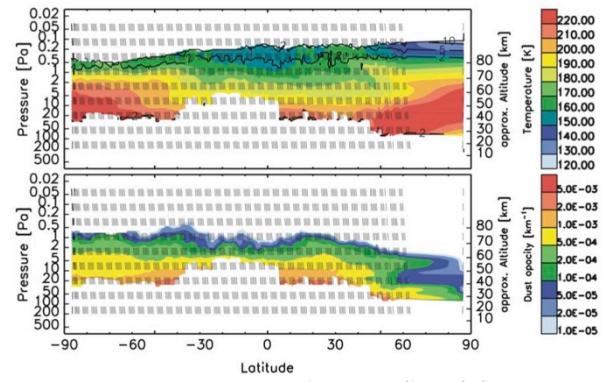


Figure 8: Temperature (top panel) and dust opacity (lower panel) vs. pressure as measured by MCS on the dayside part of one orbit on July 12, 2007 ($L_s = 274.7^\circ$, MY 28).

In the southern high latitudes dust is nearly homogeneously mixed throughout the altitude range in which retrievals can be performed. Even at 80 km the retrieved dust extinction is still $\sim 10^{-4}$ km $^{-1}$, and no fall-off of the dust profile below homogeneously mixed is discernible. The maximum altitudes at which significant dust opacities are observed to exceed the maximum altitudes at which TES limb observations detected dust in the global dust storm of 2001 [11]. Around the north pole the observed dust opacity is significantly lower than elsewhere on the planet. This is the region where the highest temperatures in the middle atmosphere are observed (~ 240 K). The absence of high dust opacities and solar heating suggests that the temperatures in this region result from adiabatic heating in the downwelling part of the overturning meridional circulation, which is strongly enhanced in global dust storm conditions.

Dust Vertical Profile: Systematic global daily profiles of dust are one of the key aspects of the MCS dataset. Comparisons with visible imagery reveal a complex relations between the visible appearance of dust storms, and the resulting vertical mixing of dust. In general, the MCS observations show that the dust is

not well mixed in the atmosphere [12], nor does it follow the classical Conrath profile [13].

Instead MCS showed that in many regions there is a relatively sharp upper boundary to the dust with essentially no dust above [14]. The boundary varies seasonally, but is only above 60 km during the largest dust storms. A second general feature of many dust profiles is a peak in the dust profile well above the surface [15]. The location and altitude of the elevated peak varies seasonally, however it is quite persistent. During most of northern spring and summer, the dust mass mixing ratio in the tropics has a maximum at 15–25 km above the local surface (Figure 9). While slightly more complex than the Conrath profile, it is possible to reasonably fit the MCS dust profiles with a combination of two distributions [15].

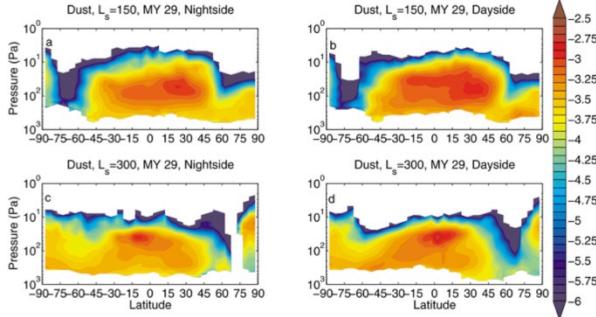


Figure 9: Log₁₀ zonal average dust density-scaled opacity ($m^2 \text{ kg}^{-1}$) as labeled. Contours are every 0.1 log units. White space below the colors indicates no data. White space above the colors and the darkest blue indicates density-scaled opacity below $10^{-6} m^2 \text{ kg}^{-1}$ (from [15]).

There are also extremely thick dust detached dust layers at quite high altitudes on rare occasions [12, 16]. These features have horizontal dimensions exceeding 1000 km, are at altitudes above 50 km (some extend to almost 80 km) and have mass mixing ratios exceeding 47 ppm (some exceed 100 ppm). Many of the events are associated with large dust storms [12]. This is not surprising since the circulation generated by the storm as well as the buoyancy from the local dust heating can loft dust to high altitudes. The layers are eventually spread in longitude into a thin haze (leading to the global middle atmosphere heating [9]). However, some of the events are instead associated with the largest volcanoes at seasons when dust storms are modest [16]. In this case they are presumably due to topographically driven flows that entrain dust and extend well beyond the tops of the volcanoes themselves.

Dust Particle Sizes: MCS is sensitive to the size of the dust particles in the atmosphere due to the broad range of wavelengths of its channels. Due to the limb geometry of the observations, it is most sensitive to the

particle sizes in the middle atmosphere (~15 km to the top of the detectable dust layer). The dust size distribution is described by the modified Γ distribution:

$$n(r) \sim r^a e^{-br^c}$$

where a (2.24), b (8.04) and c (0.647) are parameters describing the distribution of particle sizes (Figure 10) [6]. For the MCS parameters, the effective radius is ~1.06 microns and the effective variance is ~0.3. The MCS observations have not revealed significant variations in the dust size with season or location [17].

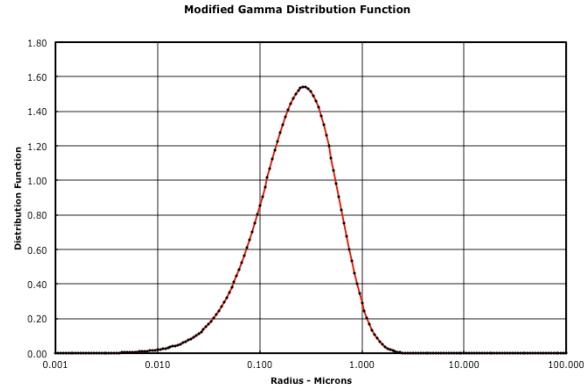


Figure 10: Particle size distribution with radius for the middle atmosphere dust ($r_{\text{eff}} \sim 1.06 \mu\text{m}$).

The MCS retrieval algorithm derives extinction (or opacity) per km^{-1} ($d_z\tau$) at $22 \mu\text{m}$ (463 cm^{-1}). It can be converted to opacity at visible wavelengths by multiplying by a factor of ~7.3 (depends on the dust spectral model) [6]. For the same assumptions of the size distribution and spectral properties, the MCS opacity per km can be converted into volumetric number density by $N_v [\text{m}^{-3}] = 2.3 \times 10^9 d_z\tau [\text{km}^{-1}]$ [15]. The mass mixing ratio is given by $q [\text{ppm}] = 1.2 \times 10^4 d_z\tau / \rho [\text{m}^2 \text{ kg}^{-1}]$ (where ρ is the density) [15].

Conclusions: Mars Climate Sounder has produced and is continuing to extend an almost six Mars year record of the atmosphere and atmospheric dust. MCS acquires daily global observations of dust profiles, thus providing a full and rich climatology of the dust for the entire planet.

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What Questions Should We Ask About The Health Effects Of Mars Dust? Lessons From The Lunar Dust Experience. R. L. Kerschmann, NASA Ames Research Center (Retired); NASA Engineering and Safety Center (consultant, rkerschmann@gmail.com)

Introduction: The first samples of dust from the Moon were returned to Earth aboard the Apollo 11 Command Module on July 24, 1969. Subsequent manned Apollo missions, as well as the robotic Soviet Luna series [1] added to the collection. Accounts of the Apollo astronauts raised the possibility of potential health problems from dust even on their short periods on the lunar surface, but a serious investigation of the toxicological effects of the samples of dust did not commence in earnest until NASA began to consider a return to the Moon. A series of workshops held on the topic at NASA Headquarters and various NASA centers started in 2004, culminating in the NASA Engineering and Safety Center (NESC) Lunar Dust Workshop held at Ames Research Center in 2007 [2]. The subsequent work on experimental toxicological effects of lunar dust using simulants and actual Apollo samples was led by the NASA Office of the Chief Toxicologist at the Lyndon Johnson Space Center in Houston (JSC) with significant contributions on the topic made by the lunar dust lab at Ames Research Center (ARC), as well as at Glenn Research Center (GRC) and other NASA facilities and universities. A comprehensive compilation of findings from this initial phase of research has been published [3], and includes some references to possible Mars dust effects. The present abstract summarizes and contrasts what we've learned from lunar dust research with what we know about Mars dust simulants and data from in situ robotic examinations on Mars, and gives some initial thoughts on what we will need to learn about Mars dust in order to assure safe manned missions in the future, and appropriate handling on Earth of any Mars soil sample return materials.

Toxicological Essentials of Lunar Dust: From studies on actual lunar dust (Figure 1), lunar dust simulants, and terrestrial dust known to be toxic, some key findings have been established about lunar dust, which are listed along with significant terrestrial analogues in the Table.

To summarize, lunar dust mineralogic properties suggests toxicity in that it displays a high size fraction in the respirable range, a jagged morphology, high surface to volume ratio, and likely high surface chemical reactivity, and contains heavy metals, all of which could contribute to toxicity. Experiments show that it generates an inflammatory response in experimental animals. Consequently, a preliminary toxicologic exposure limit has been established for lunar dust of 0.5

mg/m³, which is intermediate in toxicity between freshly fractured silica dust and “nuisance” dusts such as titanium oxide. However, virtually nothing is known about the long-term effects of pulmonary and other modes of exposure to lunar dust. This is an important focus of concern because some terrestrial analogues such as silica (quartz) dust cause major chronic pulmonary disease, and this has profound implications for the human exploration of space and planetary environments.

Studies of lunar dust may be extrapolated to the nature of dusts from other airless bodies such as large asteroids where, like on the moon, the impact of micrometeorites is the predominant process producing dust. However, planets with even thin atmospheres such as Mars are likely to produce very different types of dust due to chemical interactions and particle weathering (Figure 2). The distinction between these dusts and the impact on mitigation strategies will influence research efforts and mission designs for some time to come.

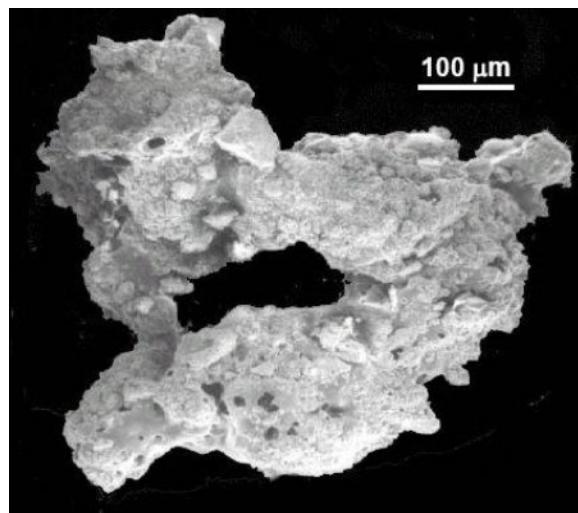


Figure 1. A large lunar dust agglutinate particle, displaying jagged morphology and high surface to volume ratio. (image credit: David S. McKay, NASA/JSC)

Apollo Mission Dust Impact and Possible Relevance to Mars Missions: The 2015 NASA Human Research Program evidence report on celestial dusts includes reports of Apollo astronaut experiences with lunar dust exposure and equipment effects. Dust contamination on surfaces of EVA suits was extensive, and allowed dust to gain entry to the atmosphere of mission

vehicles. This became a significant problem during the return to Earth when the Lunar Excursion Module returned to microgravity and dust became airborne in the vehicle. Apollo crew report difficulty with dust in their eyes and entering their upper respiratory tracts, producing impairment of vision and irritation of the sinuses. All these issues will apply to Mars dust management, but because of what we know of the divergent chemistries of the two dusts, Mars dust is highly oxidized may be more acutely irritating to mucus membranes of the respiratory tract and other systems, and less likely to be passivated by entry into the crew cabin atmospheres.

Furthermore, on the moon the amount of dust entering habitation compartments and ensuing problems seem to have been somewhat landing site-dependent, with Apollo 14 reporting less dust cloud formation on landing and also fewer subsequent problems with dust inside the vehicles. However, because all evidence points to extensive distribution of fine dust due to global-scale dust storms, at least for Mars the smaller (and likely respirable) particles may be uniformly distributed across potential landing sites [3].

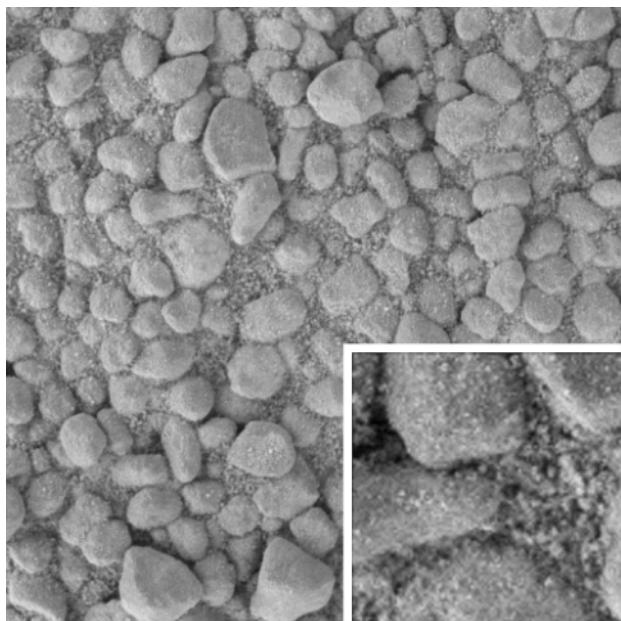


Figure 2. Mars soil imaged by the Mars Exploration Rover Opportunity, showing the rounded, weathered grains. Much smaller fine grains are seen in the inset. The larger view captures an area on the ground of approximately 2cm x 2cm. (edited from <http://www.marsroverblog.com/lanikai-under-the-microscope.html>)

Regardless, manned Mars mission designers will have benefited from the Apollo experience and from all

the science that has been performed on samples in the repository.

Dust problems on the Moon were unexpected, and could have been mission limiting if surface operations had lasted longer. While we do not have the advantage of curated dust samples from Mars, we know enough of the general chemistry from in situ measurements (including from Viking missions), from SNC Mars meteorites, and from subsequent remote sensing to know that Mars dust will be of a fundamentally different mineralogy than lunar dust. While lunar dust may be seen as glass-like, Mars dust is based on salts that are highly oxidized. In fact, because of the high oxidation, Mars dust has been compared to powdered bleach.

From what we know of the toxicology of such terrestrial commercial analogues, because of its highly oxidized state, Mars dust might be suspected to cause rapid inflammatory reactions in the upper airways and digestive tracts of crew members. In sufficient dose of dust, these reactions may be serious and even mission-threatening.

Mars dust is known to contain heavy metals that can be highly toxic, but it remains uncertain in what concentrations or chemical state these metals may be. The highly oxidized state of Mars dust can convert otherwise benign materials into toxic forms. For example, it remains an open question how much of the chromium known to be in the Martian soil is the highly toxic hexavalent form, which may be produced by the oxidative environment. This led the National Research Council to recommend that testing for this toxin be included on a robotic precursor mission [6].

There is now enough knowledge, and thanks to the Apollo missions, even direct human contact experience with celestial dusts to frame key questions that will direct research into human health effects and ultimately mitigation strategies.

Questions to address Mars dust health effects: The 2007 NESC Lunar Dust Workshop Medical Splinter Group [2] formulated questions regarding lunar dust risk, most of which fully apply to Mars dust. These questions can constitute a starting point for Mars Dust health effects discussions to generate recommendations for toxicologic research and mitigation efforts:

A. What is the full range of routes/anatomical sites of dust exposure that we need to be concerned about?

B. What characteristics/properties of lunar dust make it a hazard to crewmember health?

C. What is the full range of possible medical, physiological and pathological processes/ responses that we need to consider as a consequence of lunar dust exposure?

D. Which medical/physiological processes are reversible? If reversible, what is the time course? Which processes are irreversible?

E. What operational scenarios need to be considered to provide a framework for envisioning lunar dust exposure to astronauts?

F. What are the “expected” modes/sites of crew member exposure to lunar dust, given the nominal operational scenarios envisioned?

G. What do we need to consider in terms of “unexpected” modes of crew member exposure?

H. Can we anticipate that 1/6th gravity, radiation, and other special space environmental effects (possible reduced atmospheric pressure, reduced ppO₂) may have an exacerbating/multiplicative health impact on the physiological/medical effects of lunar dust?

I. What simple techniques for crew member “clinical status evaluation” in response to lunar dust exposure are already available, and what advanced technologies might be needed?

J. What countermeasures do we need to consider providing to remediate at least some of the effects of lunar dust exposure, both anticipated and unanticipated?

K. What treatment of lunar dust-induced disease do we need to anticipate and test?

L. To what extent are the planned “classical” toxicology studies sufficient to define all of the potential medical/physiological impacts of lunar dust exposure? What supplemental studies need to be incorporated into the roster of work that is already slated to be tackled? Where are the knowledge gaps that currently contribute to the uncertainties in lunar dust toxicity? How are those gaps best filled with targeted research?

M. What custom/special supportive facilities/technologies/methods need to be developed in order to preserve, transport, and administer lunar dust research materials: E.g. Native lunar dust and high-fidelity simulants

will passivate during transport and delivery, reducing the relevance of any testing of this material.

N. What safety procedures must be developed for handling lunar dust samples in analytical laboratories? Lunar dust and high-fidelity simulants are laboratory materials for which material safety data sheets and other safety protocols need to be developed in advance of handling in lunar and terrestrial laboratories.

O. What is the appropriate panel of mineral particulate control materials to be used for research into the toxicity of lunar dust?

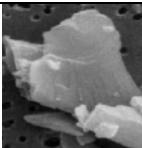
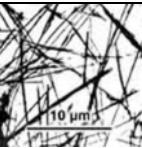
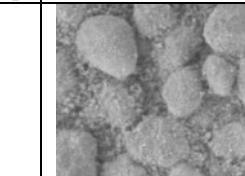
P. What are the dust risk interfaces between EVA suits and the human body? Risk of untoward cutaneous effects from lunar dust entry into the suit depends on body site-specific factors in combination with suit factors.

Conclusion: Nearly all of the areas of prior inquiry into lunar dust health effects are relevant to work that needs to be performed on Mars dust, dust simulants, and terrestrial analogs. Therefore, it is recommended that research programs for health effects of Mars dust be based on the 2007 NESC Lunar Dust Workshop.

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Table. Comparison of Toxicologic Properties of Terrestrial Toxic Dusts, Lunar Dust, and Mars Dust.

	Silica	Asbestos	Lunar Dust	Powdered bleach (Calcium hypochlorite and other compo- nents.)	Mars Dust
Major Risk	Pulmonary fibrosis	Lung cancer	Unknown	Upper airway and digestive track inflammation; severed edema: ingestion or inhalation may be fatal.[4]	Unknown
Appearance.					
Particle Size Distribution	Known in a wide variety of industrial settings.	Known in a wide variety of industrial settings.	Known for multiple Apollo landing sites.	Size profiles for commercial products are proprietary.	Unknown.
Respirable size fraction	High	High	High (2%) [3]	Low, due to manufacturing process. However, chlorine gas may be generated which can reach the alveoli.	Unknown
P.E.L.	0.1 mg/m ³ (quartz)	0.1 fiber/ cc air/ 8 hr.	0.5 mg/m ³ (episodic over 6 months)	Variable due to differences in ingredients of commercial formulations.	Unknown
Re-entrant morphology?	Yes	Yes	Yes	Low, due to manufacturing process.	Low, due to weathering.
Surface/Volume Ratio	High	High	Very high in the agglutinate fraction	Low	Low due to weathering.
Surface reactivity	High in fresh-fractured	Low due to atmospheric exposure	High, in situ, due to vacuum and radiation	High due to oxidative chemistry.	Probably high due to oxidative chemistry.
Heavy metal content.	Variable	Low in pure material.	Variable due to landing site	Low, due to manufacturing process.	Possible toxic concentrations, e.g. hexavalent chromium.
Acute toxicity.	High	Low	Mild	High	Unknown
Chronic toxicity	High	High	Unknown	Low	Unknown
Other comment	May cause subacute injury in high concentrations.	Requires water for formation. Not found on Moon.	Suspected to be rapidly passivated on exposure to atmosphere.	Chlorine generated on exposure to water.	Probably passivates in moist atmospheres. May release chlorine gas on exposure to acidic solutions.

SIMULATION OF THE SMALL-SCALE DUST ACTIVITIES AND THEIR MUTUAL INTERACTIONS ON THE ATMOSPHERIC DYNAMICS USING A HIGH-RESOLUTION MARS GENERAL CIRCULATION MODEL. T. Kuroda^{1,2} and M. Kadowaki³, ¹National Institute of Information and Communications Technology (4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795 Japan, tkuroda@nict.go.jp), ²Department of Geophysics, Tohoku University (6-3 Aramaki-aza-Aoba, Aoba, Sendai 980-8578 Japan), ³Nuclear Science Research Institute, Japan Atomic Energy Agency (2-4 Shirane Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195 Japan).

Introduction: It is well known that there are various scales of dust activities, from the small-scale ‘dust devil’ [1] to the global dust storm [2], in the Martian atmosphere. The dust cycle on Mars is similar to the water cycle on Earth; in which airborne dust absorbs solar radiation and emits in the infrared, and the created local heating and cooling affect the atmospheric dynamics at various scales [3].

Regional dust storms occur due to the strong wind stress on surface [4], mainly at sloped regions and edge of seasonal polar caps [5] possibly induced by thermal tide [6] and frontal activities [7]. Also, dust is thought to be continuously supplied to the atmosphere by convective activities [8]. Recent studies indicate that such dust activities may induce the gravity waves (GWs) which strongly affect the dynamical features in thermosphere [9,10].

The theories of dust lifting (effects of surface wind stress and small-scale convection) have been parameterized and implemented into Mars general circulation models (MGCMs) [11-13]. But the mutual impacts between small-scale dust activities and global-scale dynamical features have not been well investigated as the horizontal resolutions of those MGCMs were low (grid interval of $\sim 5^\circ$ or ~ 300 km). In this study we implement the parameterizations into our high-resolution (T106, grid interval of $\sim 1.1^\circ$ or ~ 67 km) MGCM [14,15] to investigate the mechanisms of the occurrence of local dust storms and their impacts on the generation of GWs.

Model Description: Our MGCM, DRAMATIC (Dynamics, RAdiation, MAterial Transport and their mutual Interactions) has been developed based on the CCSR/NIES/FRCGC MIROC model [16] with a spectral solver for the three-dimensional primitive equations, on which the physical parameters (surface topography, albedo, thermal inertia) and processes (condensation of CO₂ gas, snowfall and generation of seasonal polar caps) have been implemented [17,18]. In the vertical direction, the model domain extends from the surface to ~ 80 – 100 km and is represented by 49 sigma-levels. The MGCM utilizes the LTE radiation scheme for CO₂ molecules in infrared (including the 15 μm band) and near-infrared, and radiative effects of dust from ultraviolet to far-infrared.

In this study we have implemented the dust lifting

scheme which accounts for the lifting, transport by local winds and gravitational sedimentation [19]. The change of dust distribution by the scheme is interactive with the radiative calculations, which provides the feedback to the atmospheric wind and temperature. Dust is injected into the atmosphere by the parameterizations of two processes: wind stress and convection.

Wind stress parameterization. The wind stress for the dust lifting, τ , is defined as follows:

$$\tau = \rho C_M^* \left(\frac{ku(z_1)}{\ln(z_1/z_0)} \right)^2,$$

Where ρ is the atmospheric density, $u(z_1)$ is the wind velocity at the lowest layer of atmosphere ($z_1 \sim 50$ m height), z_0 is the surface roughness [20], and $k = 0.4$ is the von Karman’s constant. C_M^* is the stability function of momentum which is a function of the Richardson number Ri . C_M^* is defined as follows [21],

$$C_M^* = \frac{1}{(1 + 10Ri/\sqrt{1 + 5Ri})^2} \quad (Ri > 0),$$

$$C_M^* = 1 - 64Ri \quad (Ri \leq 0).$$

The dust flux from the surface due to wind stress, F_{wsl} (in kg m⁻² s⁻¹), is defined as follows [11],

$$F_{wsl} = \max \left[\alpha_N \frac{2.61}{g\sqrt{\rho}} (\sqrt{\tau} - \sqrt{\tau^*})(\sqrt{\tau} + \sqrt{\tau^*})^2, 0 \right],$$

where g is the gravitational acceleration, α_N is the lifting efficiency and τ^* is the threshold wind stress for lifting. In this study α_N and τ^* are set to be the order of 10⁻⁷ m⁻¹ and 0.05 N m⁻², respectively.

Convective parameterization. The dust flux from the surface due to small-scale convective motions (dust devil), F_{dda} (in kg m⁻² s⁻¹), is defined as follows [11],

$$F_{dda} = \max[\alpha_D \tau_H (1 - b), 0],$$

where α_D is the lifting efficiency (set to be the order of 10⁻¹⁰ kg J⁻¹ in this study), and τ_H is the sensible heat flux on the ground. b is defined as follows [8],

$$b = \frac{(1 - \zeta^{\kappa+1})}{(1 - \zeta)(\kappa + 1)\zeta^\kappa},$$

where ζ is the ratio of pressure at the top of planetary boundary layer (PBL) divided by the surface pressure, and $\kappa = R/c_p$ is the specific gas constant divided by the specific heat capacity at constant pressure. τ_H (in W m^{-2}) is defined as follows,

$$\tau_H = \rho c_p \sqrt{C_M^* C_H^*} \left(\frac{k}{\ln(z_1/z_0)} \right)^2 u(z_1)(\theta_0 - \theta_1),$$

where θ_0 and θ_1 are the ground surface temperature and the potential temperature of the lowest layer of atmosphere, respectively. C_H^* , the stability function of heat, is defined as follows [21],

$$C_H^* = \frac{1}{(1 + 15Ri/\sqrt{1 + 5Ri})^2} \quad (Ri > 0),$$

$$C_H^* = 1 - 16Ri \quad (Ri \leq 0).$$

With the fluxes $F_{wsl} + F_{dda}$, dust is supplied from the ground surface up to the top of PBL uniformly. The vertical extent of PBL is assumed from the static stability S defined with the vertical temperature gradient dT/dz as follows,

$$S = \frac{dT}{dz} + \frac{g}{c_p}.$$

The altitude at which the static stability abruptly changes is assumed as the top of the PBL. Dust is assumed to be able to lift from the ground infinitely, and no dust lift occurs from the seasonal polar caps.

Gravitational sedimentation of the airborne dust particles is implemented into the model assuming the pure CO_2 atmosphere [18,22]. The density and average radius of dust are set to be 2500 kg m^{-3} and $\sim 1.26 \mu\text{m}$ (to be consistent with the dust particle size assumed in the radiation scheme [23]), respectively.

Preliminary Results: Figures 1-3 show the simulated day-mean dust opacity (in visible wavelength) and dust fluxes from the surface due to wind stress (F_{wsl}) and convection (F_{dda}) at $L_s=180^\circ$ (northern autumn equinox). The dust opacity is in overall comparable to the past observations (e.g. MGS-TES). The lifting by wind stress tends to occur on slopes, especially around the mountains (Olympus and Elysium) and northern edge of the Hellas Basin. The lifting by convection uniformly occurs in low- and mid-latitudes.

In the presentation we plan to show more detailed results and analyses, e.g. results in other seasons/seasonal variances of dust conditions, key meteorological features for the lifting of dust, and generation of GWs due to local dust storms.

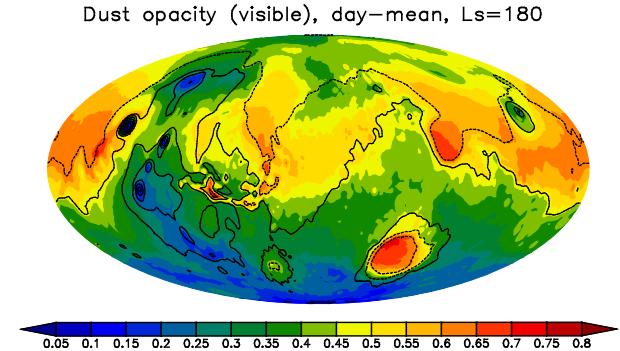


Figure 1: Horizontal distribution of day-mean dust opacity (in visible wavelength) simulated with our T106 MGCM at $L_s=180^\circ$ (northern autumn equinox).

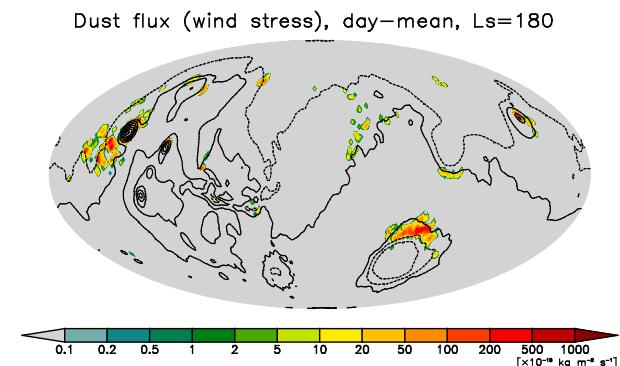


Figure 2: Same as Figure 1 but the distribution of F_{wsl} (in $\text{kg m}^{-2} \text{s}^{-1}$).

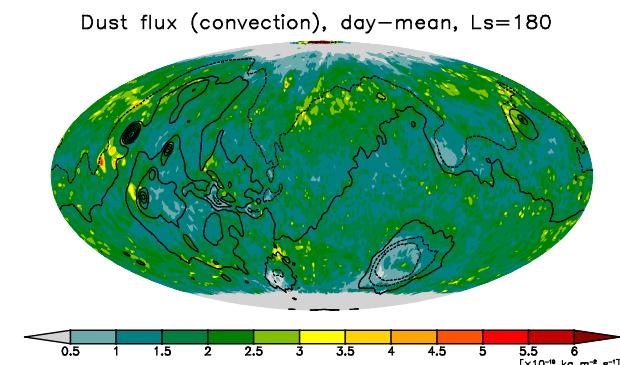


Figure 3: Same as Figure 1 but the distribution of F_{dda} (in $\text{kg m}^{-2} \text{s}^{-1}$).

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DUST IN THE ATMOSPHERE OF MARS AND ITS IMPACT ON HUMAN EXPLORATION: A REVIEW OF EARLIER STUDIES. Joel S. Levine, Department of Applied Science, The College of William and Mary, P. O. Box 8795, Williamsburg, VA 23187-8795 and NASA Engineering and Safety Center (NESC) Robotic Spacecraft TDT, jslevine@wm.edu

Introduction: The impact of Mars atmospheric dust on human exploration has been a concern of engineers, medical researchers and mission planners for many years [1-3] (For example, the National Research Council (2002) [1] and the Mars Exploration Program Analysis Group (2005) [2,3]. The impact of dust in the atmosphere of Mars on human exploration is a multi-faceted problem, including (1) The impact of Mars atmospheric dust on human health, (2) The impact of Mars atmospheric dust on surface systems, e.g., space-suits, habitats, mobility systems, (3) The impact of Mars atmospheric dust on human surface operations, and the (4) The impact of Mars atmospheric dust on the near-surface electric field.

National Research Council: Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (2002) [1]: A Review

The NRC report discusses four problem areas of chemical interaction of Martian soil and airborne dust with astronauts and critical equipment, (chapter 4) which is summarized here.

(1) Toxic Metals: Hexavalent Chromium

Airborne dust and soil on Mars could contain trace amounts of hazardous chemicals, including compounds of toxic metals that are known to cause cancer over the long term if inhaled in sufficient quantities. For example, Mars Pathfinder measurements established that chromium is present in Mars soil. Chromium contained in naturally occurring geologic materials is primarily in a trivalent state (a +3 ion), which is a stable form of chromium and minimally toxic to humans. However, hexavalent chromium (Cr VI, a +6 ion), a highly toxic form of chromium, is rarely encountered in natural geologic materials. If even a modest fraction of the chromium present in the Martian soil and airborne dust is hexavalent chromium (more than 150 parts per million), it would pose a serious health threat to astronauts operating on the surface of Mars. The NRC report outlines three reasons for being cautious about the presence of hexavalent chromium on Mars.

(2) Astronaut Exposure to Inhaling Airborne Particulate Matter

(3) Biological Degradation and Equipment Corrosion
There are high concentrations of sulfur and chlorine in Martian soil. This implies that both the soil and airborne dust might be acidic, which could pose a hazard if they are introduced into an astronaut habitat. When inhaled by astronauts, acidic soil and dust could degrade their lung tissue and, if humidified and allowed to penetrate control units inside the habitat, could cor-

rode sensitive critical equipment, such as control circuits.

(4) Hazardous Organic Compounds and Atmospheric Gases

Certain organic compounds and atmospheric gases, perhaps produced by photochemical reactions in the atmosphere, can be highly toxic to humans.

Mars Exploration Program Analysis Group: An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars (2005) [2]: A Review

The MEPAG (2005) report, An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars lists ten prioritized investigations to reduce the risk of the first human mission to Mars [2]. The prioritized investigations in this report are based on Goal IV: Preparation for Human Exploration of the MEPAG Mars Science Goals, Objectives, Investigations, and Priorities: 2015 (MEPAG, 2015) [3]. The following four highest priority investigations are of indistinguishable priority order [2]:

1A. Characterize the particulates that could be transported to mission surfaces through the air (including both natural aeolian dust and particulates that could be raised from the Martian regolith by ground operations), and that could affect hardware's engineering properties. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.

1B. Determine the variations of atmospheric dynamical parameters from ground to >90 km that affect Entry, descent and landing (EDL) and take-off, ascent and orbit insertion (TAO) including both ambient conditions and dust storms.

1C. Determine if each Martian site to be visited by humans is free, to within acceptable risk standards, of replicating biohazards which may have adverse effects on humans and other terrestrial species. Sampling into the subsurface for this investigation must extend to the maximum depth to which the human mission may come into contact with uncontained Martian material.

1D. Characterize potential sources of water to support ISRU (In Situ Resource Utilization) for eventual human missions. At this time it is not known where human exploration of Mars may occur. However, if ISRU is determined to be required for reasons of mission affordability and/or safety, then, therefore the following measurements for water with respect to ISRU usage on a future human mission may become necessary (these options cannot be prioritized without applying

constraints from mission system engineering, ISRU process engineering, and geological potential): The following remaining six investigations are listed in order of descending priority [2]:

2. Determine the possible toxic effects of Martian dust on humans.
3. Derive the basic measurements of atmospheric electricity that affects TAO and human occupation.
4. Determine the processes by which terrestrial microbial life, or its remains, is dispersed and/or destroyed on Mars (including within ISRU-related water deposits), the rates and scale of these processes, and the potential impact on future scientific investigations.
5. Characterize in detail the ionizing radiation environment at the Martian surface, distinguishing contributions from the energetic charged particles that penetrate the atmosphere, secondary neutrons produced in the atmosphere, and secondary charged particles and neutrons produced in the regolith.
6. Determine traction/cohesion in Martian soil/regolith (with emphasis on trafficability hazards, such as dust pockets and dunes) throughout planned landing sites; where possible, feed findings into surface asset design requirements.
7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

Of the ten investigations, four investigations (Priority 1, 2, 3, and 7) involve the impact of atmospheric dust on human exploration and are discussed here [2]:

Priority 1A. Characterize the particulates that could be transported to mission surfaces through the air (including both natural Aeolian dust and particulates that could be raised from the Martian regolith by ground operations), and that could affect hardware's engineering properties (This investigation is one of four investigations assessed as highest priority).

Characterization of the Martian dust (including particulates raised from the regolith during surface operations) is a relatively high priority item. Such investigations are important for mission hardware design to mitigate the effects of abrasion, adhesion, corrosion, and damage from potential electrical discharge, or arcing, as well as to mitigate potential adverse effects on human health from dust inhalation, and exposure).

The Martian atmosphere is the origin of many possible hazards to both humans and equipment. The unknown thermodynamic properties of the bulk gas fluid, including unexpected turbulence in the near-surface boundary layer [4], represent risks during vehicle entry, descent and landing (EDL). Major dust storms may also affect EDL and adversely affect a human explorer's ability to perform extravehicular activities (EVAs). More recent laboratory [5] and terrestrial desert studies [6] indicate that triboelectric effects within dust storms

can give rise to large electric fields which might prove hazardous to both explorers and equipment.

Apollo astronauts learned first hand how problems with dust impact lunar surface missions [7-12]. After three days, lunar dust contamination on EVA suit bearings led to such great difficulty in movement that another EVA would not have been possible. Dust clinging to EVA suits was transported into the Lunar Module [13]. During the return trip to Earth, when micro gravity was reestablished, the dust became airborne and floated through the cabin. Crews inhaled the dust and it irritated their eyes [14]. Some mechanical systems aboard the spacecraft were damaged due to dust contamination. Study results obtained by robotic Martian missions indicate that Martian surface soil may be oxidative and reactive [15]. Exposures to the reactive Martian dust may pose an even greater concern to crew health and integrity of the mechanical systems.

As NASA embarks on planetary surface missions to support its Exploration Vision, the effects of these extraterrestrial dusts must be well understood and systems must be designed to operate reliably and protect the crew in the dusty environments of the Moon and Mars [1].

Abrasive properties of dust accumulating on surfaces and penetrating systems could lead to failure of air generation and delivery, carbon dioxide removal, fire detection (causing false alarms) and suppression, EVA suits, rovers, windows, visors, and optics. If critical life support systems completely fail, rescue or mission termination is not feasible due to the laws of orbital mechanics.

Dust Inhalation and Ingestion

Dust Toxicity to Crew:

Risk Statement: If the crew inhales or ingests dust, adverse health effects may result. Consequences: mild illness to loss of crew. Dust in the human environment resulting from human interactions of the Martian surface may be inevitable, and dust mitigation strategies for the human habitation modules are currently not developed.

Context: Dust transported into the habitat via leakage or EVA suits may decrease effectiveness of air, water and food management systems and lead to inhalation and ingestion of dust particles. The properties of soils, which can produce medical impact to humans on planetary surfaces, include both physical and chemical reactions with skin, eyes and mucous membranes.

Sub-micron particles could lead to effects similar to black lung disease. Peroxide is chemically reactive. Martian dust may also contain toxic materials and trace contaminants. Very small particles, especially in low gravity, stay in the atmosphere longer and increase chances of inhalation. Electrostatically charged particles adhere to tissue and create bronchial deposits. Possible toxicity (acute pulmonary distress and sys-

temic effects) caused by nanoparticles, if present in the Martian atmosphere, should be considered as an added risk.

Since the site specific lung deposition of inhaled medical aerosol particles depends, among other factors, upon the aerodynamic size and electrostatic charge distributions and the gravitational forces, respiratory drug delivery may be compromised due to reduced and zero gravity conditions.

Subset Risk: Inhalation or ingestion of the dust may cause irritation or disease that can compromise an astronaut's health and their ability to carry out mission objectives. Transport of these species to the humid atmosphere of the habitation module may cause the generation of additional toxic and corrosive species.

Current State of Knowledge

Martian dust physical properties, such as particle size distribution, particle hardness, particle shape, clod size, clod hardness, particle density, friction angle, cohesion, adhesion, dielectric characteristics, magnetic effects, elemental composition, and reactivity have been modeled based on observations from surface rovers and orbital spacecraft [16].

Models indicate particle size is 0.1 to 2000 μm , particle hardness is 1 to 7 on Moh's hardness scale, dust particles are tabular, angular and rounded, particle density is 2.6 to

3.0 g/cm³, friction angle is 18 to 40 degrees, dielectric characteristics are $K' = 1.9d$, cohesion is 0 to 20 kPa, and adhesion is 0.9 to 79 Pa [17, 18]. Observations indicate the dust is magnetic [19]. Direct measurements detected Si, Al, Fe, Mg, Ca, Ti, S, Cl and Br in the soil [20]. The soil, probably slightly acidic, is generally oxidized but may be reactive.

Desired Future State of Knowledge

To reduce risk for the first human Mars mission, Earth-based laboratory and computer simulations and toxicological studies need to be performed to ensure that human systems operate properly and crew health is protected. Physical property parameters predicted by models should be verified in situ by direct measurement to ensure that Earth-based simulations and studies are valid.

In order to design human systems that would properly function in the dusty Martian environment specific knowledge should be obtained to provide simulation and study designers with detailed chemical and physical properties of Martian dust and sand to understand adhesive, electrostatic, and abrasive properties [1]. These properties include shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, chemistry of relevance to predicting corrosion effects, polarity and magnitude of charge on individual dust particles and concentration of free atmospheric ions with positive and negative polarities.

To protect the crew from potential hazards of Martian dust, reactive, corrosive and irritant properties need to be understood [1]. To obtain the needed information requires assays for chemicals with known toxic effect on humans, e.g., oxidizing species such as CrVI; characterization of soluble ion distributions; understanding of reactions that occur upon humidification and released volatiles; knowledge of shapes of Martian dust grains sufficient to assess their possible impact on human soft tissue (especially eyes and lungs), and determination of toxic response in animals should be performed.

Investigations, Measurements, and Priorities to Reduce Risk(s) and/or Cost

The Dust/Soil Focus Team evaluated each risk and recommended investigations that would be needed to provide data to mitigate the risk. It also prioritized measurements based on the probability and consequence of risks, evaluating if investigations must be performed in situ or if the mitigation could be performed on Earth using existing data to create simulated Martian environments or computer software, and considering cost of performing in-situ measurement versus the value of the data that would be obtained.

The need for Martian dust/regolith simulant(s)

An important strategy for reducing the risks related to the effects of granular materials on both engineering and biological systems is to establish one or more Martian dust/regolith simulants. Widely accepted standard materials make it possible to compare technology performances from different laboratories and to generate empirical rather than theoretical data. For risks associated with MEPAG Goal IV Investigation 1A, we recommend using the simulants to test dust accumulation on various types of materials; dust repellent, removal and cleaning technologies; various types of decontamination procedures; flight hardware designs; reliability, maintainability and waste minimization technologies; and operational procedures. For risks associated with MEPAG Goal IV Investigation 2, we recommend using simulants to perform in-vitro and in-vivo laboratory exposure testing, laboratory animal tests, establishment of respiratory and inhalation limits, and the development of operational procedures, mitigation methods, and exposure levels.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

1A. Characterize the particulates that could be transported to hardware and infrastructure through the air (including both natural aeolian dust and particulates that could be raised from the Martian regolith by ground operations), and that could affect engineering performance and in situ lifetime. Analytic fidelity sufficient to establish credible engineering simulation labs and/or performance prediction/design codes on Earth is required.

Measurements

- a. A complete analysis, consisting of shape and size distribution, mineralogy, electrical and thermal conductivity, triboelectric and photoemission properties, and chemistry (especially chemistry of relevance to predicting corrosion effects), of samples of soil from a depth as large as might be affected by human surface operations. Note #1: For sites where air-borne dust naturally settles, a bulk regolith sample is sufficient—analysis of a separate sample of dust filtered from the atmosphere is desirable, but not required. Note #2: Obtaining a broad range of measurements on the same sample is considerably more valuable than a few measurements on each of several samples (this naturally lends itself to sample return). Note #3: There is not consensus on adding magnetic properties to this list.
- b. Polarity and magnitude of charge on individual dust particles suspended in the atmosphere and concentration of free atmospheric ions with positive and negative polarities. Measurement should be taken during the day in calm conditions representative of nominal EVA excursions. Note #4: This is a transient effect, and can only be measured in situ.
- c. The same measurements as in a) on a sample of air-borne dust collected during a major dust storm.
- d. Subsets of the complete analysis described in a), and measured at different locations on Mars (see Note #2). For individual measurements, priorities are:
- i. Shape and size distribution and mineralogy ii. Electrical iii. Chemistry.

The following investigations involving atmospheric dust and human exploration are listed in descending priority order:

Priority 2. Determine the possible toxic effects of Martian dust on humans.

The Viking LR/GEX experiments indicate that some highly reactive agent is omni-present in the environment, possibly being of atmospheric origin.

FINDING: PROPOSED INVESTIGATION AND MEASUREMENTS

2. Determine the possible toxic effects of Martian dust on humans. Measurements:

1. For at least one site, assay for chemicals with known toxic effect on humans. Of particular importance are oxidizing species such as CrVI. (May require MSR).
2. Fully characterize soluble ion distributions, reactions that occur upon humidification and released volatiles from a surface sample and sample of regolith from a depth as large as might be affected by human surface operations.\

During crew occupation and EVA, dust storms may affect visibility, restrict departure times, limit EVAs, and hamper regular habitat maintenance. Operations in a major dust storm can be stalled due to obscured visibility and adhering dust. On Mars, global dust storms

can last for 3 months [4], with possible crew internment for long periods (especially if there is a passage of high opacity core regions). Mitigation strategies include designing low maintenance habitats and EVA systems and/or avoiding human occupation at times when storms are expected. The ability to predict the large seasonal storms has greatly improved with MGS/TES, but regional and local storms appear quasi-random [21]. To assess the risk, lander meteorological packages (like those suggested in point 1 above) should also have the capability to assess dust density-opacity. A remote-sensing orbital weather station (like that described in point 1 above) would have the capability to monitor dust storm frequency, size, occurrence and thermodynamic characteristics over a long baseline, and act to alert surface-stationed astronauts of impending storm activity.

Priority 3. Derive the basic measurements of atmospheric electricity that affects Take-off, Ascent and Orbit insertion (TAO) and human occupation.

Electric fields in convective dust storm may exceed breakdown, leading to discharge, arcing, RF contamination. Discharge to ascending vehicle is potentially serious issue during take- off (e.g., Apollo 12). High levels of atmospheric electricity may limit EVAs. Dust storm electrification may cause arcing, affecting TAO. Based on laboratory studies and terrestrial desert tests, there is a growing body of evidence that dust devils and storms may develop dipole-like electric field structures similar in nature to terrestrial thunderstorms [22]. Further, the field strengths may approach the local breakdown field strength of the Martian atmosphere, leading to discharges [23]. A hazard during the vulnerable human return launch from Mars would be a lightning strike to the ascending vehicle. Apollo 12 suffered a lightning strike at launch, upsetting the navigation and electrical system. During human occupation of Mars, dust storm discharges and induced electrostatic effects may also force human explorers to seek shelter, reducing EVA time, habitat maintenance, etc. Mitigation strategies include avoidance of aeolian dust clouds both at launch and during human EVA periods. However, to date, there are no measurements of Martian atmospheric electricity to evaluate the consequences of the proposed risk. The Atmosphere Focus Team suggests placing an atmospheric electricity (DC and AC E-fields, conductivity) package on at least one future landed missions to assess the risk.

Priority 7. Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA.

Local, regional and even global dust storms are likely to occur for a long- stay mission. Storms can last for months. Storm opacity in the cores may be large enough to reduce EVA times, delay departure times,

and external maintenance of habitat. (e.g., Gulf War II dust storm)

During crew occupation and EVA, dust storms may affect visibility, restrict departure times, limit EVAs, and hamper regular habitat maintenance. Operations in a major dust storm can be stalled due to obscured visibility and adhering dust. On Mars, global dust storms can last for 3 months [4], with possible crew internment for long periods (especially if there is a passage of high opacity core regions). Mitigation strategies include designing low maintenance habitats and EVA systems and/or avoiding human occupation at times when storms are expected. The ability to predict the large seasonal storms has greatly improved with MGS/TES, but regional and local storms appear quasi-random [21]. To assess the risk, lander meteorological packages (like those suggested in point 1 above) should also have the capability to assess dust density-opacity. A remote-sensing orbital weather station would have the capability to monitor dust storm frequency, size, occurrence and thermodynamic characteristics over a long baseline, and act to alert surface-stationed astronauts of impending storm activity.

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ESTIMATION OF THE SALTATED PARTICLE FLUX AT THE MARS 2020 IN-SITU RESOURCE UTILIZATION EXPERIMENT (MOXIE) INLET.

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Introduction: One of the objectives listed in the Mars Exploration Program Analysis Group (MEPAG) Goals Document is to “characterize the particulates that could be transported to hardware and infrastructure through the air (including natural aeolian dust and other materials that could be raised from the Martian regolith by ground operations), and that could affect engineering performance and in situ lifetime” [1].

This objective is becoming timely with the approaching Mars 2020 rover and its Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE). MOXIE will take in atmosphere through a filter, compress the gas to 1 atm using a scroll pump, before electrolyzing the carbon dioxide to produce oxygen [2].

MOXIE’s intake consists of a High Efficiency Particulate Arrestance (HEPA) filter, with a face area of 240×80 mm. The filter is mounted at the lower left rear corner of the rover body and is oriented downwards such that the filter face is flush with the rover belly pan, at a height of 69 cm above the surface.

Analysis and wind tunnel testing of the dust loading from suspended dust has been completed and is reported in [3]. In this abstract, we provide a first estimate of the flux of particles that may be transported to the intake by the process of saltation.

Saltation: Saltation is the mobilization of particles from the surface due to wind. There are two main parameters which can be used to analyze the process: the fluid threshold and impact threshold wind stresses. The fluid threshold is the minimum wind stress required to lift particles from the surface. The impact threshold is the minimum wind stress at which an impacting particle can eject another particle. On Earth, these two parameters are similar. However, on Mars, there is a large difference between them: the fluid threshold is much higher than the impact threshold, due to the lower gravitational acceleration and atmospheric density. As a result, saltation on Mars displays a marked hysteresis effect whereby a brief gust of strong wind can mobilize particles which continue to saltate after the wind stress reduces to below the fluid threshold [4].

Modelling: The state of the art in the modelling of saltation is the COMprehensive numerical model of SALTation (COMSALT) [5]. It is written in MATLAB and has been verified against experimental measurements of saltation on Earth. Although there is some uncertainty in the model, it can be applied to obtain a first estimate of the saltated particle flux expected at the MOXIE inlet.

Here, we briefly summarize the inputs to the model before presenting the results.

Wind profile. For the wind model, we assume a logarithmic profile:

$$u_x(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

where u_x is the horizontal wind speed, u_* is the wind shear velocity, κ is the von Karman constant, z is the height above the surface, and z_0 is the roughness parameter [6]. As recommended by COMSALT’s documentation, this is typically set to $30D$, where D is the median diameter of a regolith particle [7].

The wind shear velocity u_* can be calculated from the wind model for various roughness parameters z_0 assuming a von Karman constant κ of 0.40 and a horizontal wind speed u_x of 3.5 m s^{-1} at a height z of 1.6 m. This corresponds to the mean wind speed measured using the wind sensor on the 2008 *Phoenix* lander [8].

Regolith particle size distribution. The regolith Particle Size Distribution (PSD) used is the PSD measured at the *Phoenix* landing site for particles with diameters less than $200 \mu\text{m}$, as shown in Figure 1:

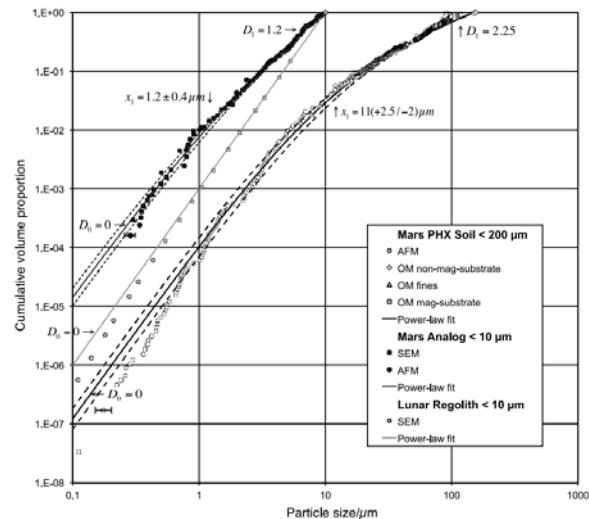


Figure 1. PSD of Martian soil as measured by *Phoenix*. The PSD used in the simulation was “Mars PHX Soil $< 200 \mu\text{m}$ ” (rightmost curve) [9].

COMSALT requires the PSD to be passed in a separate MATLAB function containing two vectors with n elements. The first vector contains the mean particle diameter of each of the n bins and the second contains the

proportion of the total volume of particles contained within each of the n bins.

The *Phoenix* PSD is approximated using two expressions for the cumulative volume proportion as a function of particle diameter $V(x)$:

$$V(x) = \begin{cases} \left(\frac{x}{x_0}\right)^{3-D_0}, & x < 11 \\ \left(\frac{x}{x_1}\right)^{3-D_1}, & x \geq 11 \end{cases}$$

where x is the particle diameter in μm , x_0 is $22.7 \mu\text{m}$, D_0 is 0, x_1 is $200 \mu\text{m}$ and D_1 is 2.25 (values obtained from Figure 1). With these functions, the PSD input to COMSALT is summarized in Table 1:

Particle diameter bin range (μm)	Mean particle diameter (μm)	Volume proportion in bin	Cumulative volume proportion
0 – 100	50	0.595	0.595
100 – 125	113	0.108	0.703
125 – 150	138	0.103	0.806
150 – 175	163	0.099	0.905
175 – 200	188	0.095	1.000

Table 1. PSD as used by COMSALT.

Additional parameters. COMSALT also requires a number of other parameters related to the numerical simulation. These are listed in Table 2 and are all set to the recommended values in the documentation [7].

Name	Description	Value(s)
t_max	Time that particles from each particle bin are simulated in each minor iteration	15 s
h	Time step with which particle motion is simulated	7.5 ms
delta_z	Spatial resolution of simulation	2.5 mm
u_fr_thr	Impact threshold (only required if Owen's second hypothesis is used)	0 m s^{-1}
filetext	String appended to the names of all output files	Various
switches	First switch determines whether or not Owen's second hypothesis is used. Second switch determines whether or not to include the effects of turbulence	(0,1)

Table 2. Listing of parameters required by COMSALT.

Finally, the density of Martian soil is required; a density of 3000 kg m^{-3} was used.

Results: Since MOXIE has a downward-facing filter, the vertical mass flux is of most interest and this is plotted for a range of surface roughness values in Figure 2:

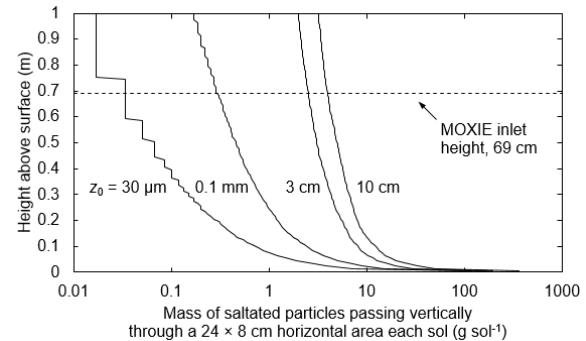


Figure 2. Vertical mass flux, expressed as the total mass of all particles that pass through a horizontal plane the same size as the MOXIE face area during one sol. The dashed line shows the height of the MOXIE inlet (69 cm).

Discussion: Figure 2 gives a first estimate of a saltated particle mass impingement rate of the order 1 g per sol at the MOXIE inlet, for typical wind conditions and surface roughnesses. Although most of these particles would be expected to bounce off the filter, when included with particle fluxes expected from landing, dust devils and storms, this contributes to the justification for a baffle in front of the filter inlet. As saltated particles will follow a ballistic path, a baffle is a straightforward way to prevent them accumulating in the folds of the filter. For larger in-situ resource utilization intakes, using baffles and mounting the intakes at a greater height will remove them from the bulk of the saltation flux.

Future work may examine the effect of variable winds, dust storms and dust devils, and include a range of PSDs as measured at various landing sites.

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“Martian Dust Toxicity: Should We Believe the Headlines?”. J. Torin McCoy¹, Valerie E. Ryder¹, Chiu-Wing Lam², Robert R. Scully², and Amy A. Romoser^{2, 1}, NASA Johnson Space Center, Biomedical Research and Environmental Sciences Division, 2101 NASA Parkway, Houston Texas 77058, ² Wyle-KBR, Biomedical Research and Environmental Sciences Division, 2101 NASA Parkway, Houston, Texas 77058

Introduction: There are a number of intriguing technical challenges and risks associated with Martian exploration, and the topic of Martian dust has garnered significant attention from both the scientific community and the popular media. This attention is likely justified when considering (1) the experience of NASA with Apollo, where lunar dust infiltration posed a serious challenge to both human health and operations, (2) observations about the unique challenges of a Martian atmosphere, dust storming, and other planetary surface phenomenon, and (3) geological data from Martian robotic missions that have confirmed the presence of notable levels of certain chemical components (e.g., chromium, perchlorate). However, a case can be made that this attention has resulted in some expected sensationalization and inflated perception of the actual risk posed by the Martian dust, at least with respect to human health.

This presentation will highlight the state of knowledge in regard to Martian dust exposure and toxicity. While Martian dust undoubtedly poses some new scientific challenges, NASA already has a decent foundation to build on in assessing related crew health risks. With the culmination of the Lunar Airborne Dust Toxicity Assessment Group (LADTAG) efforts, a permissible exposure limit (PEL) was established for lunar dust in 2014, and later translated into a NASA Standard 3001 Volume 2 standard. While this PEL is intended to be specific to lunar exposures, the presentation will demonstrate that there are tangible ways to relate this PEL to Martian exposures, especially in the context of evaluating exposures to chemicals carried within the Martian regolith. The Lunar PEL will be discussed in context, to allow the audience to understand what type of toxicity considerations are made in determining a PEL. Efforts will be made to contrast earth-based assumptions in risk assessment that are poorly relevant to spaceflight, and may lead to misleading conclusions if not recognized. A screening-level spaceflight risk assessment will be presented for several potentially relevant elements/compounds within the dust on Mars (e.g., chromium, perchlorate). Exposure potential and special considerations associated with spaceflight toxicity will be explored in detail for these stressors.

The presentation will conclude by touching on some of the research gaps and opportunities to further our understanding of Martian dust toxicity that will hopefully prove useful to the scientific community.



CHEMICAL, MINERALOGICAL, AND PHYSICAL PROPERTIES OF MARTIAN DUST AND SOIL.

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Introduction: Global and regional dust storms on Mars have been observed from Earth-based telescopes, Mars orbiters, and surface rovers and landers. Dust storms can be global and regional. Dust is material that is suspended into the atmosphere by winds and has a particle size of 1-3 μm [1-4]. Planetary scientist refer to loose unconsolidated materials at the surface as “soil.” The term “soil” is used here to denote any loose, unconsolidated material that can be distinguished from rocks, bedrock, or strongly cohesive sediments. No implication for the presence or absence of organic materials or living matter is intended. Soil contains local and regional materials mixed with the globally distributed dust by aeolian processes [5,6].

Loose, unconsolidated surface materials (dust and soil) may pose challenges for human exploration on Mars. Dust will no doubt adhere to spacesuits, vehicles, habitats, and other surface systems. What will be the impacts on human activity? The objective of this paper is to review the chemical, mineralogical, and physical properties of the martian dust and soil.

Chemical Properties: A host of lander and orbital missions have characterize the chemical composition of dust and soil. We will primarily focus on the results from the Alpha Particle X-ray Spectrometer (APXS) onboard the Mars Exploration Rovers *Opportunity* and *Spirit*. *Opportunity* has characterized the surface chemistry at Meridiani Planum for over 13 years, and *Spirit* obtained equivalent data over 6 years in Gusev crater. Basaltic soil and dust at all landing sites (Pathfinder, Spirit, Opportunity, and Curiosity) have similar compositions [6,7]. There are subtle differences in the alkaline and alkali earth cations, primary a reflection of different local basaltic mineralogies, e.g., feldspar vs. mafic mineralogy. Also, some soil shows enrichments of the local bedrock, e.g., the soil Doubloon in Gusev crater has elevated P from eroded high-P materials from the Wishstone/Watchtower rock classes [8].

Basaltic soil and dust on Mars have a composition similar to the average crustal composition [9]; however, soil and dust have enrichments in S and Cl (Table 1, [5,10]). Dust has a bit more Zn than soil (Table 1). The dust composition in Table 1 was derived from bright, undisturbed soils Desert_Gobi (Gusev crater) and MontBlanc_LesHauches (Meridiani Planum), from opposite sides of the planet. These surface materials have among the highest concentrations of nanophase iron oxides (npOx, see next section) and are thus our current best analyses of global aeolian dust [5]. Sulfur,

Cl, and npOx have strong correlations in soil and dust (Fig. 1). These elements and phases are enriched in dust (Tables 1 & 2), suggesting that they are major components of the global dust. Recently, Berger et al. [10] have characterized the chemistry of materials collecting on the science observation tray onboard the *Curiosity* rover. These measurements by APXS confirmed that martian dust is enriched in S, Cl, and Fe compared to average Mars crustal composition and soil.

Several unusual soils were discovered by *Spirit* while dragging a wheel through soil in Gusev crater. The Paso Robles class soil has high SO_3 (~35 wt. %, Table 1) and the Kenosha Comets soil subclass contained very high SiO_2 (~90 wt. %, Table 1) [8]. Although these types of soils are not common at other landing sites, human missions might encounter these unusual soils.

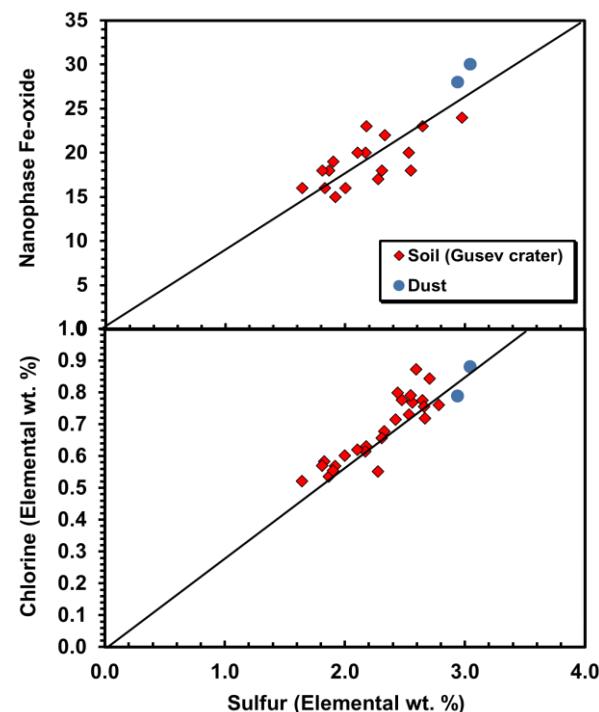


Figure 1. Sulfur, chlorine, and nanophase iron oxide (npOx) contents in Mars soil and dust. Note the higher S, Cl, and npOx in martian dust. These three phases correlate in soil and dust.

Next, we address two aspects of dust chemistry that may have impacts on human exploration – oxychlorine

Table 1. Average compositions of the Martian crust, soil, and dust. Maximum oxide/elemental compositions discovered so far in soil on Mars along with locations are listed in the last two columns.

Oxide/ Element	Average Mars Crust [9]	Average Mars Soil (Gusev Crater Panda Subclass; [5])	Average Mars Dust [5]	Max. from MER Surface Missions	
				Maximum [8]	Location
	-----wt.%-----				wt.%
SiO ₂	49.3	46.52 ± 0.57	44.84 ± 0.52	90.53	Kenosha Comets, Gusev crater
TiO ₂	0.98	0.87 ± 0.15	0.92 ± 0.08	1.90	Doublloon, Gusev crater
Al ₂ O ₃	10.5	10.46 ± 0.71	9.32 ± 0.18	12.34	Cliffhanger, Gusev crater
FeO	18.2	12.18 ± 0.57	7.28 ± 0.70	4.41	Paso Robles, Gusev crater
Fe ₂ O ₃		4.20 ± 0.54	10.42 ± 0.11	18.42	
MnO	0.36	0.33 ± 0.02	0.33 ± 0.02	0.36	The Boroughs, Gusev crater
MgO	9.06	8.93 ± 0.45	7.89 ± 0.32	16.46	Eileen Dean, Gusev crater
CaO	6.92	6.27 ± 0.23	6.34 ± 0.20	9.02	Tyrone, Gusev crater
Na ₂ O	2.97	3.02 ± 0.37	2.56 ± 0.33	3.60	Cliffhanger, Gusev crater
K ₂ O	0.45	0.41 ± 0.03	0.48 ± 0.07	0.84	Bear Island, Gusev crater
P ₂ O ₅	0.90	0.83 ± 0.23	0.92 ± 0.09	5.61	Paso Robles, Gusev crater
Cr ₂ O ₃	0.26	0.36 ± 0.08	0.32 ± 0.04	0.51	Tyrone, Gusev crater
Cl	-	0.61 ± 0.08	0.83 ± 0.05	1.88	Eileen Dean, Gusev crater
SO ₃	-	4.90 ± 0.74	7.42 ± 0.13	35.06	Arad, Gusev crater
Element	-----μg/g-----				μg/g
Ni	337	544 ± 159	552 ± 85	997	El Dorado, Gusev crater
Zn	320	204 ± 71	404 ± 32	1078	Eileen Dean, Gusev crater
Br	-	49 ± 12	28 ± 22	494	Paso Robles, Gusev crater

compounds (i.e., perchlorates/chlorates) and chromium.

Oxychlorine Compounds. Perchlorates were first discovered in surface soil at the Phoenix landing site near the northern polar region [11]. Since that discovery by the MECA Wet Chemistry Lab, the Sample Analysis on Mars (SAM) instrument has detected oxychlorine compounds in the soil and bedrock at the *Curiosity* landing site in Gale crater [12,13]. These author's used the term oxychlorine compounds because the SAM instrument detected the evolution of O₂, chlorinated hydrocarbons, and HCl. These gases are most likely from the thermal decomposition of perchlorates, chlorates, and/or chlorites [13-15]. Although, no instruments onboard *Curiosity* have the capability to detect these anions, the temperatures of evolved O₂ are consistent with thermal decomposition of perchlorate/chlorate salts of Fe, Mg, and Ca [13-16]. The amount of perchlorate measured at the Phoenix landing site was about 0.6 wt. %, which would be equivalent to about 1 wt. % perchlorate salt [11]. The amount of

perchlorate estimated from the evolved O₂ in a Gale crater windblown deposit (Rocknest) was ~0.4 wt. % (Fig. 2, [12]), similar to what was measured by the Phoenix lander. The maximum perchlorate concentration inferred by evolved O₂ in an outcrop was ~1.1 wt. % ClO₄ in a mudstone (Cumberland) in Gale crater [13]. Oxychlorine compounds (e.g., perchlorates) present in Gale crater soils and sediments have complicated the detection of organic molecules, which are combusted during pyrolysis and thermal decomposition of oxychlorine compounds during SAM evolved gas analyses [12-14]. These oxychlorine compounds may also present challenges for human health and engineering performance to hardware and infrastructure (e.g., corrosion during heating of surface soil for IRSU water extraction).

Chromium. Another concern for human missions is the element chromium (Cr). Past advisory groups to NASA have raised the possibility of the presence of Cr⁶⁺ in dust and soil and that, if present in sufficiently high concentrations, it could be deleterious to human

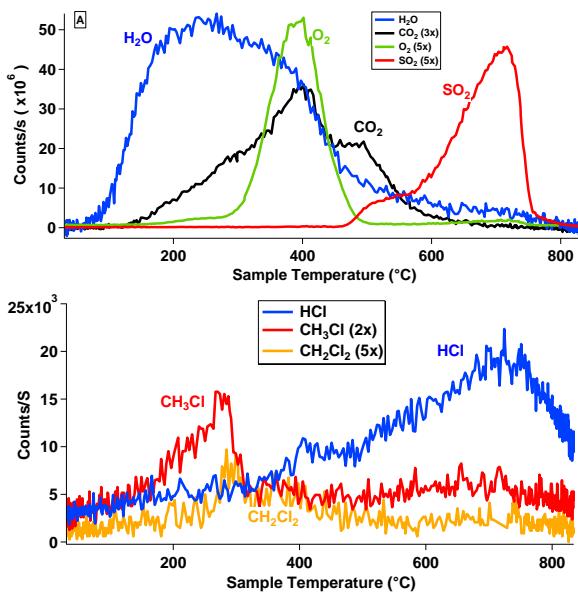


Figure 2. Gases released during Sample Analysis at Mars (SAM) pyrolysis of the Rocknest windblown deposit in Gale crater [12]. The evolution of O_2 , chlorinated hydrocarbons, and HCl suggests the thermal decomposition of an oxychlorine compound (e.g., perchlorate). Water is the most abundant gas released (~2 wt. % H_2O). High temperature SO_2 release may be the thermal decomposition of sulfides. Fine-grained Fe- or Mg-carbonate may be the source of some of the evolved CO_2 .

health [17]. We present here evidence that Cr^{6+} is highly unlikely in dust and soil. A Mössbauer spectrometer was one of the science instruments onboard the Mars Exploration Rovers that landed and analyzed surface materials at Gusev Crater and Meridiani Planum. The instrument detects only the element iron (Fe) and is separately sensitive to its oxidation state (e.g., Fe^{6+} , Fe^{3+} , Fe^{2+} , and Fe^0), coordination state (e.g., octahedral and tetrahedral), and mineralogical speciation (e.g., Fe in specific silicate, sulfide, and oxide minerals). One mission objective was to look for Fe^{6+} , the highest oxidation of Fe. No Fe^{6+} was detected in any martian surface sample, including soil and dust. Using detection limits based on counting statistics, a conservative upper limit for the Fe^{6+} concentration is 1–2% (relative) of the total Fe concentration, or about 0.2 to 0.4 wt.% for typical martian basaltic soil and dust. Assuming the same efficiency for oxidation of Cr^{3+} to Cr^{6+} , the upper limit for the Cr^{6+} concentration in typical basaltic soil is 0.003 to 0.005 wt.% using 0.32 wt.% for the total Cr concentration. Note, however, that both Fe^{6+} and Cr^{6+} are not stable in the presence of Fe^{2+} , which is abundant in martian surface materials.

Mineralogical Properties: The mineralogy of Martian dust and soil is based upon Mössbauer and Mini-TES instruments onboard *Spirit* and *Opportunity* and the CheMin X-ray diffraction instrument onboard *Curiosity*. The Mini-TES instrument indicated the presence of plagioclase feldspar in dust and soil [18]. The Mössbauer spectrometer has detected npOx in the dust and soil (Fig. 3, [5]). The npOx component can include several phases, including superparamagnetic forms of hematite and goethite, lepidocrocite, akaganite, schwertmannite, hydronium jarosite, ferrihydrite, iddingsite, and the Fe^{3+} pigment in palagonitic tephra [5, 19–21]. Other Fe-bearing phases in the soil include the basaltic minerals olivine, pyroxene, ilmenite, and magnetite [5].

The CheMin instrument has analyzed two surface “soils” in Gale crater, a windblown deposit called Rocknest and an active aeolian dune called Bagnold. We will only present the Rocknest X-ray diffraction data here because it contains a larger amount of the global dust component. The CheMin instrument accepts materials less than 150 μm in diameter through the sample processing system on *Curiosity*. Rocknest contains basaltic minerals along with several alteration phases (Table 2, [22]). The major alteration phase in Rocknest is an X-ray amorphous component that includes the npOx phase(s) [6]. The amorphous phase also contains the S- and Cl-bearing volatile phases described above (e.g., oxychlorine compounds, sulfides, sulfates). There is still a large fraction of Si in the amorphous phase that may be a secondary alteration silicate; however, we cannot rule out the possibility of unaltered volcanic or impact glass [6,23]. Other alteration phases in the Rocknest soil are Ca-sulfate (anhydrite) and hematite.

Physical Properties: We will limit our physical properties discussion of surface soil and dust to an overview. Edgett [24] presents a detailed analysis of the particle sizes and shapes of surface silts and sands in soil at the Gale crater landing site at this workshop. Microscopic imagers have flown on landed missions. The spatial resolution of the Microscopic Imagers (MI) on *Spirit* and *Opportunity* was ~30 μm , and the resolution of the Mars Hand Lens Imager (MAHLI) on *Curiosity* was ~15 μm [24–26]. The Optical Microscope (OM) on the Mars Phoenix Lander had resolution of 4 μm and could resolve particles of about 10 μm and larger. Phoenix also included an Atomic Force Microscope (AFM) that was part of the Microscopy, Electrochemistry, and Conductivity Analyzer (MECA) payload that could resolve the shape of individual dust particles down to about 100 nanometers in size. A key disadvantage of imagers on the Phoenix lander was the lack of mobility; the lander was restricted to obtaining materials in the area the Robotic Arm could reach.

Table 2. Quantitative mineralogy of the Rocknest windblown deposit (soil) in Gale crater [22].

Mineral	Rocknest Windblown Deposit Wt. %
Feldspar	26
Olivine	13
Pyroxene	20
Magnetite	2
Hematite	1
Anhydrite	1
Quartz	1
Ilmenite	1
X-ray Amorphous	35

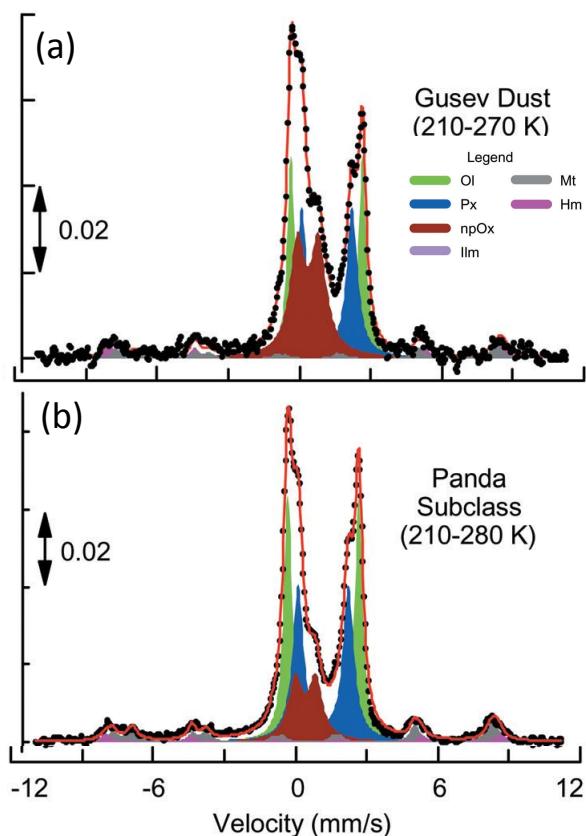


Figure 3. Mössbauer spectra for the (a) martian dust and (b) soil (Panda subclass is representative of Mars average soil composition [5]). Note the larger peaks for the nanophase Fe-oxides (np-Ox) in the dust indicating more np-Ox in the dust [legend: Ol = olivine, Px = pyroxene, npOx = nanophase Fe-oxide, Ilm = ilmenite, Mt = magnetite, Hm = hematite].

Particle size distribution. Particle size distributions of soil is poorly constrained because microscope resolution can only resolve coarse silt, sand, and larger grains. Pike et al. [27] were able to provide a particle size distribution for Phoenix surface materials by using a combination of the OM and AFM. Only about 1 vol. % of the material delivered to the AFM had a particle size less than about 4 μm . This low volume percent of clay-sized particles seems unreasonable for other soils on Mars based on alteration mineralogy and chemistry. Here, we use a combination of the CheMin X-ray amorphous and Mössbauer Fe mineralogy to provide constraints of clay-sized materials in soil encountered at rover landing sites. We assume that the npOx is in the clay-size fraction and a portion of the X-ray amorphous component is similarly sized. About 15 % of the Fe in typical Mars soil (e.g., Panda class) is in the form of npOx [5]. This amount of npOx would be equivalent to about 3 wt. % clay-sized materials based on a total FeO content of 16 wt. %. This amount of npOx would place the lower limit of clay-sized particles at about 3 wt. %. The estimated amount of X-ray amorphous materials in Rocknest windblown deposit is about 35 wt. % [22]. This fraction includes the poorly crystalline npOx phases. An upper limit on the total amount of clay-sized materials would be 35 wt. % assuming all of the X-ray scatter results from very fine particles, i.e., significantly less than 4 μm in size. We can estimate that about 21 % of the soil materials have been altered by chemical alteration based on the $\text{Fe}^{3+}/\text{Fe}_{\text{Total}}$ of 0.21 determined by Mossbauer spectroscopy on typical Mars soil although some of the Fe^{3+} could be in magnetite [5]. So it is reasonable to estimate the clay fraction in soil to be 15-25 wt. % and about 75-85 wt. % of the less than 2 mm materials in the silt and sand fractions.

Dust shape. The shape of discrete dust particles may play an important role in human health issues (e.g., dust in the lungs) and engineering performance of spacecraft parts (e.g., dust on seals). The only data we have acquired on Mars that can resolve dust particles is from the atomic force microscope (Fig. 4, [27]). Dust particles are irregularly shaped but appear to have rounded edges, possibly a result of aeolian processes.

Summary: Soil and dust on Mars have basaltic compositions, but are enriched in S, Cl, and npOx compared to crustal materials. The correlation of S, Cl, and npOx in soil/dust and their greater abundances in dust suggests that they are a component primarily associated with aeolian martian dust. The particle size of dust is about 1-3 μm . Oxychlorine compounds are found wide spread in soil/dust and are almost certainly a component of the martian dust. Chromium in soil and dust is unlikely to attain the hexavalent state and not likely to be a viable health hazard for humans.

Mineralogy of soil and dust is dominated by basaltic minerals (plagioclase feldspar, olivine, pyroxene, magnetite); however, large amounts of X-ray amorphous materials and npOx in the soil and dust suggest chemical alteration of primary basaltic materials. We estimate that about 15-25 wt. % of martian soil is composed of clay-sized materials (< 4 μm) and the shape of martian dust is irregular, but rounded edges resulting from wind processes.

Soil is produced by a combination of geologic processes including physical (impact, wind) and chemical (aqueous alteration, oxidation) processing of local and regional basaltic materials. The finest fraction of the soil, i.e., dust, is suspended by wind and has been transported at regional and global scales and remixed with surface soil. The impacts of dust and soil on human missions must be addressed, but we do not foresee any “show stoppers” based on available data.

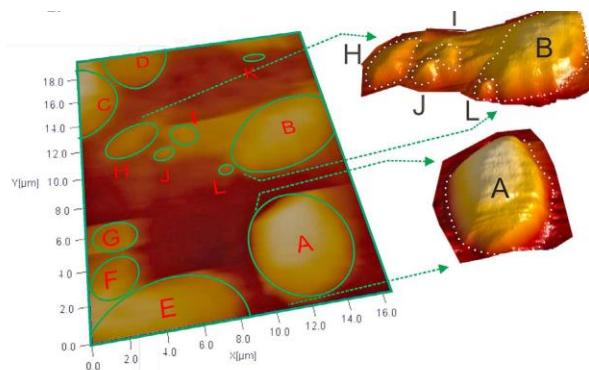


Figure 4. Atomic Force Microscope image of a dust particle from soil materials at the Phoenix landing site [27]. Particles appear to be rounded. These particles are 2-4 μm in size.

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FORECASTING DUST STORMS ON MARS: A SHORT REVIEW.

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Introduction: Martian mineral dust is radiatively active and mostly absorbs short-wavelength (solar) radiation and, to a lesser extent, long-wavelength (thermal infrared) radiation. The dust cycle is currently considered to be the key process controlling the variability of the Martian climate at inter-annual and seasonal time scales, as well as the weather variability at much shorter time scales. The atmospheric thermal and dynamical structures, and the transport of aerosols and chemical species, are all strongly dependent on the dust spatio-temporal distribution. Dust storms are the effect of strong and extended dust lifting by near-surface winds, and the behavior of dust clouds aloft both depends on and impacts the atmospheric circulation. The dust particles can represent a problem for surface mechanical and electrical systems and even for the health of future Martian astronauts.

Therefore, the spatial and temporal distributions of dust aerosol are essential observables for any fundamental or applied study related to the Martian atmosphere, including weather monitoring and forecast for robotic and possible future human exploration missions.

In this article we provide a short review focusing on the current and future capabilities of forecasting Martian dust storms.

Dust storms classification: Although small-scale dust storms can occur at any time during a Martian year, observations show that it is during northern autumn and winter (within the “High Dust Loading” –HDL- season, see [1, 2]) that the dust lifting increases, raising the probability of observing small (sizes of few tens kilometres across) and large (sizes of few hundreds kilometres across) dust storms. This well observed phenomenon coincides with the greater forcing in the atmosphere during the period around perihelion, which on Mars occurs at $L_S = 251^\circ$.

Although there is not an officially accepted nomenclature and classification of dust storms (especially for historical events), [3] showed that one can define a clear size-duration relationship by which one can distinguish three (or four) types of dust storms. “**Local dust storms**” are events that create a thick atmospheric dust loading over an area smaller than $1.6 \cdot 10^6$ km². They tend to systematically last less than 3 sols. “**Regional dust storms**” are events in which the atmospheric dust loading is important over an area larger than $1.6 \cdot 10^6$ km², lasting for more than 3 sols. “**Planet-encircling dust storms**” are referred to those multi-regional dust

storm events that spread mineral dust in the atmosphere at all longitudes (although not necessarily at all latitudes and not necessarily simultaneously), thus engulfing the planet at global scale for several months. The lifting of dust from the ground, though, does not occur at global scale, but rather at regional scale. This classification could be completed by the “**Dust devils**”, created by the convective activity during daytime, with diameters of less than 1 km and which last less than 10 minutes. It is convenient to distinguish the different types of dust events when studying the likeliness of being affected by such an event for robotic or human missions..

Current capability for dust storm forecast: A typical question that is frequently asked to Mars’ atmosphere experts is about the possibility of forecasting dust storm events, and in particular the occurrence of a planet-encircling dust storm.

Weather forecasting on Mars is very different from that on the Earth. When compared to Earth, the specificities of the Martian atmosphere (low atmospheric density, water in trace quantities, absence of oceans) provide Mars with a (generally speaking) very predictable weather. For a large portion of the year, flow instabilities in the Martian atmosphere do not grow [4, 5]. On the contrary, this situation is not likely to occur on Earth, where the atmosphere is intrinsically more chaotic. Paradoxically, this makes the prediction of the state of the Martian atmosphere with models more problematic in a certain sense, because the main source of disagreement between model and observations are possibly unknown biases (whether model or observational biases), rather than more or less known flow instabilities [6].

While forecasting the atmospheric state (i.e temperatures and winds) when the atmosphere is clear of dust is an achievable task in a large portion of the atmosphere and at most times, it becomes a much more difficult enterprise when dust storms occur. The main reason comes from the fact that, at the current state of knowledge on the Martian dust cycle, the prediction of the onset of dust storms is not yet reliable. Several factors contribute to make this prediction as such:

- The lack of deep understanding of the mechanisms of dust lifting, including the effects of dynamical thresholds [7], electric fields, sand-dust interaction, vertical fluxes;

- The lack of knowledge on the time-variable reservoirs of surface dust available to be lifted (including the possibility of differentiating between “fresh dust” and compacted layers);
- The approximate knowledge of the dust particle sizes injected in the turbulent boundary layer and beyond;
- The approximate understanding of the radiative/dynamical feedback that make a local storm transform into a regional one, and ultimately into a planetary-scale storm, within a short time-scale (usually just a few sols).

Once dust is airborne, the transport and sedimentation processes are much better constrained than lifting and atmospheric injection. Furthermore, the radiative impact of dust has been the object of several recent improvements [8, 9]. Provided the size distribution of the airborne dust is known within reasonable uncertainties, models can forecast the distribution of dust particles and the feedback on the thermal and wind structure. Paradoxically, it would therefore be easier to forecast the evolution of a dust storm that initiated a few sols before, say, the Entry Descent and Landing (EDL) of a vehicle, than to forecast the possible onset of a storm that presented no signs in the preceding sols. .

The specificity of planetary-scale dust storms: When a global-scale, planet-encircling dust storm occurs, the Martian environment switches to a new regime which strongly differs from other periods and other years from the point of view of density, temperature, and wind profiles, surface luminosity, etc. These storms typically last for several months, and must be accounted for when designing and planning a mission to Mars. However, one should note that the word “dust storm” in this case can be misleading in the sense that on most of the planet strong surface winds are not expected. In fact, as a result of the change in atmospheric stability, in many locations the surface winds can be weaker than usual within the area covered by a “dust storm”, except at the edges where temperature contrasts are the strongest. Even the word “global” can be misleading, because these storms are born when several, often separated regional-scale dust storms occur together, and a large amount of dust injected beyond the atmospheric boundary layer is transported by large-scale winds to engulf most of the planet. The role of possible “transient teleconnection events” (i.e. rapid changes of atmospheric state induced by a localized occurrence that contribute to trigger another occurrence at distance) has been put forward to account for the onset of multiple separated regional storms in the case of the MY25 global-scale storm [10, 11], but at present it would require more extensive work to be validated and generalized.

If forecasting the onset of a local or regional dust storm is difficult, forecasting the onset of a dust storm that attains the planetary scale –i.e. encircles all longitudes within a large latitudinal band– is even more difficult at the current state of the knowledge. Planet-encircling dust storms develop suddenly, rapidly, as a combination of multiple regional storms at locations possibly far apart. The atmospheric dust loading usually increases explosively by more than 5-fold within 10 sols, reaches a peak within 30-40 sols before dust lifting is shut down, then decays slowly over a long period of time (even longer than 150 sols, depending on the peak value) after sedimentation prevails, to eventually attain typical background values again.

Five confirmed global dust storms have been observed by instruments either in Mars orbit or on the Martian surface –one in 1971 (MY 9; Mariner 9), two in 1977 (MY 12; Viking), one in 2001 (MY 25; MGS), and one in 2007 (MY 28; MRO/Mars Odyssey/MEX). One additional storm, in 1982 (MY 15) was identified from Viking lander 1 pressure observations and two more confirmed storms –one in 1956 (MY 1) and one in 1973 (MY 10)– are well documented in the ground-based telescopic record. On this basis, a very rough estimation of the probability of the onset of a global-scale dust storm within a given week (7 sols) during the ~250 sols between $L_s=180^\circ$ and 330° (within the HDL season) over Martian years 1-32 yields a probability of the order of 1% [i.e. 8 storms /(32 Martian years *(250 sols/7 sols)) = 0.7% < 1%]. It must be stressed that this very general and roughly calculated value of probability does not take into account the increase or decrease of probability depending on the specific season and location, nor it takes into account the fact that the probability distribution of global-scale dust storms likely follows that of extreme episodic events rather than a classic Gaussian probability, therefore inferring probability values from past frequencies might not be a valid approach, as much as it is not valid, for instance, in the cases of the stock market and earthquake forecast.

The main difficulties in forecasting the onset of what can become a planet-encircling dust storm are:

- These kind of storms can start as a local or regional-scale storm with no apparent preferential location within an extended band of latitudes (excluding the high latitudes);
- They do not have preferential solar longitudes, although they seem to cluster around northern hemisphere autumn equinox (equinoctial storms) and winter solstice (solstitial storms);
- They do not seemingly have a preferential time interval between two consecutive occurrences (e.g. two of such storms occurred in MY 12, but three Martian years passed between the one in MY 25 and the one in

MY 28, and none occurred for the last 4 years –possibly 5, if including the currently ending MY 33).

The dust loading background in the sols preceding the onset of a planet-encircling dust storm may look very similar to the one present at the same season in years without global-scale storms. The simple monitoring of dust opacity, therefore, might not be sufficient if it is not associated to the monitoring of dynamical variables such as temperature, pressure, and (possibly derived) winds.

Future capability for dust storm forecast: A promising technique for forecasting dust storms is “data assimilation”, which consists in combining all available information to reconstruct a best estimate of the state of the atmosphere. The information comes from two sources of data: observations by instrument(s) and results from a numerical model of the considered system. Thus, assimilation can be seen as an (optimal) extrapolation or interpolation of observations in space and time using a numerical model. The current research in assimilation for Mars’ atmosphere has focused on nudging (Analysis Correction scheme) and ensemble Kalman filtering. All in all, these schemes are not mature enough yet to be used for the purpose of predictability of dust storms. Promising results using the assimilation of temperature and aerosol observations could lead to prediction of the evolution of dust days in advance, once it has already been lifted, injected and observed in the atmosphere. This is made possible by the capability of a numerical model to efficiently simulate the horizontal and vertical transport of dust on a global scale. However, the complexity of dust lifting and atmospheric injection mechanisms (see e.g. [7, 12]) and the lack of continuous synoptic observations, which induce a lack of understanding of the onset of dust storms, are the main reasons why it is quite unlikely to have soon an assimilation tool that is fully able to predict the occurrence of a dust storm.

Finally, we would like to mention that none of the missions to Mars so far has been able to provide both continuous and synoptic monitoring of Martian aerosols, which would allow for studying their dynamics in detail. A truly innovative method to obtain continuous synoptic observations of the dust distribution (at least the horizontal one) would be to use a Mars-stationary (areostationary) satellite rather than a polar orbiter.

Frequent and extended observations of large portions of the Mars’ atmosphere allow to properly monitor and understand the rapidly evolving dynamics of the aerosols -intrinsically linked to the atmospheric thermodynamics and circulation. An areostationary satellite, similarly to a geostationary one, can continuously monitor changes in a region of the planet at least 60° wide

centered at the equator, affected by meteorological phenomena such as the formation and evolution of Martian dust storms as well as water ice clouds, and evolving surface characteristics. Nonetheless it is not well positioned to observe the vertical structure of the aerosol distributions.

For Mars, the areostationary altitude is 17,031.5 km above the equator (semi-major axis = 20,428.5 km). The sub-spacecraft point is at 0° latitude at the chosen longitude, and the satellite can observe the surface up to 80° away from it, although the portion of the disk useful for scientific purposes might be limited to about 60° away. The view of Mars from areostationary orbit is similar to that shown in Fig. 1 where a regional storm that developed in Martian year 24 is seen as from the point of view of such an orbit.

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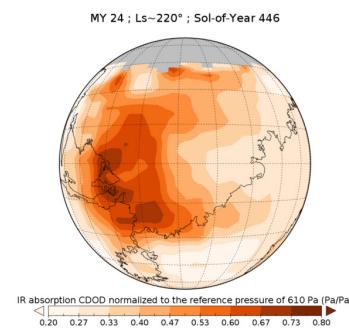


Figure 1.

OPTICAL PARAMETERS OF MARTIAN DUST AND ITS INFLUENCE ON THE EXPLORATION OF MARS. A. V. Morozhenko¹ and A. P. Vidmachenko^{1,2}, ¹Main astronomical observatory of NAS of Ukraine, Str. Ak. Zabolotnoho, 27, Kyiv, 03680. ²National University of Life and Environmental Sciences of Ukraine. vida@mao.kiev.ua.

Introduction: There is a well-founded assumption that dust can interfere with the colonization of Mars. Quite often, there are global dust storms on Mars. At this time, more than a billion tons of small particles enter the atmosphere [17]. This is several orders of magnitude greater than in the largest dust storms on Earth. The dust is so shallow that it penetrates through any obstacles. In conditions of a limited amount of oxygen and small solar radiation, astronauts can only live in special rooms and go to the surface of Mars - only in special spacesuits with special protection. Therefore, they will not directly inhale toxic dust.

But the Martian wind, the bombardment of micro-meteorites and charged particles, scatter this very small dust over the entire surface of the planet [1-3, 18]. Constantly circulating in the atmosphere, the dust particles probably acquired a static charge. Therefore, they will fit snugly against the surface of the spacesuit and penetrate inside. In this case, even with careful processing, the dust will get into the dwelling; There it will fall into the lungs of the settlers of Mars. And this will happen, even if the astronauts go into the protected blocks through a special vestibule. Dust will clog up air filters, water purifiers and other vital items in living quarters. Dust will spread like smoke, and can penetrate into all moving parts of spacesuits and mechanisms, and lead to their mechanical wear.

Studies have shown that Mars dust contains a large number of toxic compounds such as perchlorates (salts of perchloric acid). They were first discovered by the Phoenix Mission of Mars in 2008 near the North Pole [6]. Apparatus "Curiosity" also found huge reserves of minerals like gypsum. Its particles when inhaled will cause dangerous diseases. Thus, small particles of gypsum can lead to serious lung diseases, cause irritation of the eyes, skin and respiratory system. Comparison of remote observation data with laboratory studies has shown that the dust that covers almost the entire surface of Mars also consists of a fine-grained silicic acid salt (silicates). When ingested in human lungs, this salt reacts with compounds in human tissues, resulting in the formation of dangerous chemical compounds. Martian dust contains, among other things, many chromium compounds.

Features of Martian aerosols: Atmospheric aerosols play an important role in the formation of the cli-

mate of Mars [7]. Using the results of our photometric and polarimetric [10] observations of Mars, we determined some optical characteristics and basic parameters of aerosol particles, such as their size r_0 , the real and imaginary parts of the refractive index n_r and n_i for various conditions of development of the Global dust storm [4, 5, 7, 8, 16]. The influence of the shape of dust aerosol particles in the Martian atmosphere on the value of the imaginary part of the refractive index n_i , obtained from photometric observations during the period of the greatest activity of the dust storm, was also studied. In the calculations, spherical particles and flattened spheroids of different sizes were used in the lognormal distribution of particles in size.

A similar analysis was carried out for the average particle radii r_0 and the optical thicknesses τ_0 of the dust layer, estimated from polarization observations during periods of high atmospheric transparency. As a result of the performed analysis it was shown that the obtained values of these optical parameters depend on the adopted aerosol form. Thus, the values of n_i , r_0 and τ_0 found for spheroidal particles turned out to be twice as large as for spheres [5]. A similar analysis for periods of high transparency was carried out with respect to estimates of the average particle radius r_0 and the optical thickness of the dust layer τ_0 , which were obtained from the polarimetric measurements [10]. It was found that the aerosol form adopted influences these optical parameters. Namely, the values of n_i , r_0 and τ_0 obtained for spheroidal particles turned out to be approximately 2 times larger than for the spheres. For the greatest activity of a dust storm in 1971, it was found that with an optical thickness of a dust cloud of $\tau_0 \geq 15$, the particle size would be in the range $4.5 \leq r_0 \leq 7.5 \mu\text{m}$. It turned out that the real part of the refractive index n_r of dust particles was practically the same for both the transparent atmosphere and during the maximum development of the dust storm and equal to $1.54 \leq n_r \leq 1.62$.

We believed that the measurements of the reflection coefficient of the Martian disk [4, 8] obtained during the dust storm peak in 1971 (at a phase angle $\alpha = 42^\circ$) were most suitable for determining the imaginary part of the refractive index n_i . In this case, the Martian atmosphere can be accepted as semi-infinite. Under such conditions, the contribution to the reflection of light by the underlying surface can be neglected. Assuming that

the dust layer consists of spherical particles with $n_r = 1.57$ for the lognormal particle size distribution, the value $n_i = 0.0001-0.0025$. As a result, the best agreement was obtained between the observed and calculated values of the reflection coefficient of the Martian disk at $r_o = 4.5 \mu\text{m}$. Such a value of r_o corresponds fairly well to data obtained from our polarimetric observations ($r_o > 5.7 \mu\text{m}$). These values of n_i are an order of magnitude smaller than the data, obtained for the highly transparent atmosphere of Mars. The obtained values of n_i correspond quite well to the dust analogues obtained in the laboratory, such as basalt and basalt glass. Note that the results of laboratory measurements and calculations carried out for spherical and randomly oriented nonspherical particles of the same effective radius have shown that the influence of the shape of the particles is not significant in the analysis of photometric data [8, 16]. More careful calculations showed that in the early stage of a dust storm in the clouds there are particles with a size of 1 to 20 μm ; during the period of the greatest activity of the dust storm, the mean particle radius was $\sim 8-10 \mu\text{m}$, and in the final stages $\sim 1 \mu\text{m}$. The value of the real part of the complex refractive index of particles turns out to be equal to $n_r = 1.59 \pm 0.01$ and is in good agreement with the hypothesis of their silicate nature.

On the surface of Mars, three regions are distinguished in the middle and low latitudes: Tharsis, Arabia and Elysium, where the night temperatures allow almost all seasons [9, 11-13, 19] to convert carbon dioxide from the atmosphere to frost on the surface. All three areas are covered with dust. Therefore, the temperature in these places varies much faster than in areas not covered with dust. These regions are cold at night, and the warmest - in the daytime. Therefore, these small dust particles very quickly heat up during the day, and are cooled at night. Formed by frost hoar - separates motes. In the morning the frost evaporates, and the dust on the surface becomes very fluffy. That is, frost constantly prevents the joining of grains of dust into one whole. And such a cycle "carbon dioxide - frost" leads to a change in the soil and can cause erosion processes [15].

Flights to Mars: Both states and private companies are regularly spoken about the flights to Mars. Some of them recruit future Martian colonists. For example, in early 2015, the "Mars-1" project conducted the third round of recruitment of future Martians, having already selected 100 candidates. However, the time has not even come to test the Martian ships. It is clear that a Martian ship must be very large and heavy for the delivery of astronauts, a lot of food, water, fuel, air, scientific

tools, spare parts, etc. Of course, technology does not stand still. And the initial mass of a potential Martian ship can significantly decrease. But still the Martian ship should be assembled in orbit around the Earth in several stages. And only after assembling the ship will go to Mars. This circumstance complicates and increases the cost of the project.

The flight to Mars can last from six to nine months. People on Earth and in its orbit are protected by the magnetic field of the Earth. But having gone to Mars, the astronauts are deprived of this protection. For 15 months of flight to Mars and back the astronaut will receive about 1 sievert of radiation. This dose is set as the maximum permissible for astronauts in their entire career. But 15 months is a long time, and during this time a powerful flash can occur on the Sun. In this case, the dose can be increased by an order of magnitude and the crew can easily be killed. Experiments show that a dose of 3-5 sievert leads to death from radiation sickness within 30-60 days with a probability of 50%. Therefore, a serious problem on Mars is a weak magnetic field [14, 20, 21]. Together with the rarefied atmosphere, this increases the amount of ionizing radiation that reaches the surface.

Conclusions: Therefore, it is believed that the flight to Mars is a huge risk, and the exploration of Mars can be delayed. The main reason for the delay is the presence of a large amount of toxic dust on the Red Planet. If such dust gets into the body, the earthly inhabitant can get sick, the work of vital organs can be broken or even stopped. In addition, because of the rarefied atmosphere on Mars, there is a much more likely meteorite threat [1-3, 18]. These factors make us seriously think about the very possibility of organizing a Martian expedition even in the distant future. But it is possible that given the technical, physiological and psychological aspects, the flight to Mars will soon become quite real.

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SUMMARY OF MARTIAN DUST FILTERING CHALLENGES AND CURRENT FILTER DEVELOPMENT

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Introduction: Traditional air particulate filtering in manned spaceflight (Apollo, Shuttle, ISS, etc.) has used cleanable or replaceable catch filters such as screens and High-Efficiency Particulate Arrestance (HEPA) filters. However, the human mission to Mars architecture will require a new approach. It is Martian dust that is the particulate of concern but the need also applies to particulates generated by crew. The Mars Exploration Program Analysis Group (MEPAG) highlighted this concern in its *Mars Science, Goals, Objectives, Investigations and Priorities* document [7], by saying specifically that one high priority investigation will be to “Test ISRU atmospheric processing systems to measure resilience with respect to dust and other environmental challenge performance parameters that are critical to the design of a full-scale system.” By stating this as high priority the MEPAG is acknowledging that developing and adequately verifying this capability is critical to success of a human mission to Mars. This architecture will require filtering capabilities that are highly reliable, will not restrict the flow path with clogging, and require little to no maintenance. This paper will summarize why this is the case, the general requirements for developing the technology, and the status of the progress made in this area.

Filtering Applications: The surface equipment required for human missions to Mars drive the need for dust filtering in a number of applications. Some will have to operate in the low pressure CO₂ Martian environment and some will operate in pressurized habitable volumes. The following is a summary of the systems which, if implemented in the human mission to Mars architecture, will need the capability to filter out Martian dust.

In-Situ Fuel Production from Martian Air. In most mission architectures fuel for an ascent vehicle is generated before the crew ever arrives. The pre-positioned In Situ Resource Utilization (ISRU) system must operate for years without the need of maintenance. Air ingested and put through chemical processing must be as clean as possible or the system will be fouled, leading to reduced performance at best and total failure at worst. The filter must be 100% reliable either in design, fault tolerance or redundancy since no one is there to empty, clean or replace it.

Habitat O₂ Production from Martian Air. Similar to the ISRU fuel production system, but presumably part of the habitat, this system shares the same challenge. Here, however, maintenance could be an option.

Airlock Pump Down Systems. The habitat will have an airlock even if suit ports are used for EVA in order to bring suits or machinery for maintenance and to bring supplies and equipment into the habitat. This system may include a pumping unit to remove the thin, dust laden CO₂ before repressurizing with habitat air. The dust in the Martian air will need to be filtered out to prevent degradation of the pumping system.

Habitat and Pressurized Rover ECLSS. Mitigation techniques will be implemented to minimize the amount of Martian dust introduced into the habitat and pressurized rover environments but it will not be 100% precluded. This issue is of specific concern due to the potential of crew health hazards related to the constituents in the dust. If traditional HEPA filters are used for the cabin a reliable prefilter for dust may be needed since the loading rate is unknown. It will not be practical to bring a large number of replacement cabin filters “just in case” the rate is high. Furthermore, since dust may settle or cling to the floor or other surfaces in the habitat it may be necessary to provide dedicated filter systems near the likely points of entry

Derived Filter Design Requirements: The challenge of addressing the filtering needs becomes evident when attempting to derive the high level requirements for such a system. Loading rates are unknown and will vary, especially for systems that operate in the Martian atmospheric environment. Reliability, as mentioned earlier is also a key driving requirement. What follows is a first order summary of the key requirements that must be established:

Reliability. As mentioned, for the ISRU fuel production system the filter Mean Time Between Failures (MTBF) must be longer than the expected operating time before crew arrives. This period has been described in terms of years. The remaining applications have the potential of being repaired by the crew.

Maintainability. Maintenance capabilities must be carefully considered due to limited mass and volume considerations. Additionally, designing the capability for crew maintenance can increase mass and volume of the habitat systems and limit design options. In some applications it will be a necessary penalty, but each circumstance will be scrutinized to ensure it is necessary.

Volume, Power and Mass. Always drivers for every spacecraft, these parameters will need to be minimized. Design options that include dedicated fans, pumps and electric fields all require more power.

Load Rate Capability. The rate at which the dust particulates are introduced is a key design driver. The system must maintain a minimum removal efficiency at the maximum expected load rate or risk break through. This rate is not well understood for the external systems and subject to the variability of exploration operations for the internal systems. One approach taken by researchers has been to use optical data from the MER missions which found dust concentrations of about 6 particles/cm³ [6]. However, this rate will vary based on the presence of winds and will increase greatly in the presence of a dust storm. One estimate has put the density of dust particles in a dust devil at about 10 particles/cm³ [3][4]. The flowrate of this dust laden air depends on the design of the ISRU system, but 88 g/h has been used in development testing [2].

Load Characteristics. Robotic missions have gathered a fair amount of data about the Martian dust and simulants have been generated for years. Landis, et al [5] have determined a size distribution between 1 µm and 40 µm for the bulk of the airborne particulate.

Working Environment. As noted by Agui [1] and Calle, et al [2], the thin CO₂ Martian air presents a challenge to traditional catch filter and electrostatic precipitator (ESP) technology. Additionally the temperature swings must also be taken into account.

Not surprisingly the test and verification process to prove that the filter technology meets the derived requirements described above will be a challenge, especially considering that all tests will be done using Mars dust simulant and not the real thing. A development program will need to plan significant amounts of time to test reliability, loading rates and the environmental conditions.

Filter Design Progress: The need for filters to meet the mission architecture has not gone unnoticed in the research community. Several efforts have been underway led by NASA KSC and GRC.

At the NASA GRC a unique testing platform was built in the form of a closed-loop air flow system to test filter media. This system has the capability to maintain a Mars-like environment and introduce particulate and detect how much may have made it past the filter [1]. This facility has already been used to test HEPA filter media in Martian conditions. As of a 2015 report the system needed some improvements to its laser sheet particle detection system in order to better assess filter performance in support of future filter development testing [1].

At NASA KSC Calle et al [2] have tested an Electrostatic Precipitator (ESP) style filter using Mars simulant dust in a Martian simulated environment with some success. There are challenges remaining in this design as it was expected to have much less effective-

ness than initial tests showed which needs to be better understood. Also led by Kennedy Space Center, the Blazetech Corporation has been developing a two stage filtration device, presumably based on the earlier ESP testing, intended for ISRU system use. Their plans are to mature the design to TRL 6 in 2017. [9]

The development of these systems and test facilities over the past few years is a promising and well timed activity. The maturation of appropriate filter systems must be done now to support missions to Mars in the 2030's as outlined in the latest NASA budget proposal. However, a specific mission architecture still needs to be defined so that detail requirements can be derived. Without knowledge of packaging, mass and power limitations the prototype filter systems being developed now may be faced with a redesign, negating some of the work and testing already done.

The Mars 2020 rover payload Mars Atmosphere Resource Verification InSitu (MARVIN) will provide a wealth of knowledge directly applicable to the human mission architecture. Within this system the Atmosphere and Dust Measurement and Filtration (ADMF) subsystem is being designed to test filtration methods, as well as the absence of filtration, and observe the results in the ISRU system performance. The baseline design will test a HEPA filter with a bypass line included to test the effects of unfiltered Martian air. An option is being considered for the bypass line to include an ESP filter that can be turned on and off. Also, of great interest is the plan for the ADMF to include sensor technology to measure particle sizes and quantities. The results of the MARVIN payload will enable future designers to more fully define the requirements discussed earlier. [8]

Summary: The Martian dust filter in an ISRU fuel production plant is its Achilles Heel. A clogging or other failure of the filter during the long unmanned fuel production phase would cause an abort of the human mission due to fouling or cascading failure of the fuel producing process. Additionally, filter devices will need to be included in several other surface systems including habitat and rover ECLS. While initial technology developments are promising, much work has yet to be done to address all the driving requirements of dust filtering. As seen in this paper, these requirements are still vague in key areas. Furthermore, an adequate test program needs to be developed to ensure the design is verified and validated. Adequately resolving the airborne dust concerns is just one piece of the puzzle which must be assembled for a successful human mission to Mars. As with other challenges, the sooner we converge on a solution the better.

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DUST STORM IMPACTS ON HUMAN MARS MISSION EQUIPMENT AND OPERATIONS. M.A. Rucker, NASA Johnson Space Center, 2101 NASA Parkway, Houston, Texas 77058, michelle.a.rucker@nasa.gov

Introduction: Although it is tempting to use dust impacts on Apollo lunar exploration mission equipment and operations [1] as an analog for human Mars exploration, there are a number of important differences to consider. Apollo missions were about a week long; a human Mars mission will start *at least* two years before crew depart from Earth, when cargo is pre-deployed, and crewed mission duration may be over 800 days. Each Apollo mission landed at a different site; although no decisions have been made, NASA is investigating multiple human missions to a single Mars landing site, building up capability over time and lowering costs by re-using surface infrastructure. Apollo missions used two, single-use spacecraft; a human Mars mission may require as many as six craft for different phases of the mission, most of which would be re-used by subsequent crews. Apollo crews never ventured more than a few kilometers from their lander; Mars crews may take “camping trips” a hundred kilometers or more from their landing site, utilizing pressurized rovers to explore far from their base. Apollo mission designers weren’t constrained by human forward contamination of the Moon; if we plan to search for evidence of life on Mars we’ll have to be more careful. These differences all impact how we will mitigate and manage dust on our human Mars mission equipment and operations.

Impacts to Equipment: Martian dust is expected to influence the design of Mars surface power systems, habitats, rovers, Extravehicular Activity (EVA) space-suits and tools, and Mars Ascent Vehicle (MAV).

Surface Power Systems. A key decision facing Mars mission designers is whether to rely on solar power for surface operations. Atmospheric dust and accumulated dust on the arrays can both reduce array efficiency [2]. Unlike NASA’s Mars Exploration Rovers (MER) that could retreat to a very low-power state to conserve energy [3], human Mars missions are estimated to require at least 15 kW “keep-alive” power simply to keep critical life support and spacecraft functions on-line [4]. Landing sites far from the equator or along seasonal dust storm tracks will be even more difficult to support with solar power. To reduce risk, designers must over-size solar arrays or expand energy storage capability (both of which add landed mass), or consider alternatives such as nuclear power. Although nuclear power systems would allow full power even during a severe dust storm, provisions for clearing accumulated dust from thermal radiators must be considered. Regardless of power source selected, power cable

connections between multiple surface assets will have to be made, driving the need for dust-resistant connectors. To further complicate matters, some of these connections may be made by robots before the crew arrives.

Surface Habitat. Two-person Apollo crews accessed the lunar surface via an EVA hatch. With the hatch open and no airlock to serve as a “mud room,” lunar dust migrated into the cabin, quickly becoming a nuisance [1]. For the longer-duration Mars missions, alternative crew ingress/egress methods are being studied, including airlocks, suitports [5], and hybrid combinations of these. Ingress/egress systems will all require dust-resistant pressure seals and locking mechanisms, perhaps with retractable covers to protect against dust while exposed to the surface.

In spite of best efforts some dust is likely to migrate into the habitat, with implications to critical life support system hardware. For example, cabin fans and filters must be sized to remove airborne dust, and regenerative air and water systems must be compatible with chemical compounds in the dust that find their way into these systems. Softgoods in the cabin, such as Velcro® fasteners, may be very difficult to rid of dust once contaminated. A portable vacuum cleaner may be needed to reach dust in crevices; note that even small vacuum cleaners require high peak power, with implications to power system mass, which in turn has implications to thermal system mass. Dust mitigation is likely to play a role in a disposable vs. washable crew clothing decision, with implications to cargo mass and volume. Planetary protection considerations will influence trash disposal; cleaning materials that have been exposed to both Martian dust and the internal cabin environment may require special handling or containment. The surface mission lengthy duration, combined with repeated habitat use by subsequent crews, will drive the need for creative dust mitigation and remediation to ensure the habitat is able to complete its intended life cycle.

Outside the cabin, dust accumulation on windows, handrails, and radiator panels must be addressed, with implications to crew maintenance time vs. the mass and power of autonomous cleaning systems.

Rovers. Unpressurized, robotic rovers may be used to ferry tools or samples between various work sites, or used to scout crew excursion routes. As demonstrated by the MER rovers, solar-powered rover operation can be affected by dust storms but even the Apollo battery-

powered rover ran into trouble when dust accumulation on the battery case caused overheating [1]. Telerobotic systems that allow crew to operate a rover remotely must be resistant to dust and scratched optical surfaces.

To explore more than a few kilometers beyond the landing site, a pressurized crew rover capable of serving as a mobile habitat will be required. Unlike the robotic rovers, a crewed rover will need substantial power for life support function. One of the worst-case scenarios would be a solar-powered crew rover caught in a lengthy, severe dust storm, unable to generate enough power to return to the habitat. Even with alternate power sources such as fuel cells or batteries, poor visibility could make driving in a storm treacherous through boulder fields and hidden sand pits. Such a scenario may drive the need for crew rescue schemes, remote safe havens, better storm prediction, or surface navigation and hazard avoidance provisions.

Storm concerns aside, a pressurized rover will have many of the same dust-related issues as the surface habitat: crew ingress/egress dust mitigation, seal and mechanism integrity, and managing dust accumulation on windows, handrails, and radiator panels. Optical elements critical for surface navigation, such as the windscreen or externally mounted camera lenses, must be dust and scratch-resistant to ensure safe negotiation of visible terrain hazards.

EVA Spacesuits and Tools. An EVA spacesuit is essentially a one-person spacecraft, subject to the same dust concerns as the habitat and pressurized rover: crew ingress/egress dust mitigation, seal and mechanism integrity, and managing dust accumulation on the helmet visor, backpack, boots, gloves, and thermal components. Sharp dust particles may cause abrasion damage to seals and helmet visors. Once embedded in softgoods, such as suit fabrics, it may be difficult to shed dust.

EVA suits were re-used to support multiple Space Shuttle and International Space Station crews but planetary protection considerations make returning dusty Mars spacesuits to Earth problematic. Potentially, each crew must dispose of their EVA suits on Mars and return to Earth in their Intravehicular Activity (IVA) suits. This will require the suit customization that is normally performed by specialists on Earth (to accommodate different crew members' height, girth, arm length, etc.) to be performed by the crew on Mars instead (higher risk), or alternatively manufacture new EVA suits for each mission (higher cost).

One area of particular concern is how to perform routine maintenance on dusty spacesuits. Maintenance of small, intricate parts would be difficult while wearing EVA gloves, so the preference is to bring suits into a pressurized cabin where maintenance could be per-

formed in a shirt-sleeve environment. The question is: which pressurized cabin? Crews will eat and sleep in both the habitat and pressurized rover, making them unsuitable for dusty suit maintenance. Adding a purpose-built maintenance module is a solution, but would increase landed mass (and cost). Other options include partitioning the pressurized rover or habitat (though this may drive additional complication, such as a separate environmental control system for the maintenance compartment) or utilizing an ingress/egress airlock as a maintenance space. Personnel protective clothing to work on dusty suits may add to consumables mass and volume.

EVA tools—particularly power tools—have many of the same dust concerns outlined above: overheating, grit abrasion on seals or mechanisms, and maintenance or repair of dusty tools. EVA cameras will require dust-resistant housings, with scratch-resistant optical panes.

Mars Ascent Vehicle. The MAV will transport crew from the Mars surface to an Earth transit vehicle loitering in Mars orbit. The MAV plays a key role in Earth planetary protection because the amount of dust returning with the crew to Earth will be limited to what migrates into the MAV. As a one to three day-duration vehicle, the MAV cabin will be much smaller than either the surface habitat or pressurized rover, but will share many of the same dust concerns: airborne dust in the cabin, grit abrasion on seals and mechanisms, reduced visibility due to accumulation on windows, and thermal system malfunction due to dust accumulation.

The key to minimizing dust inside the MAV may be to use it as little as possible while on the surface and never open the hatch to the Mars environment. As noted above, leaving dusty EVA suits behind and ascending in pristine IVA suits is helpful, but how will crew transfer from their habitat to the MAV without going outside? One option is to change suits inside the pressurized rover, then tunnel from the rover to the MAV [6]. This virtually eliminates dust migration into the MAV, then to Earth, but at a landed mass, complication, and cost penalty for a retractable tunnel.

Preliminary study has not identified any reason the MAV could not launch during a dust storm. However, limited visibility and dust accumulation could make pre-launch preparations (likely performed by EVA crew) more difficult and risky.

Impacts to Operations: Martian dust is expected to influence landing, surface operations, and crew ascent in several ways.

Landing. The prevalence of seasonal dust storms along well-worn tracks [7] may influence landing site selection and potentially even timing. Landing on Mars during a dust storm could make it difficult to detect and

avoid hazards such as boulders and sand dunes, or other mission surface assets such as rovers or the surface habitat. Mitigation might include advanced hazard detection and avoidance systems--or simply waiting for the dust to clear. Once in Mars orbit, landers will have some flexibility to delay landing, but a storm lasting months could affect overall mission timeline and cut into schedule margins for critical surface operations, such as manufacturing in situ propellant for crew departure on the MAV. Note that the landers themselves may generate dust plumes as the descent engines interact with loose regolith during approach and touchdown. The equipment previously noted as sensitive to dust accumulation would be equally affected by these man-made dust storms, but with the added complication of potentially unburned propellants or propellant byproducts mixed with the dust. Descent flight paths that avoid surface infrastructure overflight will be desirable.

Habitat Operations. Long crew surface stays and the possibility of reusing the surface habitat for multiple crews will require robust housekeeping. The most significant dust-related impact to habitat operations is likely to be crew housekeeping time, either maintaining equipment to keep dust out of the habitat, or cleaning dust that migrates inside. Housekeeping on the International Space Station involves disposable wet wipes but the high cost of shipping consumables to Mars makes reusable cleaning tools desirable, in spite of the added time penalties to clean the cleaning tools for reuse.

Keeping dust out of the habitat is likely to involve special operational procedures that could add time getting EVA crew back inside. This would be a problem in an emergency, such as an EVA crewmember requiring immediate medical care.

Reduced visibility through habitat windows due to dust accumulation or storm conditions could disrupt telerobotic operations such as cargo handling or robotic sample collection.

Rover Excursions. The potential for reduced driving visibility and solar power availability during a storm could influence surface exploration planning. Exploration close to the landing site may be scheduled during storm season, with excursions farther from the landing site planned when the risk of dusts storms is lower.

As with the habitat, special operational procedures could add time getting EVA crew back into the rover, potentially delaying emergency medical care.

EVA Operations. Ideally, equipment will be designed to shed dust, or will include autonomous dust clearing provisions. If not, EVA crews could spend a considerable portion of their day maintaining outdoor equipment, leaving less time for science or exploration.

As with the habitat, time will likely be devoted to cleaning dust from EVA suit components, or repairing grit-damaged seals and mechanisms.

MAV Operations. Like the lander's descent engines, the MAV's ascent engine could create a man-made dust storm resulting in lofted dust—potentially mixed with ascent propellants or residues—settling on the habitat or rovers. Ascent flight paths that avoid surface infrastructure overflight will be desirable.

Conclusions: NASA has accumulated a wealth of experience operating in dusty environments between the Apollo program and robotic Mars rover programs. However, there are key differences between those missions and a human Mars mission that will require unique approaches to mitigate potential dust storm concerns.

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MARTIAN DUST AND ITS INTERACTION WITH HUMAN PHYSIOLOGY: AN EMERGENCY PHYSICIAN'S PERSPECTIVE. Peter A. Sim, MD, FACEP, peteralansim@gmail.com

Introduction: Adverse health effects are to be expected when unprotected humans are exposed to significant amounts of Martian dust. Primary prevention of exposure by engineering reliable barriers (e.g., EVA suits, habitat construction, electronic dust shields, filtration of inspired atmosphere) is of critical importance. But inevitably, barriers will be compromised and exposures will occur. Because of delayed communication with Mission Control, prompt and proven medical interventions should be instituted by a self-reliant crew trained to the physician level for common, treatable-on-Mars emergencies, including dust exposures.

Astronauts have had contact with extraterrestrial dust only during the Apollo program. Harrison Schmitt experienced the noxious effect of inhaled lunar dust during Apollo 17 —“lunar dust hay fever” [1], and the abrasive, micron-sized electrostatic dust on the moon will be a significant challenge for inhabitants of a future lunar base.

Characteristics of Martian Dust: Although Martian dust has yet to be exhaustively analyzed, we do know it is abrasive, electrostatic, magnetic, highly oxidative and chemically reactive, containing known harmful ingredients like fine silicate materials, gypsum, perchlorates, and trace amounts of hexavalent chromium [Cr(VI)], arsenic, cadmium and beryllium. Based on a survey of EPA exposure risk estimates, the elements that are toxic at the lowest concentrations are hexavalent chromium (Cr VI), arsenic (As), cadmium (Cd), and beryllium (Be) [2].

It appears that Martian dust is of uniform chemical composition regardless of its location on the fourth planet. Soil analyses from three landing sites separated by thousands of kilometers are quite uniform [3]. This is likely due to the recurring global dust storms, which act like a giant mixing bowl. From multispectral imaging the average diameter of airborne Martian dust is 3.4 microns [4], and particles of this size would remain suspended in the thin atmosphere almost indefinitely at most wind speeds [5].

The respiratory system, gut, eyes, and skin are most at risk from exposure to Martian dust, and systemic absorption of toxins from any of these sites is possible. I will briefly and individually discuss the currently understood hazards and treatments of the most toxic components of Martian Dust.

Specific Toxic Effects of Martian Dust: The respirable particle average concentration of inhaled air

(currently set at 1 mg/m³) must be carefully controlled, in order to be within the acceptable risk range for multiple potential toxins [6]. Pulmonary inflammation and fibrosis may result from inhalation exposure to a variety of mineral dusts, and primary prevention is key, since only symptomatic therapy is available for established disease. Inhaled silicates may eventually result in a variety of forms of silicosis, a restrictive lung disease. Gypsum inhalation may cause illness similar in pathophysiology to “black lung”, or coal worker’s pneumoconiosis.

Perchlorates: These compounds were first discovered in Martian soil by the Phoenix lander (May 2008), and in orders of magnitude greater concentration than found anywhere on Earth. As much as 1% of the soil’s weight in some locales may be perchlorate [7]. The highly oxidized chlorine blocks thyroid function by diminishing the body’s ability to absorb iodine, which is essential for thyroid hormone production. Potassium perchlorate was medically prescribed as a treatment for hyperthyroidism in the 1950’s-60’s, but a small number of patients developed aplastic anemia and agranulocytosis, and it was replaced with better-tolerated antithyroid agents. Medical opinion is divided on the true threat of Martian perchlorate, except for fetuses, infants and children, where hypothyroidism can result in irreversible mental impairment. Monitoring of Martian astronauts’ perchlorate blood levels will be warranted.

Chromium VI: Hexavalent chromium is genotoxic, causing structural and mutagenic changes in DNA [7]. Acute toxicity is a result of its strong oxidative properties. To determine if there is a substantial threat to astronauts from this compound, precise measurements of hexavalent chromium concentration in Martian dust are necessary, either in-situ or on samples returned to Earth. Assuming Cr(VI) is present at a concentration of 150 ppm in 1 mg/m³ respirable particulate matter (8), a 2 year exposure is estimated to result in a cancer risk of 5/100,000. The NRC’s Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars places that risk in the middle of its acceptable risk range (9).

The lungs are most affected by chronic chromium exposure, resulting in a pneumoconiosis — disease due to the inhalation of dust, characterized by coughing, inflammation, and reactive fibrosis (10). Breathing hexavalent chromium increases the risk of lung cancer (especially squamous cell carcinoma) and bron-

chospasm/asthma. The permissible exposure limit (OSHA) for airborne Cr(VI) is 5 micrograms/m³ (11). An acutely toxic inhalation of chromium fumes demands evacuation from further exposure, O₂, ventilatory support, albuterol for bronchospasm, and continuous positive airway pressure if noncardiogenic pulmonary edema ensues (12). Repeated ingestion of chromium VI over time is linked with oral cavity and small intestine cancers, and liver toxicity. (13). Because it is a known corrosive and may result in mucosal burns, an acute overdose (on Mars) should be addressed with gastric decontamination, but emesis is contraindicated due to possible gastric or esophageal rupture. If within 1 hour of ingestion, dilution and careful nasogastric lavage with a 10% ascorbic acid solution is indicated since ascorbate converts Cr(VI) → Cr(III), which is nontoxic (14). Continued doses of vitamin C, 1 gram every 20 minutes x 3, preferably IV (11) are given. Since vitamin C is well absorbed orally, repeat oral doses of ascorbate might also be beneficial, if IV dosing is unavailable. Oral ascorbate has been shown to prevent chromium toxicity in rats (15). Forced diuresis with urine alkalization (to pH 7.5) enhances elimination and helps prevent acute tubular necrosis if erythrocyte hemolysis is present. IV (or oral) n-acetylcysteine (Mucomyst) in the same doses as used for acetaminophen toxicity has been shown to boost urinary elimination in an animal model (16). Chelation therapy with dimercaprol or EDTA is not effective (17).

Cr(VI) surface exposure may damage the skin and nasal epithelium (18). Skin is washed copiously with soap and water, followed by a 10% topical ascorbic acid solution. Once skin exposure ceases, chromium-induced skin ulcerations typically heal spontaneously in weeks to months. For chronic low-level exposure, the nasal septum is protected from corrosive necrosis and eventual perforation by daily nasal irrigation followed by barium or zinc ointment applied to the septum (19).

Arsenic: There is a dose-dependent correlation between various forms of cancer (skin, lung, liver, kidney, and bladder) and chronic arsenic exposure (20). A small but measurable increased risk for bladder cancer occurs at 10 ppb (the WHO recommended limit in drinking water). Acute arsenic poisoning symptoms include abdominal pain, vomiting and diarrhea (often bloody), and encephalopathy. Chronic poisoning presents with abdominal pain, diarrhea, darkened and thickened skin, numbness, heart disease, and cancer (20). For acute poisoning, dimercaptopropane sulfonate (DMPS) or dimercaptosuccinic acid (DMSA) are recommended chelating agents (21).

Cadmium: There is no known biological function for cadmium. Classified as a human carcinogen, any

exposure is to be avoided. The OSHA PEL for people occupationally exposed to cadmium is 5 µg/m³ (fumes). Over-exposure may occur even in environments with trace amounts of the metal, and inhalation or ingestion is linked to cardiovascular disease, hypertension, early atherosclerosis (22), and kidney disease (23). The neurological, respiratory, gastrointestinal, and reproductive systems are also affected. It is possible cadmium interferes with hormone signaling pathways, thereby disrupting various parts of the endocrine system. Cadmium is a catalyst in forming reactive oxygen species, increasing lipid peroxidation and depleting antioxidants, glutathione and protein-bound sulphydryl groups, as well as promoting the production of inflammatory cytokines.(24)(25)

Inhaling cadmium-containing dust can quickly lead to pulmonary and irreversible renal problems, and even death from renal failure. Acute inhalation exposure is treated in standard supportive fashion: fluids, oxygen, and mechanical ventilation if necessary.

A flu-like illness (“metal fume fever” or “the cadmium blues”) results from inhaling cadmium fumes; spontaneous resolution of symptoms in about a week will occur if exposure ceases. More severe inhalation exposures may produce a pneumonitis or pulmonary edema.

Immediate poisoning, with damage to the kidneys and liver, result from ingestion. Timely emesis or gastric lavage is indicated. Activated charcoal is not effective (26).

Cadmium exposure may be measured indirectly with the urinary beta-2 microglobulin test, and monitoring astronauts' levels makes sense until the cadmium situation on Mars is fully elucidated. Blood or urine cadmium levels provide a better evaluation following acute poisoning.

Beryllium: The Be (2+) ion, small and highly charged, easily enters cells and tissues, and appears to target cell nuclei. Because of chemical similarity to magnesium, beryllium may displace magnesium from many enzymes (among those are enzymes used for synthesizing DNA), thereby altering their function (27). Once beryllium is absorbed into the body, there is no current method for removing it (28).

Beryllium and beryllium compounds are considered Category 1 carcinogens by the International Agency for Research on Cancer. OSHA has published permissible exposure limits (time-weighted averages and peak levels). The level immediately dangerous to life and health is 4 mg/m³. Beryllium dust or powder is well known to be toxic, and acute beryllium disease presents as a chemical pneumonitis. Susceptible individuals (there appears to be a genetic component to

beryllium sensitivity) experience a cell-mediated immune response resulting in pulmonary fibrosis. Chronic beryllium disease (CBD, or Berylliosis) is an allergic response of the lungs to exposure, causing granuloma formation and a restrictive lung disease resembling sarcoidosis. Lung cancer may ultimately be induced. CBD may present over a variable period of time (week to decades), with shortness of breath, cough, chest pain, fever and weight loss being prominent symptoms.

Eye and Cutaneous Exposures to Martian Dust: Because the highly oxidative and caustic Martian dust may burn the cornea and exposed skin (similar to lye or bleach), it is essential to have ready access to prolonged eye and cutaneous irrigation. For eye irrigation, lactated Ringer's (Hartmann's) solution is preferred due to its low cost, tolerability, and close to neutral pH, but normal saline solution (or even plain water if the other solutions are unavailable) may be used to flush out debris and neutralize the pH. The skin may be washed with soap and water, followed by continued irrigation with water. Total removal and neutralization of a concentrated alkali or acid on either the cornea or dermis may take hours of irrigation. Checking the pH of the affected area with litmus paper may help to define an end point.

Conclusions: We have not completely characterized the chemical composition of Martian dust, or the concentrations of known (and possibly as yet unknown) toxic constituents. A return of dust and regolith samples to Earth for analysis would be ideal. Keeping humans and Martian dust apart, with no direct exposure, will be the goal. If barriers are breached (almost inevitably), astronauts must be equipped with the knowledge and resources to institute specific emergency response plans on their own.

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THREE FACES OF MARTIAN DUST: DUST FOR COVER, DUST TO BREATHE, AND DUST EVERYWHERE

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Introduction: In the human exploration of Mars, it is not expected for the endeavor to take place using completely sealed systems [1]. This means that interchange between the martian environment and the terran-like environments that the astronauts bring with them would be an inevitability. From a planetary protection perspective, the impact of atmospheric dust in this situation is threefold:

First, dust particles have the potential to cover Earth microbes, possibly for a long, long time, protecting them against UV irradiation [2].

Second, there is the possibility for dust with unknown toxicity to be inhaled or ingested by the crew, with similarly unknown potential for acute and chronic effects on their health status.

Third, the dust is everywhere and, similarly to Apollo [3] will represent a challenge for habitation exploration systems and act as a carrier (in and out) of microbial life, both Terran and Extraterrestrial (should there be any).

Planetary Protection as an Issue for Human Exploration: The international consensus goals for planetary protection in the Outer Space Treaty (to which all spacefaring nations are signatories) are expressed as: “*The conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants must not be jeopardized. In addition, the Earth must be protected from the potential hazard posed by extraterrestrial matter carried by a spacecraft returning from another planet or other extraterrestrial sources*” [4].

While detailed approaches, implementations and requirements to achieve this are mature for robotic missions [5], only high-level guidelines are available for how planetary protection might be implemented on crewed missions. More information is needed before the following dust-related factors can be addressed in a planetary protection risk assessment, and adequate mitigations be identified and deployed.

Dust as a Shield: Several studies have concluded that the UVC fluence rates at the surface of Mars would rapidly kill unshielded microorganisms, even UV-resistant spores, reducing the exposed bioburden by several orders of magnitude on timescales ranging from minutes to hours [e.g., 6]. This finding holds true even on the undersides of spacecraft, but under protective layers of dust, spores could remain almost indefinitely, waiting for conditions to change that

would allow them to replicate. This could be due to dust deposition onto spacecraft hardware, or onto the martian surface where contaminant organisms had been released from a spacecraft hardware element or crewmember.

Dust to Breathe and Ingest: On the issue of astronaut health, it has to be considered what the impact of a ~500 day exposure to martian material would be. Based on the properties of dust we have seen displayed during robotic explorations [7] and the chemistry of the dust, some ingestion of perchlorates by astronauts would seem to be an extremely likely scenario. Goiter, caused by iodine depletion, is the most well-known ailment on Earth that might result from exposure to a perchlorate-rich environment like Mars. As well as swelling in the thyroid, it can also be responsible for fatigue, weight gain and depression in sufferers, with severe cases resulting in serious mental health problems, brain damage and death. As well as perchlorate, chemical constituents such as hexavalent chromium (or any other toxic trace contaminant) that may be present in the martian environment could cause illness that may be indistinguishable based on present information from effects of exposure to a martian organism. More data is needed about the chemical composition of martian dust.

Dust as an Environmental Constant:

For the Apollo crews dust was a significant contributor to equipment failures, even after stays of only a couple of days. [3] While the martian dust may not be as aggressive as lunar dust, there is still the threat of performance degradation over the time of a 500-day mission, affecting not only the exploration activity, but also the elevation of cross-contamination risk.

Dust can also be the vehicle for movement of microorganisms across the planet. A preliminary lab study by Mancinelli [8] indicated that microorganisms would be shielded by lofted dust. However, sufficient protection may only occur on relatively large lofted grains (~3-45 µm), rather than on the smaller grains (<~3 µm) that comprise large dust storms on Mars. Larger grains are not typically transported far from their source regions, so that locally-lifted particles may be the most important contribution to forward contamination. However, quantitation of these parameters (size and bioload of contaminated dusts) is needed before quantitative assessment of planetary protection risk can be made.

Conclusion: With current planning for human exploration of Mars goes a two-way contamination

threat. First, there is the threat of dust contaminated by terrestrial organisms being released and dispersed in the martian environment. This threatens our ability to determine whether Mars has (or ever had) its own biosphere, and potentially compromises our ability to exploit Mars' natural resources, should they become contaminated. Next is the threat that astronauts, affected by the Mars environment, might be unable to ascertain whether their ailment is simply due to exposure to chemical irritants or due to exposure to an environmentally-encountered martian organism.

Mitigation of these threats comprises a multi-part solution. First, a significantly enhanced knowledge of the martian environment and its effects, particularly the dust environment, its chemistry and habitability is required. Second, a more complete understanding of the release, processes and fate affecting terrestrial biota introduced into the martian dust environment is required. Third, the performance requirements for the systems and operations of the mission architecture is needed to appropriately control the ingress and egress threat of martian and terrestrial material, respectively.

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A LOW-COST, LOW-RISK MISSION CONCEPT FOR THE RETURN OF MARTIAN ATMOSPHERIC DUST: RELEVANCE TO HUMAN EXPLORATION OF MARS. M. Wadhwa¹, L. Leshin², B. Clark³, S. Jones⁴, A. Jurewicz¹, S. McLennan⁵, M. Mischna⁴, S. Ruff¹, S. Squyres⁶, and A. Westphal⁷, ¹School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, ²Worcester Polytechnic Institute, Worcester, MA 01609, ³Space Science Institute, Boulder, CO 80301, ⁴Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, ⁵Department of Geosciences, Stony Brook University, Stony Brook, NY 11794, ⁶Department of Astronomy, Cornell University, Ithaca, NY 14853, ⁷Space Science Laboratory, University of California, Berkeley, CA 94720.

Introduction: SCIM—Sample Collection to Investigate Mars—is a revolutionary concept for a low-cost, low-risk mission that would bring back the first-ever samples from Mars. Using an innovative mission design, SCIM would gather samples of martian dust during a Mars aeropass, without landing or even entering orbit around Mars (Fig. 1). Utilizing the extensive experience gained from the Stardust and Genesis missions, these samples would then be returned to Earth. This mission would collect a suite of samples that is distinct from that currently being planned for other sample return missions that are under consideration. As such, SCIM would serve as a scientific, technological and operational pathfinder for future surface sample return and human exploration to Mars.



Figure 1. Artist's concept of the SCIM spacecraft making a Mars aeropass at an altitude of ~40 km to collect dust particles.

Mission overview: The baseline payload for the SCIM mission concept consists of aerogel collector modules (similar to those successfully flown by Stardust) and a camera. SCIM would incorporate stringent planetary protection features consistent with COSPAR and NASA Planetary Protection policies

(<https://planetaryprotection.nasa.gov>). Only after both the aeropass and the sterilization processes have been successfully implemented would deep space maneuvers retarget SCIM back to Earth, where the Sample Return Capsule would descend by parachute in an identical manner to the Stardust mission.

SCIM is responsive to MEPAG and Planetary Science Decadal goals: NASA's systematic Mars exploration approach over the previous decade has deployed missions that have studied martian processes with increasing precision, resolution, and specificity. As highlighted in the most recent National Academies Planetary Science Decadal Survey [1], the next major step in Mars exploration is returning samples to terrestrial laboratories for analysis, where the variety and precision of measurements far exceed practical in situ or remote sensing capability. Sample return missions enable the analytic capability required to achieve high-priority science as defined by the science community as well as to address concerns specific to future human exploration.

Surface sample return missions to Mars are necessarily faced with significant challenges of entry, descent, landing, surface operations, followed by launch and orbit rendezvous, and planetary protection, which result in high mission risk as well as cost. SCIM uses a novel, innovative mission design to lower the mission risk by eliminating many of these challenging steps while returning the first martian samples with a much lower risk. Recently returned Stardust and Genesis samples illustrate the value of applying high precision, cutting edge terrestrial laboratory instruments to extraterrestrial materials collected and returned to Earth. In particular, experience with the comet Wild 2 coma dust particles collected in aerogel and returned by the Stardust mission validates the approaches that would be used for the collection, extraction and analysis of martian atmospheric dust by SCIM (Fig. 2). Indeed, analysis of the Stardust samples has resulted in findings that have fundamental implications for the origin of cometary bodies and their components (e.g., [2] and references therein). Martian dust samples returned to terrestrial laboratories by SCIM and analyzed with state-of-the-art instrumentation in Earth-based laboratories (Fig. 3)

would likewise provide fundamental new constraints on martian hydrologic, sedimentary, volcanic, and climatic processes, and a unique comparative basis for understanding how and why Mars has evolved so differently from Earth. In doing so, SCIM would be responsive to two of the three themes identified in the recent Planetary Science Decadal Survey [1], i.e., (1) Planetary habitats—searching for the requirements for life, and (2) Workings of solar systems—revealing planetary processes through time.

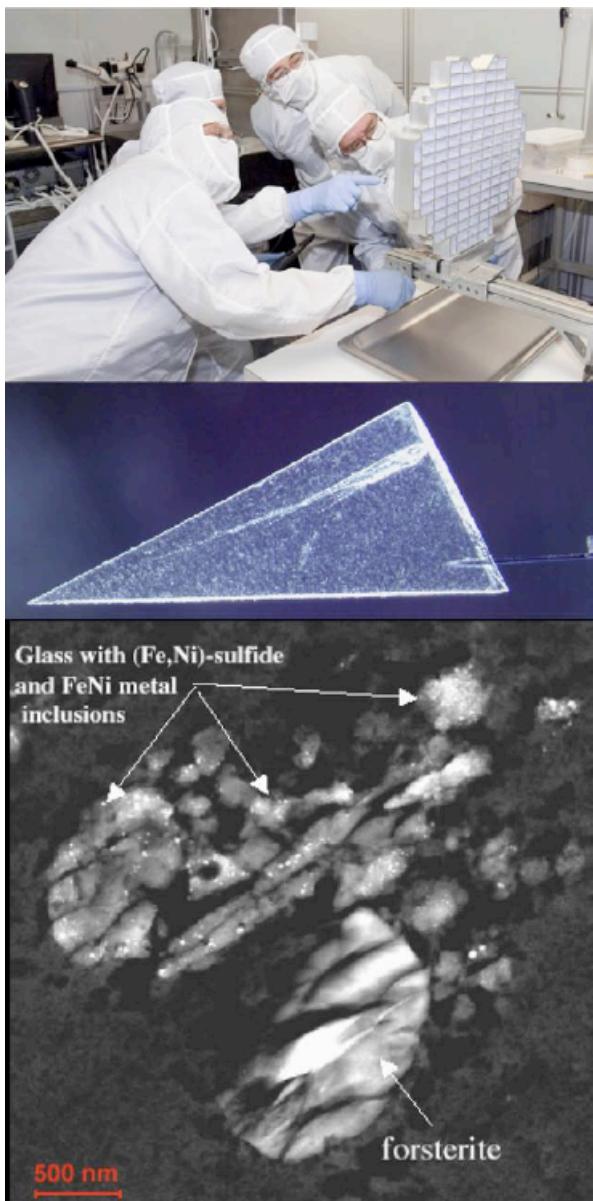


Figure 2. Top: The Stardust team examines the sample tray in the Johnson Space Center curation facility. Middle: A slice of Stardust aerogel with a 5 mm long particle track. Bottom: Electron microprobe dark field image of a 5 micron grain. Image credit: NASA.

The particular priority questions within these themes that would be addressed include: (a) Did Mars host ancient aqueous environments conducive to early life, and is there evidence that early life emerged?; (b) Can understanding the roles of physics, chemistry, geology and dynamics in driving planetary atmospheres and climates lead to a better understanding of climate change on Earth?; (c) How have the myriad chemical and physical processes that shaped the solar system operated, interacted and evolved over time?

Moreover, SCIM would also fulfil some key objectives of three of the four goals identified by MEPAG [3], i.e., goals II (understand the processes and history of climate on Mars), III (understand the origin and evolution of Mars as a geological system), and IV (prepare for human exploration). Mars atmospheric dust is thought to approximate a global average of the martian crust and, furthermore, represents the only planetary regolith besides Earth's known to have been exposed to hydrolytic, atmospheric, and possibly even biologic weathering processes. As such, this dust provides an opportunistic sample of crustal materials, likely including both primary igneous and secondary altered materials. Accordingly, atmospheric dust was also recognized by the End-to-End International Science Analysis Group (E2E-iSAG) [4] as a high priority sample for return to Earth, but one that may be problematical to obtain from the Mars surface. The return of even a small amount of martian fines as represented by the atmospheric dust samples to be returned by SCIM would complement the future return of a cache of well-characterized geologic samples from a specific, compelling landing site, as advocated by MEPAG.

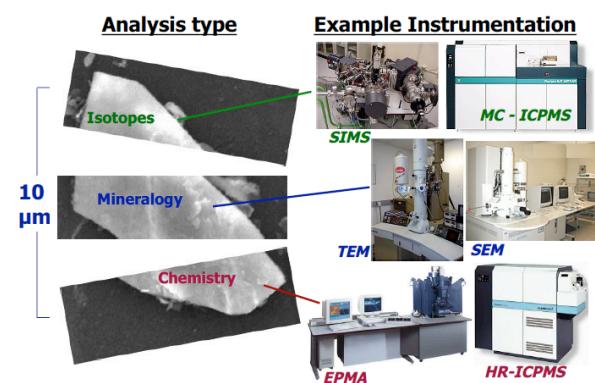


Figure 3. Recent advances in the manipulation and preparation of small samples as well as in analytical techniques have made it possible to fully characterize the chemistry, mineralogy and isotope compositions of micron-sized individual particles.

SCIM is relevant to human exploration of Mars: As discussed in the previous section, SCIM would funda-

mentally advance our knowledge of the geology, climate and habitability of Mars. However, analyses of Mars atmospheric dust samples returned by SCIM would also provide critical constraints for assessing the potential hazards that this dust presents for future human exploration of Mars.

The martian atmosphere typically contains 10-400 billion metric tons of dust [5], ranging in diameter from <1 to >10 μm [e.g., 6,7]. The ubiquity, abundance and fine-grained nature of this dust makes it a potentially significant hazard for human health as well as the engineering aspects of future crewed missions to Mars. While some of the bulk characteristics of martian fines have now been characterized (e.g., [8-10]), there is still a lot of uncertainty about the detailed mineralogy and geochemistry of the fine-grained atmospheric dust (particularly at the sub-micron spatial scale, and for components that may be present at the minor or trace levels). Understanding in detail the composition of the martian dust sample that would be returned by SCIM would help to more rigorously assess the hazard posed by this material. Without this, the uncertainties in the potential risks posed by this dust could drive the design and costs of human missions.

Finally, SCIM would advance the goals of human space exploration of Mars not only through its science, but also through its systems. It would demonstrate our ability to perform a round-trip to Mars, and would do so while traversing deep into the atmosphere, allowing “aerocapture-like” atmospheric parameters to be measured in the process. However, the entry angle and streamlined shape of SCIM’s aeroshell would not allow it to be captured, but rather it will exit the atmosphere and retain enough velocity to return to Earth. The SCIM shape, more slender than blunt, is comparable to the vehicle designs that may be flown to Mars for crewed missions. SCIM would allow NASA to gain experience flying such vehicles prior to sending actual crewed spacecraft. Moreover, by performing the entry and exit through the upper atmosphere for the aero-pass, SCIM would provide valuable new data on atmospheric conditions that could be compared to that obtained with prior missions and would enhance the data set needed for accurate targeting of landing sites by future missions, including crewed missions to Mars.

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ELECTROCHEMICAL REACTION AT SURFACE INDUCED BY ELECTROSTATIC DISCHARGE DURING MARS DUST STORM AND DUST DEVILS. Alian Wang¹, Y. C. Yan¹, Z. C. Wu², ¹Dept. Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis, 63130, USA; ²Institute of Space Science, Shandong University, Weihai 264209, China; (alianw@levee.wustl.edu).

Electrostatic Discharge (ESD) induced by near-surface atmospheric events: Triboelectrical (frictional) charging of dust particles is expected to happen in volcanic eruptions, grain saltation, and especially, during martian dust storms (MDS) and martian dust devils (MDD). MDS occurs annually in regional scales and once per 2-3 years in global scales, which cover the majority of martian surface for months at a time[1]. MDD occurs frequently throughout the planet [2-4].

A general understanding is that the frictional electrification tends to result in negative charge on smaller grains (e.g., dust) and positive charge on larger grains (e.g., sand) [5]. During a convective Aeolian processes (MDD & MDS), the upward lifting of lighter and negatively charged grains with the heavier and positively charged grains remaining closer to the surface would generate a large scale charge separation, an active electric (E) field (Fig.1)

This understanding was supported by many terrestrial E-fields measurements during the passage of small dust devils, some have measured strength $> 100\text{kV/m}$ [6-8], depending on the size of DD, wind velocity, and the atmospheric conductivity. Once a local E-field reaches a saturation value (*breakdown electric field strength, BEFS*), the *electrostatic discharge (ESD)* would occur. The *BEFS* value on Mars ($\sim 20-25 \text{ kV/m}$) is estimated 1/100 - 1/150 times of that on Earth ($\sim 3 \text{ MV/m}$), because of its thin CO₂ atmosphere near the surface, i.e., **ESD is much easier to occur on Mars.**

ESD can happen in different forms [9], i.e. *Townsend dark discharge(TDD)*, or *normal glow discharge (NGD)*, or *lightning/arc* (Fig. 2). Regardless of the exact nature, *ESD* events would generate large quantity of high-speed-electrons (electron avalanche). When colliding with the molecules in Mars atmosphere, CO₂, O₂, N₂, Ar, and H₂O, they would cause the molecular ionization and/or dissociation, resulting positive and negative ions, plus neutral molecules of new species[10]. These charged particles with considerable

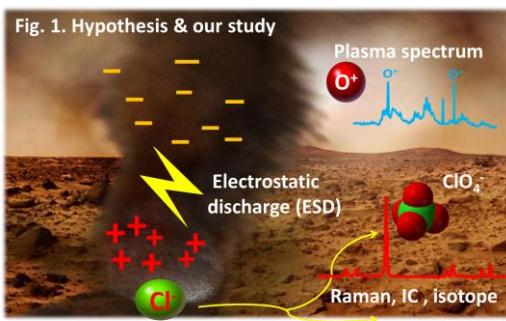
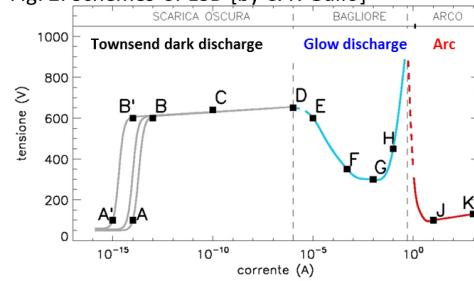


Fig. 2. Schemes of ESD [by C. F. Gallo]



kinetic energy would stimulate the *electrochemical reactions* in near-surface atmosphere and in martian surface/shallow subsurface.

Electrochemical reactions might be a mechanism to drive Cl-phase transformations at Martian surface: Large amount of materials from secondary processes were found at the surface and shallow subsurface on Mars. For obvious reasons, *aqueous chemistry processes* have been considered responsible for the majority of secondary phases, e.g., silica, phyllosilicates, and salts [11]. The finding of perchlorate by Phoenix mission [12, 13], with abnormally high ClO₄/Cl ratio, brought up the

importance of *photochemistry processes* [14]. Through the efforts of modeling, experiments, and terrestrial analog studies, the role of *photochemistry* in the generation of chlorate/perchlorates was supported, its importance in Cl-cycle on Mars is also implied [14-17].

Nevertheless when going into the quantitative details, it was found that 1D photochemistry model was unable (by seven order of magnitudes less, 10^{-7}) to account for the abnormally high ClO₄/Cl ratio found by Phoenix [18]. In addition, a set of abnormally negative $\delta^{37}\text{Cl}$ was recently found in all seven solid samples analyzed by MSL-SAM instrument at Gale Crater [19]. These Martian data are largely different from those observed in the samples from Atacama Desert, for which *photochemistry process* was accepted to be the major contributing mechanism [14, 17]. These discrepancies posted a call for a NEW mechanism that would potentially take the major responsibility for Cl-bearing phase transformations on Mars.

We proposed [20-22] that the *electrochemistry processes* induced by Mars Dust Storm (MDS) and Dusts Devil (MDD) can be an important & dominant mechanism responsible for the transformation of chlorides (Cl⁻¹) to oxychlorine salts (Cl⁺¹, Cl⁺³, Cl⁺⁵, Cl⁺⁷) by Mars atmosphere–surface interaction. A recent modeling paper [23] also suggests the role of *electro-*

chemistry process, induced by Galactic Cosmic Ray (GCR), Solar Cosmic Ray (SCR), and Solar Energetic Particles (SEPs).

Simulated ESD experiments in PEACH: We have designed and conducted a set of ESD experiments to study the generation of oxidants in simulated Mars atmosphere in a Mars chamber[21] and the phase transformation from Cl-1 to Cl+1, Cl+3, Cl+5, Cl+7 [24]. Our goal is to search for an important mechanism responsible for large amount of perchlorate found on Mars.

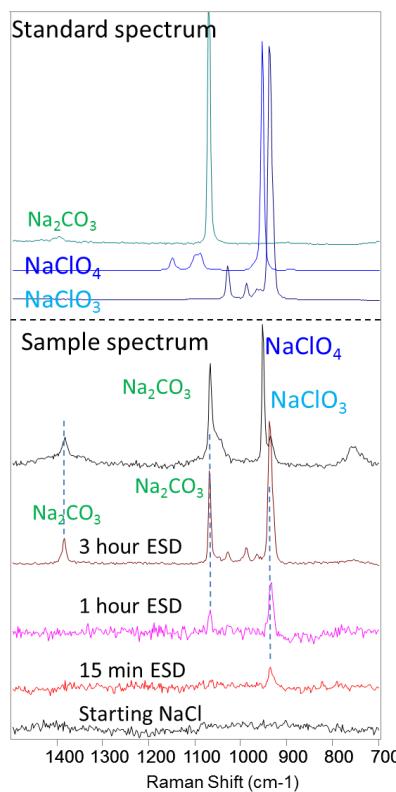
We have built an apparatus and realized stable ESD in our Planetary Environment and Analysis Chamber (PEACH[25]), which is capable to maintain Mars atmospheric pressure, composition (pure CO₂, CO₂+H₂O, and Mars Simulating Gas Mixture, MSGM), and a well-controlled sample temperature (T) range relevant to Mars surface and shallow subsurface. Furthermore, PEACH is equipped with four *in situ* sensors for the characterization of molecular species, before, during, and after the ESD-experiments.

Our first set of ESD experiments concentrated on identifying the oxidant species generated from simulated Mars atmosphere. In pure CO₂, CO₂+H₂O, and a MSGM of 95% CO₂, 2% N₂, 2% Ar and 1% O₂, the major oxidants identified by *in situ* plasma optical spectroscopy are: CO₂+, O (I), Ar (I), N₂, H_α, and OH- [21]. Our second set of experiments concentrated in Cl-bearing phase transformation stimulated by ESD. A powdered NaCl sample was the starting phase.

We have generated ESD by using both DC and AC power supply, with most experiments conducted using AC power for the convenience of laboratory operations. In addition, we controlled our ESD experiment in form of *Normal Glow Discharge (NGD)*, in order to use plasma optical emission spectroscopy (Fig.1) to identify the generated oxidants.

Breakdown Electric Field Strength (BEFS): In our experiments, the ESD in form of *Normal Glow Discharge (ESD-NGD)* could only be seen when the pressure in PEACH (pure CO₂, or CO₂ + H₂O, or MSGM, or

Fig. 3. Identification of chlorate and perchlorate formed from chloride stimulated by ESD in a Mars chamber



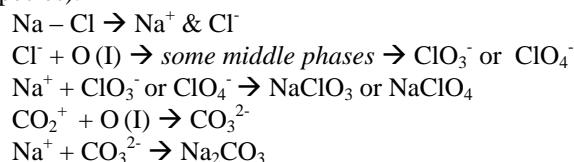
air) being reduced to < 9 mbar. The measured BEFS is a strong dependent of atmosphere pressure (P) that is consistent with the prediction. It is also a dependent of atmospheric compositions, a result of breakdown energy required by different types of molecule in atmosphere. We found the BEFS for ESD-NGD at 3mbar was ~ 34 kV/m in CO₂ or MSGM and ~ 28.5 kV/m in air. We thus demonstrated that **ESD would be much easier to occur on Mars than on Earth.**

Raman characterization of Cl-phase transformations through ESD: We first use laser Raman spectroscopy to characterize the molecular species generated in the electrochemistry reaction between plasmatic oxidants and NaCl. Fig. 3 shows the Raman spectra measured *in situ* on the solid samples in ESD sample cup.

Note the starting phase NaCl does not have a fingerprint Raman peak owing to the ionic nature of Na -- Cl bond (bottom spectrum in Fig. 3). A Raman peak at 936 cm⁻¹

first appears in a sample after 15 min ESD experiment in PEACH at 3 mbar CO₂ (Fig. 3), suggesting the **instantaneous formation of an oxychlorine salt**. The intensity of this peak increases following the lengthening of the ESD duration (to 3 hours). At a few sampling spots, a Raman peak near 954 cm⁻¹ appears, suggesting the occurrence of NaClO₄, which obviously is a minor component in the ESD products. Furthermore, a strong peak at 1068 cm⁻¹ and a weak peak at 1386 cm⁻¹ appear later in every Raman spot, whose positions suggest the occurrence of Na₂CO₃.

The identified new molecular species in ESD products would imply the following possible electrochemistry reactions (pending further study of some middle species):



IC (Ion Chromatography) to quantify the produced oxychlorine species:

Fig. 4a shows the detected ClO_3^- (in ppm) from four layers of two ESD samples. The IC data first confirmed that the generated oxychlorine salt is dominantly NaClO_3 , whose quantity increases with time exposed to ESD under Mars environmental conditions, and consistent with Raman detection. There is also an obvious surface enrichment (Fig.4a, 4b) of both oxychlorine species, implying a link to an atmosphere-surface interaction.

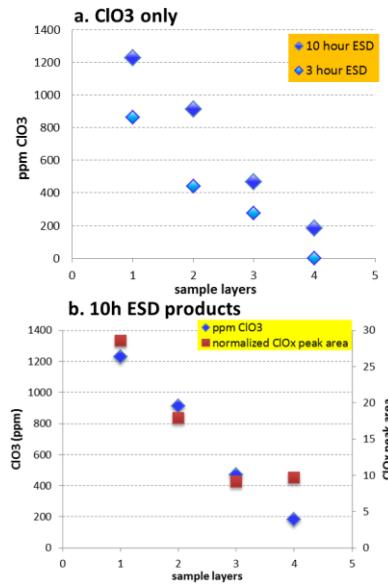
Although at this moment, we cannot fully identify and quantify the ClO_x^- in ESD products, its IC peak area should be a linear function of its concentration. There is a close agreement in relative abundance of both products can be found. It is likely a reflection of a fixed relative probability for two reactions (of forming ClO_3^- or forming ClO_x^-) to occur in our specific plasma-solid electrochemical reaction, which needs further investigation.

This study demonstrated the formation of oxychlorine salts from chloride stimulated by electrostatic discharge in an environment simulating the ESD that might occur in MDS and MDD. The data imply (1) the formation of oxychlorine salts is instantaneous; (2) the formation is through an atmosphere-surface interaction; (3) there might exist a fixed pattern between the forming reactions of two types of oxychlorine salts in this specific electrochemical reaction that is worthy further study.

Implication --Electrostatic Discharge on Mars: Two E-field sensors were planned for two missions to Mars, ECHOS/MATADOR for the Mars Surveyor 2003 mission [6] (Mars mission line was restructured in 2000-2001 and Mars03 was then replaced with MER) and MicroARES [8] for ExoMars entry, descent and landing demonstration module (EDM, crashed in 2016 during landing). In addition, the dust devils observations made by MER rovers have not provided convincing evidence for ESD occurrence during MDD.

Hitherto, without an actual E-field measurement on Mars, it is hard to guess which type of ESD, *Townsend Dark Discharge* (TDD) or *Normal Glow Discharge* (NGD), might occur during Mars atmospheric events. In order to detect oxidants, we controlled our simulation experiment in NGD regime, which has a larger

Fig. 4. quantification of ClO_3 and ClO_x by IC



electron flux but lower kinetic energy per electron than TDD (Fig. 2). If in some cases, ESD on Mars takes the form of TDD[13], it would have a slightly higher capability in generating oxidants than our experiment[21], but it would take a longer time in forming chlorate/perchlorate than our experiments [24]. For both cases, the results from our simulation experiments are valid in a conservative way.

Acknowledgement: NASA MoO project (06-Scout06-0027-#49137- NRA 1295053) for ExoMars, a special support from McDonnell Center for the Space Sciences at Washington University in St. Louis, Bill Farrell and Paul Dowkontt for many advices.

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Martian Dust Impact on Human Exploration

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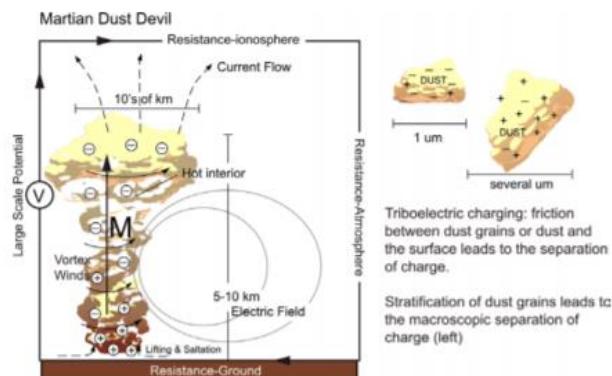
Introduction: Local, regional, and global dust storms have been blowing small, fine, and probably electrostatic grains in Martian atmosphere. Through the surface operations on the Moon of Apollo missions, it is expected that preventing Martian dust from penetrating into spacesuits, human habitats, and mobility systems will be challenging.[1] The thin Martian atmosphere warmed by sunlight as well as mobility system operation and astronaut walk will lift dust off the ground. Understanding Martian atmospheric electricity, and dust impact on human health, surface mechanical systems and surface operations are critical to reduce the risks of the human exploration on Mars.



Martian dust over Tempe Terra, seen by Mars Express on June 17, 2011 (Credit: ESA)

Electrical properties of Mars atmospheric dust: Significant data about dust properties have been obtained from Phoenix, MER (Opportunity and Spirit) and Curiosity. However, none of the instruments did soil conductivity test, which is critical to reduce the risks during Martian surface operations. Laboratory experiments and observations suggest that triboelectric effect causes dust electrification, and smaller particles tend to gain negative charge while larger particles

tend to gain positive charge during collusion.[2][3][4]



A model of a Martian dust devil demonstrating how charged particles generate electric fields (Credit: Delory et al. 2011)

Direct measurement of Mars atmospheric electricity will be helpful to understand the charge transfer mechanism in details. The Schiaparelli Entry and Descent Module(EDM) of ExoMars 2016 crashed in October 19, 2016; consequently, its payload DREAMS(Dust Characterization, Risk Assessment, and environment Analyzer or the Martian Surface) is no longer available to measure the atmospheric electric fields close to the surface of Mars. ExoMars 2020, launched in July 2020, will directly measure Martian atmospheric electricity using its scientific instruments Dust Suite (Dust particle size, impact, and atmospheric charging instrument suite) and RDM (Radiation and dust sensors). Furthermore, the sample return of Mars dust collected by MARS 2020 is expected to answer many questions in regard to Martian atmospheric electricity.

Martian dust impact on human health: None of the instruments sent to Mars could measure how toxic Mars dust and regolith are

to humans. On Mars, silicate minerals, perchlorates and gypsum exist in regolith or atmospheric dust. It is known that silicate dust causes respiratory disease silicosis, perchlorates damage thyroid gland, and substantial amount of inhaled gypsum damages lungs.[5] Especially, it is critical to understand the presence and distribution of Hexavalent Chromium (CrVI), which is known as a carcinogen.[6]



Dust covered Apollo 17 astronaut Gene Cernan, seen on the lunar surface (above) and aboard the lunar module (below) on the Moon in December 1972 (Credit: NASA)

While astronauts of the six missions (Apollos 11, 12, 14, 15, 16, and 17) were exposed to lunar dust less than 10 days, astronauts on Mars will be exposed to Martian dust at least one year if dust enters and remains in their habitats and spacecraft for their return trip to Earth, which may be long enough to develop serious illness.

Martian dust impact on human health can be better understood through data collected to study the association between human health and dusts such as Dust Bowl in 1935, and seasonal African and Asia dusts. In all three cases, a higher rate of respiratory problems is reported when dust density increases in the air.[7] Many findings and health prevention practices to avoid dust impact on Earth are worthwhile in the effort to protect astronauts on Mars.

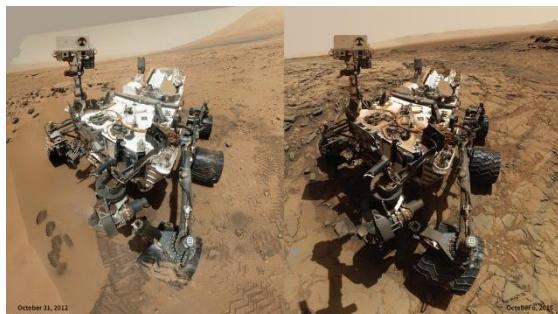
In order to protect astronauts from inhaling Martian dust, all possible preventive measures need to be developed and available onsite. Astronauts should be aware of the strength of electric fields before EVA. Electrometer [8] to detect static levels on Mars and charge-dissipation technology such as anti-dust agent need to be developed. Astronauts need to carry portable electrometers during EVA to avoid highly charged area, and permanent electrometers need to be installed in Service Field Station, Science and Resource Regions of Interest (ROIs) in Exploration Zone (EZ). Disposable Martian airtight dusters need to be developed. By wearing a disposable airtight duster on a spacesuit, an astronaut can prevent dust from sticking on the spacesuit. Furthermore, an effective airlock system as well as filtering technology to remove imported dust in living quarters need to be developed. The human landing site on the surface of Mars should be chosen among sites with a history of minimal local and regional dust storm occurrence and weak electric fields close to the surface.

Martian dust impact on surface mechanical systems and surface

operations: Significant data about dust effects on mechanical surface systems on Mars have been obtained from Phoenix, MER (Opportunity and Spirit) and Curiosity. MEPAG Goal IV Science Analysis Group (2010) highlights the importance to understand the effect of dust on seals and electrical properties of mechanical surface systems, and the corrosive chemical effects of dust on different materials.[9] The effort to understand Martian dust properties using current assets on Mars should be continued until a sample of Martian dust returns to Earth.

Spirit and Opportunity, designed for a minimum 90 days operation, far exceeded their lifespans and survived during the global

dust storm in 2007. Curiosity has exceeded its target lifespan also. The performances of the three rovers are promising in terms of supporting human exploration on Mars.



Dust accumulated on Curiosity in October 31, 2012(left) and October 6, 2015(right) (Credit: NASA/JPL-Caltech)

Human presence on Mars will significantly reduce the adverse effects of dust on surface systems. Trained astronauts will be able to maintain the surface systems in a properly working condition by removing dust on surfaces, fixing or replacing malfunctioning components, and minimizing or preventing corrosion with anti-corrosion agent treatment. Technology to manufacture mechanical parts using 3D printers need to be developed for the use in Exploration Zone (EZ).

Sunlight is expected to be a significant energy source to surface mechanical systems and surface operations on Mars. During the global dust storm in 2007, Spirit and Opportunity experienced a dramatic decrease of solar power supply. All possible ways to harvest energy should be considered. A solar panel system with maximum performance in dust storms, equipped with panel cleaning capability such as dust wipers, is needed to be developed. Due to the low atmospheric density on Mars, which is about one percent of Earth's, harvesting energy using wind force is expected to be minimal. Nevertheless, the wind power system, which is relatively easy to install, can supply an additional energy when a dust storm passes through Exploration Zone (EZ). A radioisotope power system (RPS), which can complement the solar panel

system and the wind power system, and an efficient energy storage system need to be developed.

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The Spatial and Temporal Distribution of Dust in the Atmosphere of Mars. Richard W. Zurek, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Mail Stop 321-690, Pasadena, CA 91109. *Richard.W.Zurek@jpl.nasa.gov*

Introduction: The presence of dust in the atmosphere of Mars profoundly influences its density-temperature structure and wind patterns, as well as the surface environment. The absorption of solar radiation during the day and the exchange of infrared radiation both day and night provides a powerful thermodynamic drive for atmospheric circulation. In many respects, dust is the heat reservoir for the non-polar Mars atmosphere in that its redistribution and subsequent radiative heating and cooling alter vertical and horizontal temperature and pressure gradients. This provides a major feedback for the system: Winds lift dust into the atmosphere and heating of the dust alters pressure and temperature at a given height and these changes drive winds.

Atmospheric dust affects the environment in other ways, as well. Dust aerosols serve as nucleation centers for the condensation of water and carbon dioxide ice. These condensate clouds, optically thin outside the winter polar region, also affect the environment, primarily through their infrared radiative effects, but also by scavenging water and the dust itself from the atmosphere. In the polar regions, dust particles can nucleate carbon dioxide snow whose fall-out affects the surface ice properties, particularly in the south.

Dust Entry into the Atmosphere: Dust enters the atmosphere wherever it is present and winds are strong enough to lift it. This can occur by winds blowing across the surface through saltation of sand-size grains and lofting of the finer particles they dislodge, but also by mesoscale low pressure vortices whose entrainment of dust forms dust devils across much of the planet.

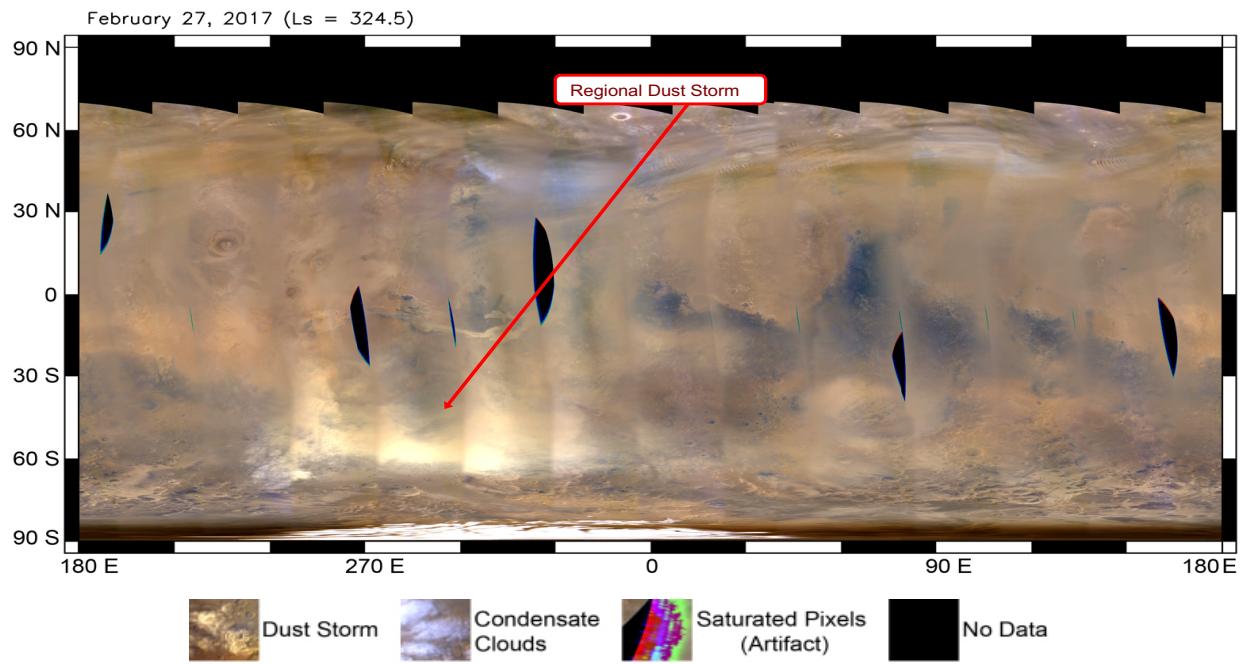
The strongest winds near the surface occur at the edges of the polar caps where strong temperature/pressure gradients occur across the boundaries of bare ground and icy surfaces. Undulation of these jet streams can spawn local storms which concentrate the winds along fronts or convective rolls. When these are strong enough, dust is actively raised and the storm is now a local dust storm. Generated at high latitudes, some of these local dust storms move to lower latitudes and thus affect much of the planet. On occasion these storms can grow, or centers of activity can coalesce, to cover large portions of the planet. Events covering $\sim 10^6 \text{ km}^2$ are classified as regional storms and a handful of these can produce hazes that encircle the planet.

During the present epoch, these regional and planet-encircling events occur in the southern hemisphere during its spring and summer, often triggered by local dust storms generated near the northern winter polar vortex that then travel south through the great northern basins (primarily Acidalia and Utopia), eventually crossing the equator.

Observations of Dust Distribution: Telescopic observers of Mars glimpsed such storms on occasion as movable “yellow clouds”. Today we have the benefit of ~20 years of practically continuous coverage of the weather of Mars, including these storms, thanks to the daily global coverage of the Mars Global Surveyor (MGS) Mars Orbiter Wide Angle Camera (MOC-WA) and its successor, the Mars Reconnaissance Orbiter (MRO) Mars Color Imager (MARCI)^{1,2}. Figure 1 shows recent daily global maps from the latter. MARCI looks limb to limb across the near polar spacecraft ground track. This, of course, is not a true synoptic view of Mars; all areas are not seen at one moment in time. Instead, the map is a composite of swaths imaged on the 12-13 orbits MRO makes each day. This means that the center of each swath is near 3 p.m. local time while the edges are closer to 1.5 hours earlier and later, so that the phase angle of the Sun varies significantly from left to right across the swath, giving rise to the visible discontinuities across the map. Similar maps of column dust opacity are made on a less frequent basis from IR radiometers³; e.g., the Mars Odyssey (ODY) THEMIS instrument. Maps of dust extinction and temperature can also be made for different pressure levels from globally sampled limb profiles retrieved from MRO Mars Climate Sounder data⁴.

Readily apparent on many of the daily visual image maps are the local dust storms in both hemispheres, typically moving in the jet streams along the edge of the polar caps. On occasion these local storms can bloom into regional events, usually in the southern hemisphere, during a “great dust storm season”⁵ that spans much of southern spring and summer. In the south such regional storms arise by expansion or coalesce of local storms as they move from the seasonally varying polar cap edge into southern mid-latitudes. From the north, a local storm may move out of high latitudes and across the equator where it may develop into a regional storm once it reached the southern mid-latitudes.

Figure 1: MARCI Daily Global Map for late southern summer in Mars Year 33. A large regional dust event is shown. The black gores (no data) are produced when the MRO spacecraft rolls to the left or right to target observations by high-spatial-resolution imagers. Also, the winter (north) pole is still in polar night. (Malin & Cantor, Malin Space Sciences Systems, all rights reserved).



Dust Storm Pathways and Evolution: Local dust storms can occur in any season and can affect nearly any place on the planet, but there are preferred storm tracks where local storms more frequently move from the high latitudes of storm generation towards the equator. Model simulations show that the tracks for the northern dust storms are due in large part to the channeling by topography of essentially western boundary currents in the large basins. Whether these local storms cross the equator can depend on the time of day, as the large-scale winds at low latitudes have a significant diurnal variation, opposing or amplifying the storm movement, producing a “tidal (time-of-day) gate”⁶.

The cause of local dust storms expanding into regional events is not understood. There are examples of apparently identical local dust storms in two different Mars years but otherwise at the same season and traveling the same path; one grows into a regional event, the other does not. Possibly, it has to do with the vertical penetration of the storm.

Most local dust storms have little temperature signature above the planetary boundary layer.

However, once dust is lofted higher into the atmosphere, it will be transported away from the active dust-raising centers, producing a haze expanding longitudinally with both in situ and wide-ranging temperature effects observable using atmospheric infrared sounders^{3,4}.

There is a pattern during the southern spring and summer seasons, when Mars is near perihelion and solar heating is greatest, of typically 3 regional events, of varying size (Fig. 2)⁷. In some, but certainly not all Mars years, a regional storm will expand such that the dust haze produced by spatially limited dust raising centers spans essentially all longitudes, producing a planet-encircling, hemispheric or even global dust storm. Historically, the planetary-scale dust events appeared to occur every 3-4 Mars years⁵. This is consistent with events recently observed in 2001 and 2007 (MY 25 and 28). However, there have been no planet-encircling dust events in the last 5 Mars years.

During these events, dust is lofted to quite high altitudes (> 70 km for the 1971 global dust storm).

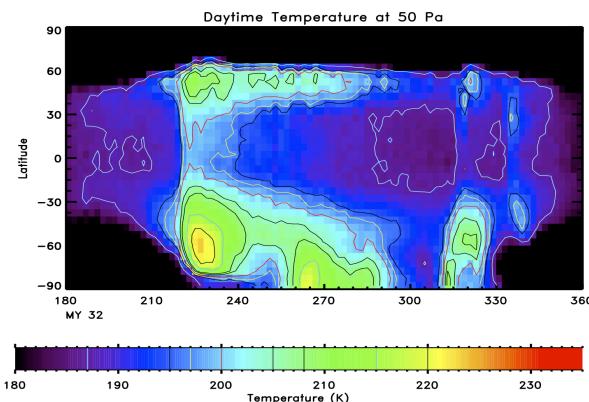


Figure 2: MRO Mars Climate Sounder temperatures at ~25 km altitude showing the direct response of solar heating of regional dust storms in the southern hemisphere and their indirect dynamical (adiabatic) heating in the north. (Kass et al., 2016).

Clearing of the atmosphere after these events takes several months, while regional dust storms may affect the atmosphere for a few weeks and local storms for one to a few days. The clearing of the dust is not necessarily uniform, horizontally or vertically, subject to the large-scale atmospheric circulation. Even the background dust haze produced by more local processes or the tails of these dust events is not uniformly mixed with height⁸.

The potential effects of dust on human missions are several:

- Dust can be anywhere on the planet, but some surface areas and some atmospheric zones are known to be particularly troublesome. As shown in Fig. 3, even during the clearest periods, there is some background dust haze.
- Dust falling from the atmosphere does degrade the efficiency of solar panels such as those on the Mars Exploration Rovers. Fortunately, winds can remove such dust on occasion, which accounts for the multi-year longevity of the solar-powered rovers. During local and more expansive dust events, solar power at the surface can be substantially reduced.
- The surface thermal environment also changes: Daytime temperatures are lower (less sunlight reaches the surface) while nighttime temperatures are warmer due to (infrared radiation by the atmospheric dust, a “greenhouse” warming effect).
- Dust alters the vertical density profile, modifying the environment for entry and landing and aeromaneuvering; the atmosphere can “bloom”

even at high altitudes, affecting aerobraking spacecraft.

Dust Uncertainties: Major uncertainties about the dust distribution are:

- As noted earlier, the full process by which dust storms are generated and evolved are not fully understood; modeling of these developments is known to be deficient in simulating the numbers of events in a given year and in predicting their evolution to larger scales, when that occurs.
- In particular, interannual variability of the largest events has not been successfully replicated.
- Dust reservoirs (i.e., places where dust can be injected into the atmosphere by seasonal winds) are not well delineated; it is possible that some interannual variation is caused by previous removal of the movable dust.

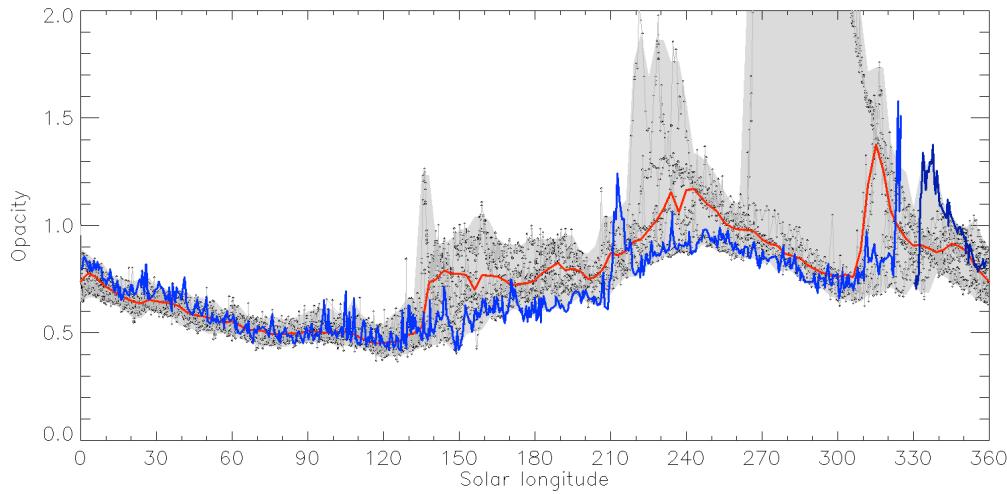
Needed Measurements: Measurements that could improve our understanding of the temporal and spatial distribution of dust in the Mars atmosphere include:

- Continued observation of the global weather and climate of the Mars atmosphere, requiring extended measurements of the current visual imaging and IR temperature/aerosol sounding. New observations, particularly of:
 - Atmospheric temperatures and water vapor, especially near the surface and even in the presence of dust (e.g., at microwave or submillimeter wavelengths).
 - Winds at multiple altitudes, perhaps using active devices like lidar or passive observation of the Doppler shift of emission line features (to model dust redistribution).
 - Detailed characterization of particle composition, size and electrical properties, either in situ or on returned sample materials (to improve physical parameterizations).
 - Storm (weather) prediction desired to support humans on the surface will require a combination of orbital and surface meteorological observations.

Atmospheric Models: Also needed are improved Atmospheric General Circulation Models:

- Fully radiative-dynamic interactive codes (i.e., dust is not prescribed, but is transported and radiatively active).
- Improved dust lifting & removal parameterizations.

Figure 3: Column Dust Opacity above the Opportunity Rover for 2004-2017. Blue line is for last Mars year; red is the median in approximately weekly steps for all years. Gray shaded area includes 95% of all values. (M. Lemmon, Texas A&M University)



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