MHP SSG
Atmosphere Focus Team

A Hazard Assessment from 11 Mars Atmospheric Scientists

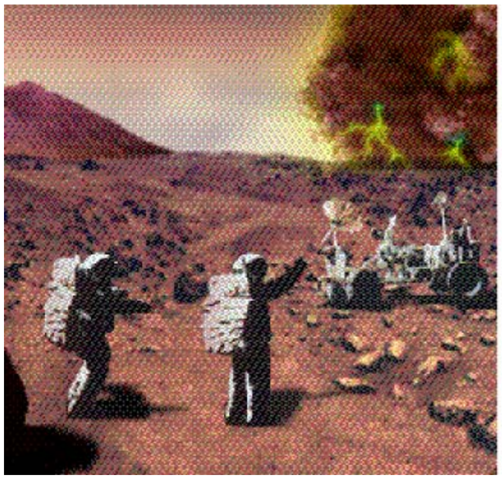
AFT Team Members

W. Farrell	NASA/GSFC	Meteorological and Electrical Processes
S. Rafkin	SWRI	Middle Atmosphere Dynamics
S. Fuerstenau	JPL	Aeolian Electrostatic Processes
G. Delory	UCB	Meteorological and Electrical Processes
D. Banfield	Cornell	Atmospheric Fluid Dynamics
S. Cummer	Duke	Meteorological and Electrical Processes
J. Marshall	SETI	Aeolian Electrostatic Processes
J. Levine	NASA/LaRC	Atmosphere Composition
N. Renno	U. Michigan	Aeolian Fluid Processes
P. Withers	Boston U.	Upper Atmosphere Dynamics
J. Murphy	New Mexico St.	Aeolian Fluid Processes

Four telecons:

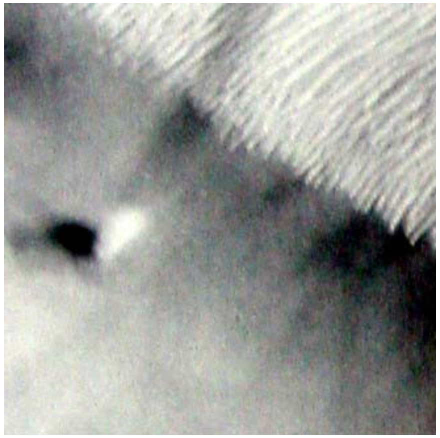
8/11/04 – 11 attendees
8/20/04 – 9 attendees
8/25/04 – 4 attendees
9/1/04 - 10 attendees

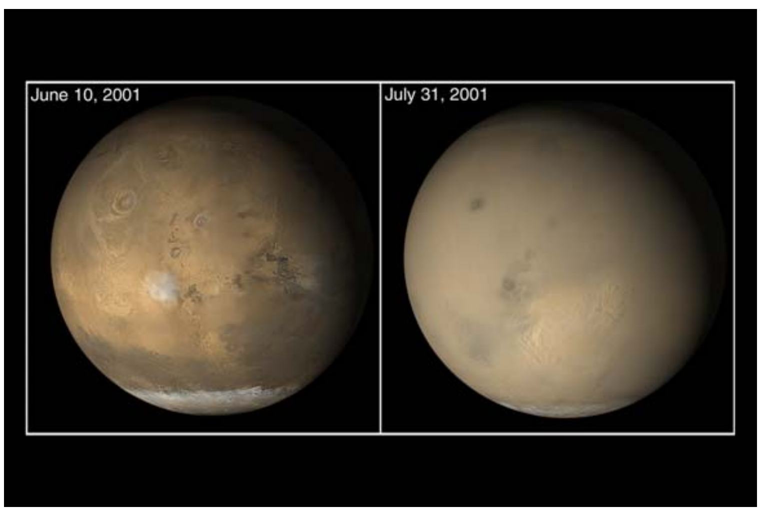
Motivation



- Martian atmosphere is the origin of many possible hazards to both humans and equipment
- The unknown properties of the atmosphere represent a risk to EDL and TAO sequences
  - e.g., MER entry
- Major dust storms may limit EVAs and keep explorers "house-bound"
- Aeolian dust can charge and give rise to large-scale electric fields in dust devils and storms
- The photochemistry may present a hazard to explorers (ties to soil and dust group).
- The AFT will collect these risks and assess their likelihood, consequences, and priority, and provide a set of measuremental objectives for quantification of these risks

Scope





- Consider atmospheric risks from the ionosphere to ground level
- Focus on fluid dynamics with complementary composition and electrical elements
- Some elements of focus already in HEDS portion of MEPAG via

  -4.A.3: Variations in atmospheric parameters that affect flight and suface activity

  -4.A.6: Electrical effects of atmosphere
- More detail will be provided here as compared to MEPAG, including measurementаl objectives

Assumptions

- Human explorers engaged in 3 kinds of activities while on Mars:
  -General maintenance/habitat upkeep requiring local EVA's
  -Outreach/Public Demonstrations (hit golf ball) requiring local EVA's
  -Science exploration as predicted by the 2030 Science Focus Group featuring extended EVA's to study biospheres, etc.
- Science exploration may not be a main driver for Mars Exploration (see ISS). Just getting humans there and back safely may be the minimum success criteria, thus EDL and TAO are issues no matter which activity is engaged
- Exploration code has substantial but not infinite resources. By "substantial" we assume enough funding to support a number of precursor missions including long-stay lander and orbiter (~$1-2B)
- Assume human flight has a run-out cost of >(or >>) $30B

Investigation #1: Determine the fluid variations from ground to 90 km that affect EDL and TAO including both fair-weather and dust storms

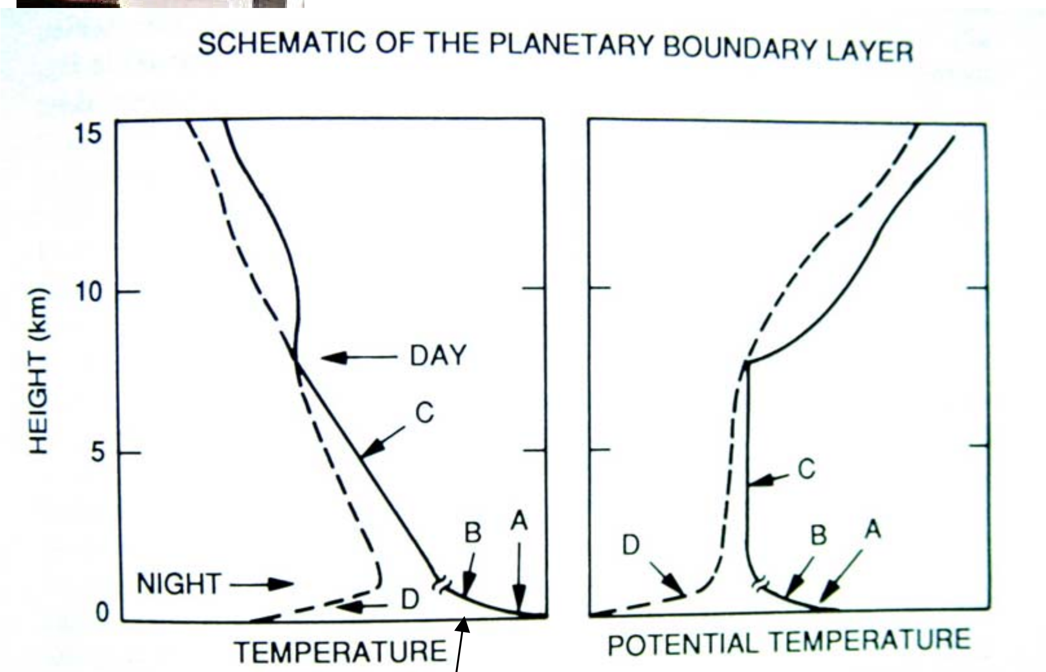
- **Hazard:** That wind shear and turbulence will create unexpected and uncompensatable trajectory anomalies.
- Two primary regions of interest: 30-50 km altitude in middle atmosphere where maximum forces occur and 0-10 km altitude where slow speed and long duration parachute descent is modified by dense moving, atmosphere
- Wind drifts can destroy precision landing
- Could place explorers far away from forward-deployed habitat and supplies
- Density anomalies could lead to unexpected high-impact landings
- Need to design with most extreme conditions in mind
- Some primary questions still unresolved:

  - Density variations at entry

  - Turbulent layers (like in jet streams)

  - Boundary layer dynamics

Mars PBL



Unstable

- Example: Planetary Boundary Layer
- Warm layers lie below cooler layers…naturally unstable
- Daytime unstable region forms near the surface (Region B)
- Gone at night (Region D)
- Convective Region, C , is marginally stable but becomes unstable in summer afternoons leading to turbulence several kilometers thick
- Spacecraft is moving slow and very susceptible to shears and turbulence in this region
- Need to focus on obtaining measurements in this 0-10 km region from orbit to get global view of PBL instabilities
- Tough to do (Doppler Lidar?)

Example: Lessons from MER Landing

- Spirit designed with range of atmospheric states for during EDL
- A week before entry TES observation of dust storm changed anticipated atmosphere
- Based on TES, a new density vs altitude profile was created
- However, the reconstructed atmosphere, done post-flight, indicated a significantly different density (reduced by 15% between 20-30 km) from TES calculation, and was very close to the limit of system performance
- Also, steadily increasing oscillations of both Spirit and Opportunity before parachute deployment nearly exceeded safe range (could get tangled chute).
- Oscillations due to either unexpected atmospheric turbulence (some unknown aerodynamic instability) or mechanical instability of vehicle in fluid.
- Lesson: The atmospheric state is not well quantified, with both models and NRT calculations yielding weather predictions with large intrinsic errors
- Lack of atmosphere information may affect vehicle design, possibly creating unstable descent system
- There are still unexpected turbulent layers, and unexpected affects from large atmospheric dust storms

Special Case: EDL and TAO in Dust Storm

- During EDL and TAO, dust storms give rise to temperature increases that inflate the atmosphere, and effects are felt even by MGS at 100 km.
- Storms capable of exciting large-scale fluid waves and turbulence that give rise to wind drifts and density changes that affect vehicle passage in EDL/TAO.
- The presence of minor dust storm created an unexpected MER EDL profile, even with "up-to-the-minute" data
- Need to understand not only fair-weather Martian atmosphere, but the effects of more violent dust storm case that appears to have affect all heights.
- Entry system designs appears to be set by expected fair-weather atmosphere (which we actually don't know that well)
- EDL design should be upgraded to a set point for the survival through the most violent storm.
- Need to get fundamental information on both fair-weather and storm conditions to establish this set point

Synopsis of the Murphy-Banfield AFT report on Potential Risks vs Altitude

Altitude	Perceived Hazard	Measurement	Instrument
> 90 km	Frictional drag, atmospheric inflation/deflation on aerobraking	Density derived from s/c aerobraking maneuvers	Three-axis accelerometer UV measurements Radio occultation (obtain electron peak height influenced by thermal neutral atmosphere)
60-90 km	Thermodynamic variations affecting trajectory	Few previous measurements T, V, and variations over globe and long baseline	Very difficult to observe remotely, just above IR range and below radio occultation range…in situ measurements from multiple preceding EDLs UV occultation could give density, P, and T Need orbital instrument development
30-60 km	Thermodynamic variations from stochastic processes and waves affecting trajectory in maximum dynamic pressure region, critical region for aerocapture	T, 2-D or 3-D wind field, density over globe and years	Orbital IR nadir spectral measurements giving T profiles to 40 km and limb scans to 60 km, independent wind measurement via in situ EDL sensor and any possible remote sensed instrument (to be developed) UV occultation could give density, P, and T
10-30 km	Thermodynamic variations affecting trajectory with greater dynamic coupling	T, horizontal V over globe and years	Orbital IR nadir spectral measurements giving T, independent wind measurement via in situ EDL sensor and any possible remote sensed instrument (to be developed)
Surface-10 km	Large density and wind speeds could create wind drifts Aeolian electrostatics(?)	Mean and variable T, V over globe and years	Surface upward IR (like Mini-TES) EDL instrumentation Need orbital instrument development (Doppler Lidar?)
Surface	Dust Devil, Dust Storm, Aeolain electrostatic, thermally-generated electric potential	P, V, T, dust density, DC and AC E-field, atmospheric conductivity	MET station – anemometer, pressure gauge, thermocouples, field mill, radio, conductivity probes (atmosphere and ground) Network MET stations

- **Mitigation:** Need a tool to predict the weather both for design purposes and possibly for the actual landing. Best tool is computer codes to predict velocity and density profile expectations along EDL. Need to integrate dust storm conditions into the codes.
- However, verification of codes via measurements is poor/non-existent. Surface measurements limited and very spatially and temporally spread. EDL comparisons basically non-existant.
- Relegating MET measurements to "low priority" relative to life science packages has left fundamental measurements off current platforms (MER, MSL).
- Need high resolution (spatial and temporal) T, V, and P measurements to both set model initial conditions and validation

- **Measurements to Assess Hazard:**

  - V, P, T and n for EDL should be a standard, facilities measurement obtained in **EVERY** future landed missions, including both Science and Exploration missions. Obtain as many profiles at various times and locations as possible. Measurement resolution should be high (~ 100 Hz) to quantify turbulent layers.

- Surface V, P, T should be a standard, facilities package included on **EVERY** landed missions, to help define barometric fronts and surface features used in setting initial conditions for high altitude modeling.

- Dedicated Code T Atmospheric Orbiter mission to remote-sense weather (like GOES project on Earth). Optical camera, IR nadir and limb scans, radio occultation, UV occultation instrumentation, in situ density, temperature information, long baseline mission (see General Recommendations)

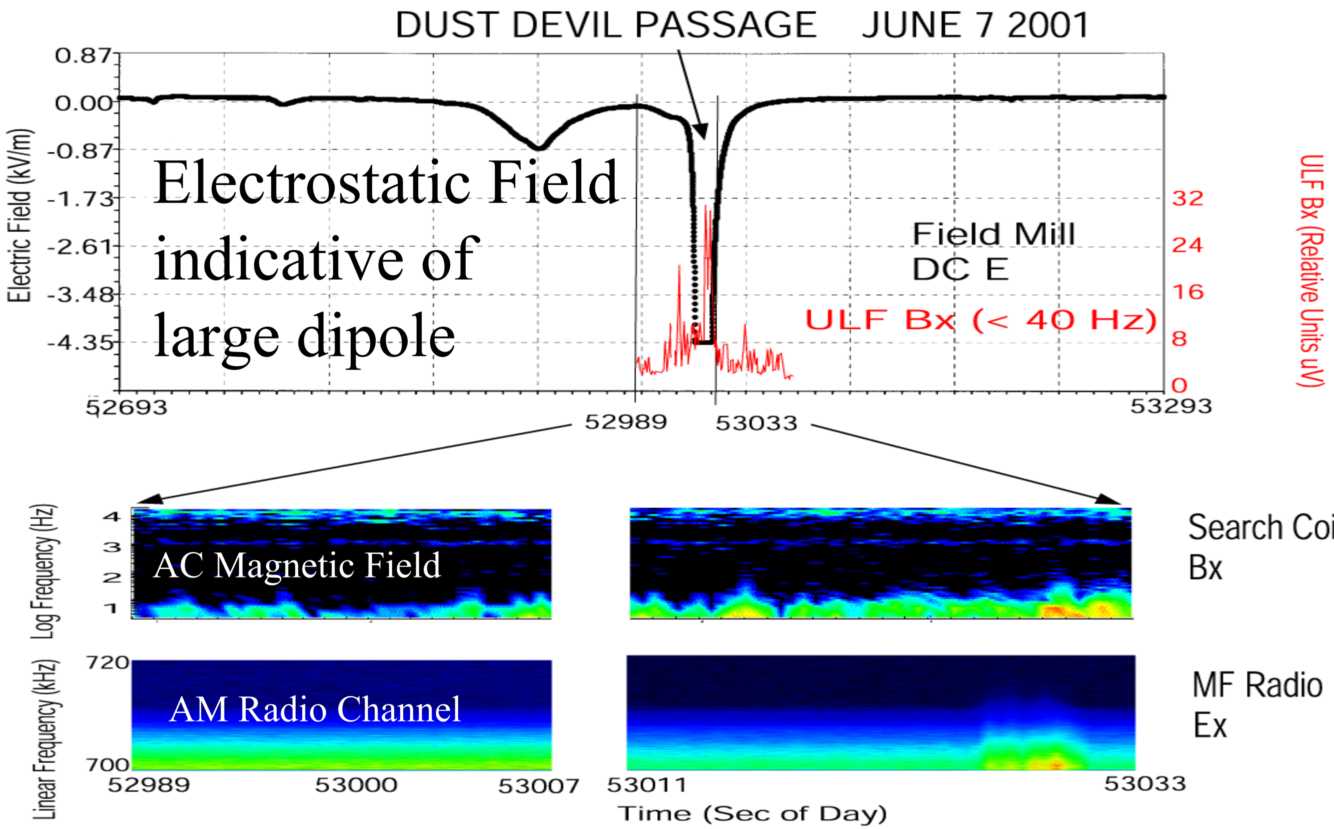
- **Helpful Remote Sensing Tools:** Climate Sounder like on MRO can get thermal profiles to 60 km, UV-IR occultation system, like SPICAM on MEX, can get vertical profiles of concentrations of specific constituents like CO_2 (20-160 km), H_2O (5-30 km), CO (5-50 km), and the trace O_3 (10-50 km)
- **Instrument Need:** A method for coverage of 0-10 km and PBL
- **Priority: 1**

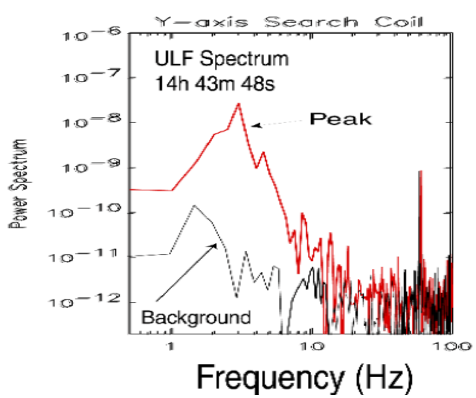
Investigation #2: Derive the basic measurements of atmospheric electricity that affects TAO and human occupation

- **Hazard:** That dust storm electrification may cause arcing, RF interference, and force human explorers to seek shelter during storms
- Recent terrestrial dust devil studies and theory suggest that Mars dust storms and dust devils could contain significant amounts of electrical energy
- Dust storm electrostatic fields can increase local electron current flow to an object, leading to differential charging and possible arcing in the low pressure Martian atmosphere.
- Discharges between charge centers in the dust cloud and ground may adversely affect explorers & equipment, and generate RF contamination in the ULF and HF bands.
- Charged dust leads to increased adhesion, which can be detrimental particularly if the dust is inherently toxic (see Soils/Dust Focus Team report).
- Electrical designs of habitat need to locate a reference “ground”, but this reference is difficult to identify (local atmosphere may be more conductive than near-surface).

- **Mitigation:** Much like terrestrial thunderstorms, the best hazard avoidance strategy might be to seek shelter, with the shelter designed to be electrically safe. However, in major global dust storms that last for months, this strategy could lead to a cessation of EVA's and habitat external maintenance for long periods.
- To date, we have NO fundamental knowledge of the Martian atmospheric electrical system to base any kind of habitat design and mitigation strategy.
- Models based on terrestrial lab studies and desert studies have been created, but NO associated Mars data to verify anticipated behavior

Example: Electric Effects from a passing Terrestrial Dust Devil





- Large DC E fields saturates Field Mill near -4.3 kV/m
- ULF Magnetic signals detected as devil approached and receded
- MF Radio contamination as charged grains impact antenna

MATADOR Dust Devil Study, PI: P. Smith U Ariz.

Special Case: Lightning Discharge during TAO

- Take off and ascent through the near surface dust cloud might induce a discharge, as Apollo 12 did during its ascent. Apollo 12 discharge caused a computer upset that was manually overridden.
- Because the most basic information on Martian dust storm electricity does not exist, one cannot venture on the likelihood and consequences.
- Hazard avoidance by simply not launching if dust storm in proximity, but this strategy could hold up an emergency launch
- Launching vehicle may also create its own local dust cloud which may become electrically active
- For example, Phoenix landing thruster system may erode 0.3 m^3 of soil which is a cloud containing a few hundred kilogram of loose soil and dust

<u>Example:</u> Numerical Simulations of Martian Dust Cloud Electrostatics

Melnik and Parrot, 1998
Numerical Simulation

Nearly 300 kV difference between top and ambient potential

Should a rocket launch near this? Ionized trail could connect ground to high potential region, creating a discharge current path

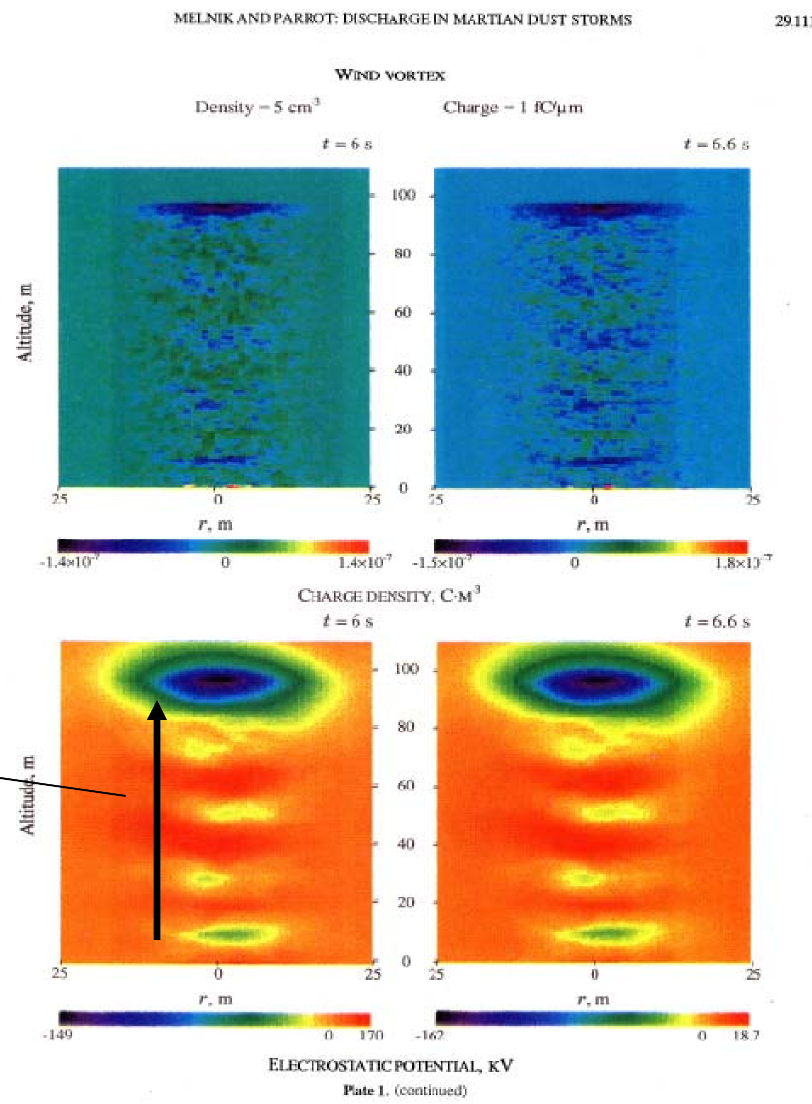
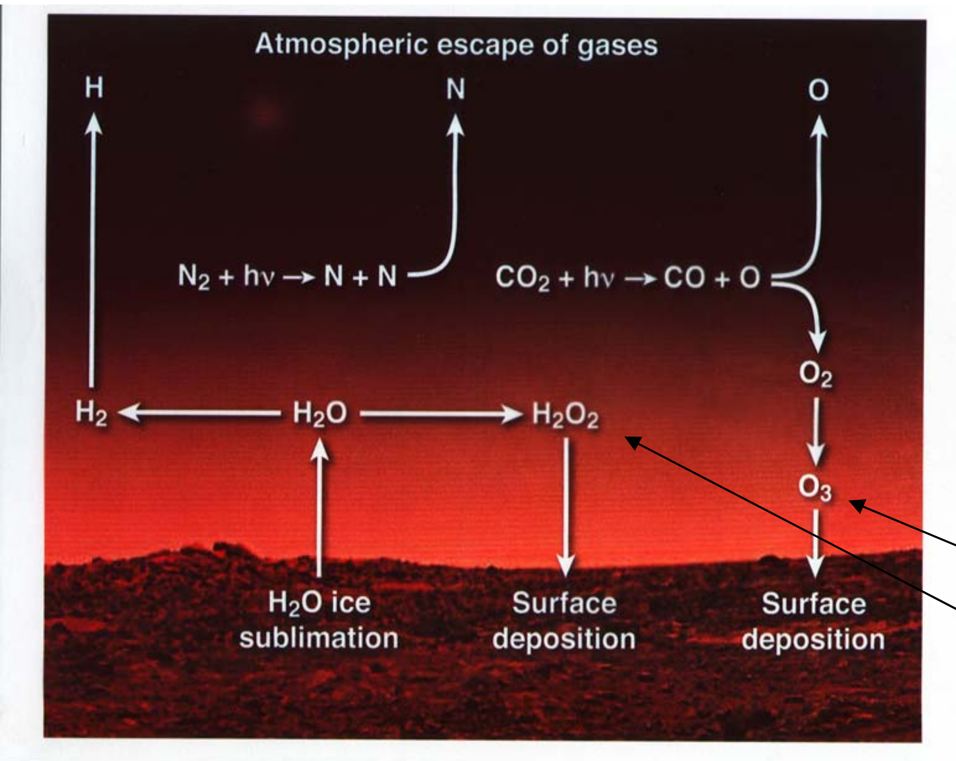


Plate 1. (continued)

- **Measurements to Assess Hazard:** DC E-fields (electrostatic fields), AC E-fields (RF from discharges & RF contamination assessment), atmospheric conductivity probe, and surface conductivity probe
- Combine with MET package to correlate electric and its causative meteorological source over a Martian year, both in dust devils and large dust storms.
- Call system “electro-meteorology” package
- Such a package should be used to determine safe launch conditions at TAO
- Parallel to the electric (field mill bank) and meteorological systems at KSC to ensure safe terrestrial launches

- **Priority: 2T**

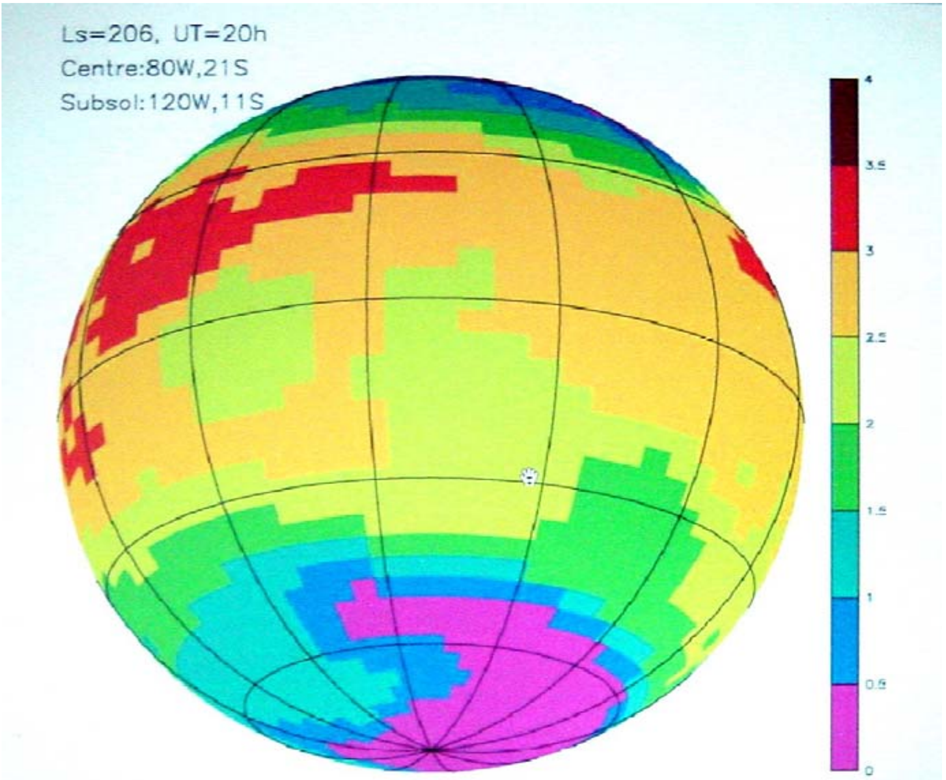
Investigation #3: Assess the photo-chemically produced reactive atmospheric chemicals that can create toxic or corrosive environment for explorers



- **Hazard:** Photochemical and chemical reactions in the atmosphere are capable of creating chemically-reactive gases that are deposited on the surface and can potentially corrode equipment, e.g., human habitat, space suits, etc. and/or create a toxic environment for humans
- Hydrogen peroxide (H2O2) and ozone (O3) are two examples of chemically-active gases that are photochemically and chemically produced in the atmosphere and deposited on the surface of Mars

- The photochemical and chemical production of reactive gases may be greater at specific locations, like near the poles (with increased water) or generated at high altitudes and transported downward. May also possess a diurnal, seasonal and solar cycle dependency
- A complete trace gas compositional analysis (with a sensitivity on the order of a part per billion by volume) of the atmosphere of Mars is required to accurately assess the hazard
- Topic has complementary effort in soils/dust focus group, where soil toxicity and atmospheric/surface chemical reactivity is a high priority
- In fact, the soil/dust may obtain its reactivity from an atmospheric source….the two are systemically linked.

Example: Hydrogen Peroxide Mixing Ratio



Model of H2O2/CO2 mixing ratio [Encrenaz et al. 2004]

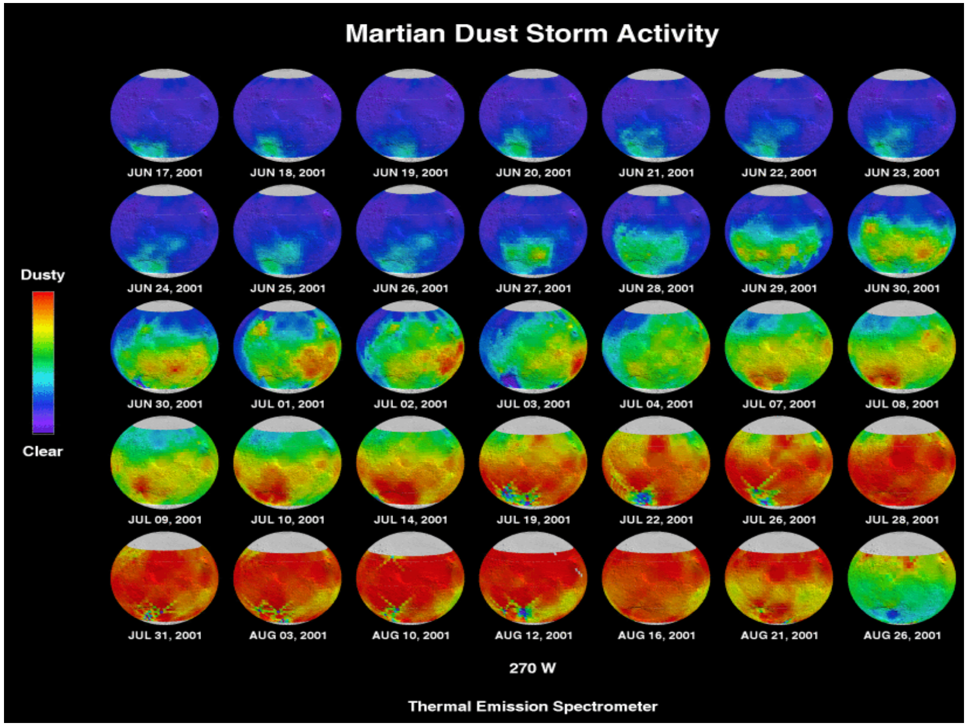
- Hydrogen peroxide is a known very chemically-reactive agent
- Very recent ground-based observations recently detected H_2O_2 in Martian atmosphere [Encrenaz et al, 2004]
- Observed levels close to those from chemical modeling with mixing ratios of

  $H_2O_2/CO2 \sim 3 \times 10^{-8}$
- High spatial resolution measurements of H_2O_2 needed
- Are there pockets of more intense oxidant production?
- Are the intensities large enough to do damage to surface equipment
- Need in situ measurements of reactive gases to parts per billion by volume

- **Mitigation:** Use of photochemical models to predict reactive species level. Requires validation with measurements at numerous locations and in various seasons
- If surface truly toxic/corrosive environment, humans may require special suite/habitat design and limited EVA's. Mitigation may be to avoid surface all-together. Could be an exploration show-stopper.
- To date, an in situ compositional analysis with modern mass spectrometers has not occurred, and should occur to quantify the amount of reactive compounds in the atmosphere.
- **Measurements to Assess Hazard:** Atmospheric composition/Mass Spec from 2-100 AMU of near-surface trace gases. Surface concentration sensitivity to < parts per billion.
- EDL mass spec would be next priority, to obtain estimates of flux and deduce vertical source region.
- Orbiter and terrestrial remote sensing measurements not too helpful since only columnar values obtained. Difficult to determine surface concentration, which is the primary measurement of interest.
- **Priority: 2T**

Investigation #4: Determine the meteorological properties of dust storms at ground level that affect human occupation and EVA

- **Hazard:** That during crew occupation and EVA, dust storm may affect visibility to the point where EVA's for regular habitat maintenance becomes compromised.
- Recent Iraq conflict was stalled by regional dust storm
- Global dust storm could last up to 3 months, with possible crew internment for the period
- **Mitigation:** Design systems for low maintenance, to withstand a dust storm, and/or avoid human surface occupation during times when storms are expected.
- The meteorology/opacity information within the dust storm is limited. Viking 1 lander measured wind speeds < 30 km/sec and inferred opacities near 9, but these values were not in central portion of storm
- Opacities could be much higher in global storm cores or in regional/local dust storms
- The ability to predict larger storms via Martian seasonal phase is much improved but smaller regional, local storms appear quasi-random



Courtesy of M. Smith and J. Pearl

Example: Dust Storm 2001

Starts in end of June

End near end of August

The conditions at ground level within such events is currently unknown.

V1 and V2 not in "genesis" regions

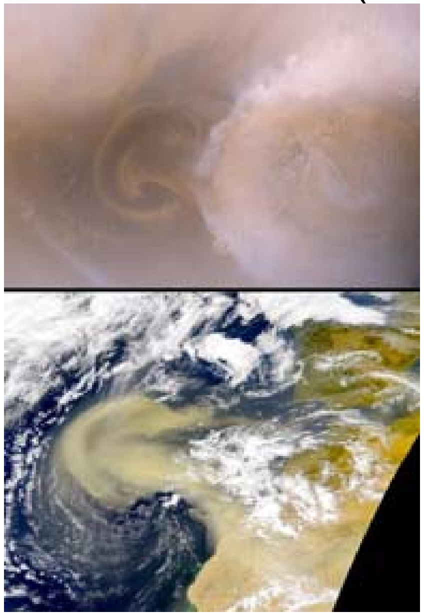
Could affect decisions to stay, decisions to launch

What is going on underneath?

- **Measurements for Assessing Hazard:** P, V, T, n, and dust density (opacity) as a function of time at the surface, for at least a Martian year, to obtain an understanding of the possible MET hazards inside dust storms. Dust particle properties should be quantified (see Soil/Dust FT)
- Orbiting weather station: optical and IR measurements could monitor the dust storm frequency, size and occurrence over a year, & measure terrain roughness and thermal inertia. Climate sounder would enable middle atmosphere temperature measurements. In situ density or spacecraft drag sensors could monitor the dust storm atmosphere inflation at high altitudes. Get top-to-bottom effect. (see General Recommendations)

- Priority: 2T

View from Orbit:



Mars

Earth

Investigation #5: Assess atmospheric parameters that affect communication and navigation

- **Hazard:** That atmospheric conditions on Mars, at times, may lead to communication losses
- On Earth, the ionosphere is modeled very well, HF wave ionosphere refraction and reflection effects well-understood
- On Mars, the mean ionosphere and its variations are not well known.
- A GPS-like system on Mars may suffer errors due to unknown ionospheric scintillations from density variations (happens at Earth as well)
- Some preliminary large-scale measurements of mean ionosphere with Viking orbiters [Zhang et al., 1990], but smaller scale "Spread-F" like turbulence is not known.
- Dust storms also represent times when RF communication can become contaminated (see Investigation #3)
- **Mitigation:** Use frequencies well above the peak ionospheric plasma frequency and also frequencies that can easily propagate though any atmospheric disturbances. Insulated antenna and comm system could reduce effect from in situ grain impacts

- **Measurements to Assess Hazard:** A better understanding of the ionosphere via radar sounding or in situ electron density and temperature measurements (aeronomy investigation) can be made via orbital platform. On surface, AC electric field basic measurements of dust storm (see Investigation #3) can determine the negative effect dust storm RF contamination
- **Priority: 5**

Investigation #6: Assess the water condensation that affects human operation

- **Hazard:** That Mars has seasonal condensation and ground fogs that can permeate into equipment and possibly cause an electrical failure
- Humidity changes will also alter expected atmospheric photochemistry (see Investigation #2)
- To date, the operation of any landed mission has not been affected by condensation
- However, high latitude/polar mission might have to take this hazard very seriously.
- **Mitigation:** Design systems to reduce/eliminate direct exposure to condensation
- Models can predict expected condensation
- With good designs, risk of failure expected to be small
- **Measurement to Assess Hazard:** The possible inclusion of humidity sensor and water flux quantification with surface MET packages, to assess the risk of condensation and define guidelines for its reduction
- **Priority: 6**

General Recommendations

- Common theme: **MET systems on EVERY landed vehicles for EDL and surface.** Code T development funds should be used to build a standard package for all flights (EDL and surface packages), and treat it as a spacecraft subsystem like the EDL landing camera, EDL comm system, etc. Should not have to compete with "life-science" packages for lander space. Mass and power book-kept on subsystem side, not on science side. Both internal and extrenal atmospheric science community given liberal access to data for model validation
- Exploration directorate should insist that a MET package be on MSL EDL and surface rover (supercede MSL radiation package ?) and Phoenix EDL
- **Dedicated Code T MET Orbiter**: to study upper, middle, and lower atmosphere. Includes: Optical & IR camera for dust storm occurrences, climate sounder for middle atmosphere dynamics, UV occultation limb scans, in situ upper atmosphere density, pressure, velocity and possibly composition (aeronomy-like measurements). Deployable probes to study lower layers or dust storm interior (?). Fly for many Martian years. Aeronomy science measurements integrates directly into Code T atmospheric risk assessment.
- Develop instruments & techniques to remote sense 0-10 km from orbital platform: develop probes to get as close to surface as possible

- Special emphasis placed on **integrating data into GCMs** to be used as a prediction tool to obtain variations expected for vehicle EDL/TAO design and possibly to obtain local weather at EDL/TAO period (if model ultimately prove reliable).
- **Pre-descent and pre-ascent sounding probes**: To further guarantee reliable weather at EDL/TAO, any manned mission should include a deployable weather sounding probe to release along expected EDL trajectory to map out immediate weather along trajectory. If there are forward-deployed stations, they could launch rockets or balloons prior to EDL. Prior to TAO, sounding rocket/balloon should be launched to obtain high altitude MET conditions. Analogy to KSC atmospheric sounding prior to rocket launches.
- For actual EDL, use probes along with orbiter GOES-like weather monitor to get as much info as possible
- Mass Spec should be flown more consistently to obtain composition at various locations and heights
- An atmospheric electricity package has to be flown AT LEAST once to quantify dust storm electricity and determine its consequences

Summary of AFT Investigations

Hazard Investigation	Likelihood (1-5, 5 being great likelihood)	Consequences (1-5, 5 being severe)	How well understood? (1-5, 5=least well)	Recommended measurements	AFT Prior ity
1) Fluid variations from ground to 90 km that affect during EDL and TAO	5 Turbulent layers are a natural part of any atmosphere and should be expected at Mars, especially within PBL. Such turbulence can create wind shears and density anomalies that alter planned vehicle trajectory. MER experienced unexpected MET conditions. EDL and TAO during dust storms may be very turbulent.	5 Wind drift can destroy precision landing, placing explorers far from forward-deployed resources. Density anomalies can altered expected impact velocity .	4 Number of EDL profiles very limited. Models need measurement set for verification otherwise will have values with large uncertainties. Effect of dust storms not well-quantified in modeling	-V, P, T, and n included on all future mission (both EDL and surface) at ~100 Hz resolution -Orbital platform with optical, IR, UV occultation, and in situ measurements -Development of 0-10 km probing instrumentation	1
2) Atmospheric electricity that affects TAO and human occupation	4 Requires incidence with a larger local storm, or regional/global storm. For long duration mission, there is a reasonable probability of encounter.	4 Discharges may require explorers to seek shelter and RF conductive contamination can be offset by good insulating design. Discharge at launch could be catastrophic.	5 To date, no fundamental measurements of atmospheric electricity. Must fly package at least once to assess this hazard.	-DC E-field, AC E-fields, atmospheric conductivity and ground conductivity over a Martian year. -MET package will complement AE package -Orbital platform not effective	2T
3) Reactive atmospheric chemistry that create toxic or corrosive environment	5 The Viking LR/GEX experiments indicate that some highly reactive agent is possibly omni-present in the environment	3 Landed missions have yet to fail from reactive agents, but season and location may be factors in degradation	5 While missions not fail, the lack of fundamental measurements does not allow an assessment of caustic chemicals	-Mass Spectrometer 2-100 AMU in near surface and over long duration (seasons). Many stations at various latitudes would determine effects of polar water, etc. -Orbital platform not effective	2T

Hazard Investigation	Likelihood (1-5, 5 being great likelihood)	Consequences (1-5, 5 being severe)	How well understood? (1-5, 5=least well)	Recommended measurements	AFT Priority
4) Dust Storm Meteorology that affect human occupation and EVA	4 Local, region, global dust storm are likely to occur in the course of a long-duration mission	3 Storm opacity may become so large as to reduce EVAs and external habitat maintenance	4 Viking provided some opacity data from edge of large storm, but to date, no data from inside core region of dust storm	-P, V, T , n and dust density (opacity) as a function of time over a Martian year -Orbiting optical/IR measurements of dust storm frequency, size over Martian year.	2T
5) Atmosphere effects on COMM/NAV	4 COMM and NAV systems usually operate at frequencies well above ionosphere effects, but a GPS-like system may have to work through ionospheric scintillations	2 To date, no COMM failure has resulted from atmospheric effects, even in dust storms. However, intense dust storm cores have not been intersected by a landed mission which could give rise to RF interference or attenuation	4 Ionosphere of Mars not well quantified both in latitude and longitude and more importantly, in vertical profile. Dust storm anomalies have not been characterized as well	-ionosphere density as a lat, long and height -surface AC E-field measurements in dust storm	5
6) Condensation and its affect on human operations	5 Seasonal and diurnal condensation along with ground fogs are well-known occurrences	2 To date, condensation has not interrupted operations on any landed mission, but long stay in polar region should design to reduce its effects	2 Models can predict seasonal and diurnal effect	-Humidity as a function of time -Water flux	6

Cost Trades

- Investigation #1: MET EDL/surface packages ($15M) versus over-designed EDL precision landing propulsion system and loss in exploration payload mass ($100M?)
- Investigation #1: MET EDL/surface packages ($50M) versus under-designed EDL propulsion system (cost of program/$30B)
- Investigation #2: Atmospheric electricity package (~$10M/ea) versus habitat shelter design enhancement to max perceived electrical threat (~$100M)
- Investigation #2: Atmospheric electricity package (~$10M/ea) versus loss of vehicle on TAO (cost of program)
- Investigation #3: Mass Spec (~$15M/ea) versus compromise in mission return (cost of program)
- Investigation #4: A opacity measurements from IR sounders (~$15M) versus limited EVA/habitat maintenance (cut mission short, cost of part of program)
- Investigation #5: Ionospheric probing with aeronomy or radar sounding package (~$10-20M) versus high frequency radio for comm (~$2M)
- Investigation #5: Ionospheric probing with aeronomy or radar sounding package (~$10-20M) versus Mars GPS nav location (~$900M)
- Investigation #6: Humidity sensor (~$1M) versus design and buid cost for reduction in exposure of critical electronics (0.1% of total cost or $30M)

Conclusions

- Unlike Earth, continuous GOES-like monitoring of Mars atmosphere not occurring, but should before humans visit…understand PBL, middle atmosphere, dust storms, etc.
- Modern models contain uncertainties that make their use in real flight situations questionable. These models are mathematically correct, but require initial conditions based on real measurements and model/measurement validation to reduce uncertainties
- MER had a serious difficulties because of the errors in current prediction techniques
- Making use of every MET EDL and surface opportunity is a “must-do” to provide data for model validation and initial conditions
- Chemical/reactivity issues suffer from similar problem: More data required to advance the atmospheric chemical models for prediction
- Electricity hazard has virtually no Mars data and even some small amount (fly even once) can aid in determining the real risk of this hazard
- Ultimate Cost Trade: Skimp on atmospheric science for risk assessment now may lead to an over-design (or worse, under-design) of a powered landing system later. Much larger cost later either in design and build of overpowered landing system (or program interruption from system loss).