Mars Weather and Climate:
An Orbital Constellation for Atmospheric Profiling and Surface Thermophysics

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Introduction:

Over the last decade considerable progress has been made in understanding the structure of the martian atmosphere and surface-atmosphere interactions. Current work focuses on identifying dynamical processes and radiative effects that are responsible for shaping the atmosphere of Mars. Progress in the area of weather and climate on Mars will depend on achieving two major science goals:

1. **Build a Long-term Record of the Current Martian Climate to Characterize the Amazonian Epoch**
2. **Globally Characterize Martian Weather**

Both goals require the continued measurement of temperature, dust, water ice, and water vapor with global coverage and high vertical resolution. For Goal 1 the deployment of an limb infrared radiometer with the characteristics of the Mars Climate Sounder (MCS), enhanced by the capability of measuring water vapor profiles, is suggested. This could be achieved by deploying such a regular orbiter or even a SmallSat or a CubeSat and would ensure continuity and comparability with the current MCS climatology.

For Goal 2 we propose a constellation of SmallSats or CubeSats in polar orbit. This would allow the global characterization of weather phenomena such as dust storm formation and development as well as water vapor transport and cloud condensation. This would also help overcome crucial challenges in Mars data assimilation, which could pave the way towards forecasting martian weather.

The mission concept would advance the under-standing of how physical processes in our solar system operate, interact and evolve as outlined in the 2014 NASA Science Plan. The MEPAG Goals document explicitly solicits the measurement of atmospheric parameters at multiple local times.

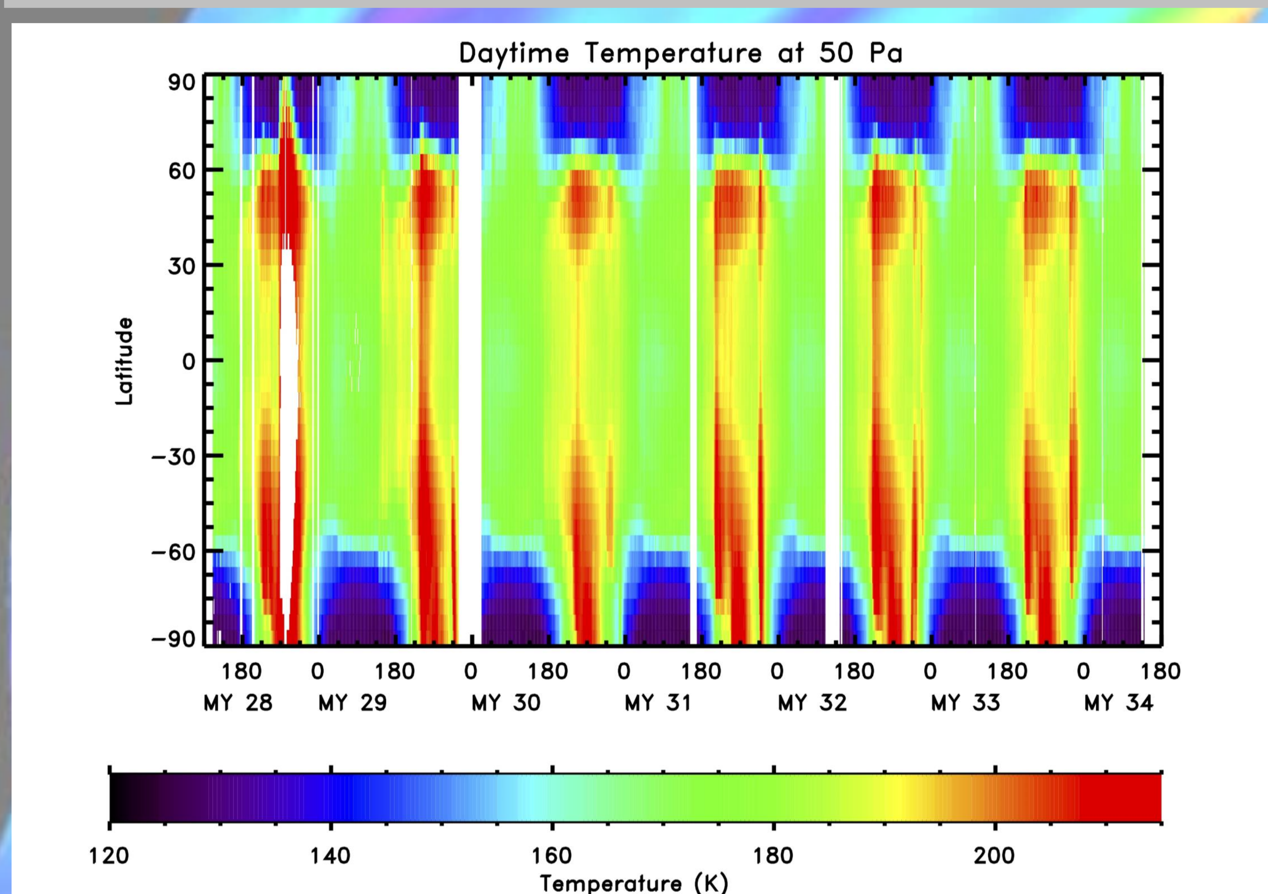

Fig. 1: Multi-Mars Year climatology of temperature at 50 Pa (~25 km altitude) from MCS on MRO.

Goal 1: Build a Long-term Record of the Current Martian Climate to Characterize the Amazonian Epoch

Goal 1 addresses the question of whether there are significant changes in the martian climate on 10 to 1000 year timescales [1]. With atmospheric and surface observations by the Thermal Emission Spectrometer on Mars Global Surveyor from MY 24-26 and by the Mars Climate Sounder (MCS) on Mars Reconnaissance Orbiter (MRO) from MY 28 to the present (Fig. 1) [2] we are about to enter an era where time series of orbital measurements allow extrapolation to Amazonian time scales. Only long-term climatologies allow the characterization of interannual variabilities and systematics [3]. Global dust events have major impacts on the surface and atmosphere in some years but the hiatus in their occurrence since MY 28 emphasizes the need for long-term observations. Trends, e.g. in dust storm occurrences and dust fluxes, will only be uncovered by long-term stable and consistent measurements.

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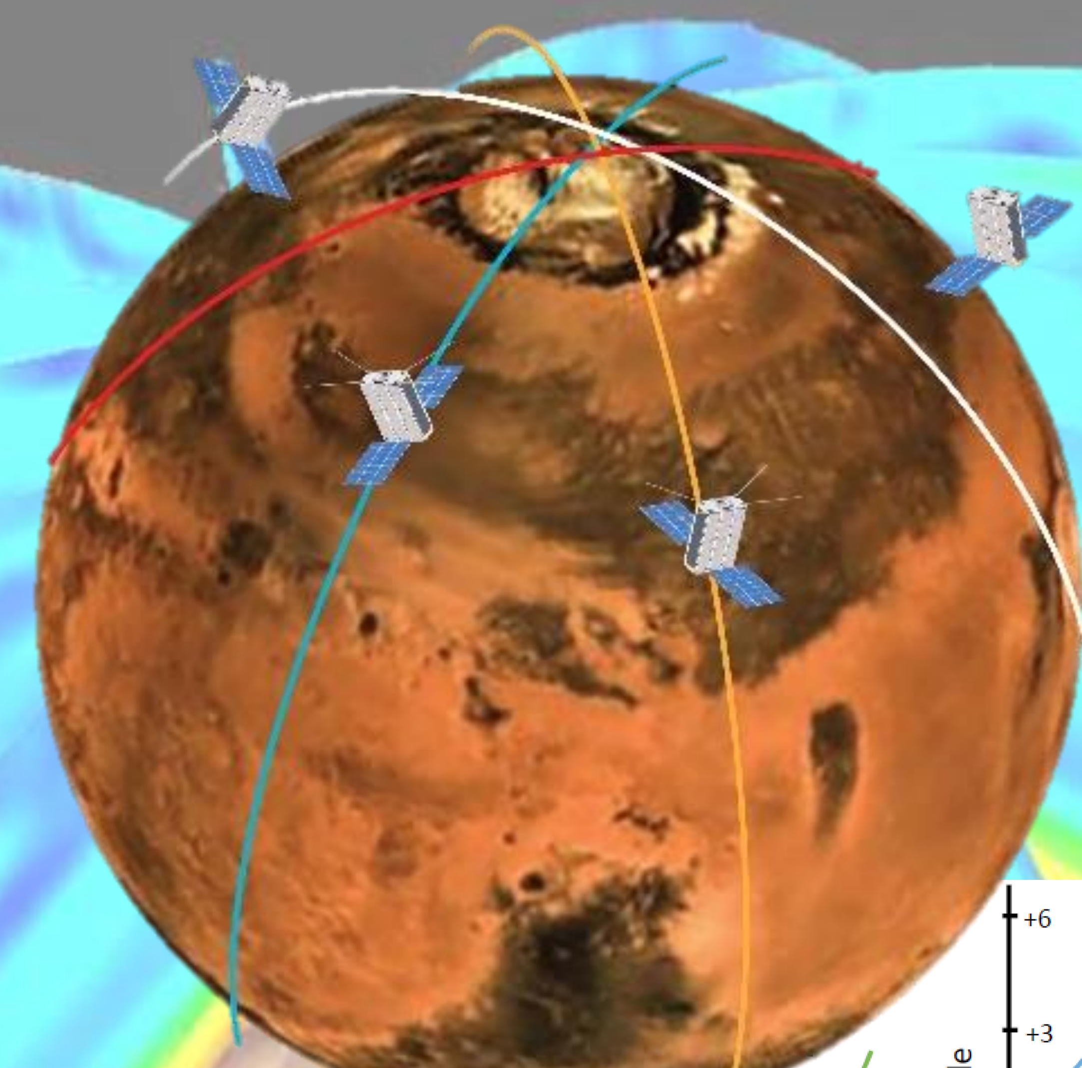


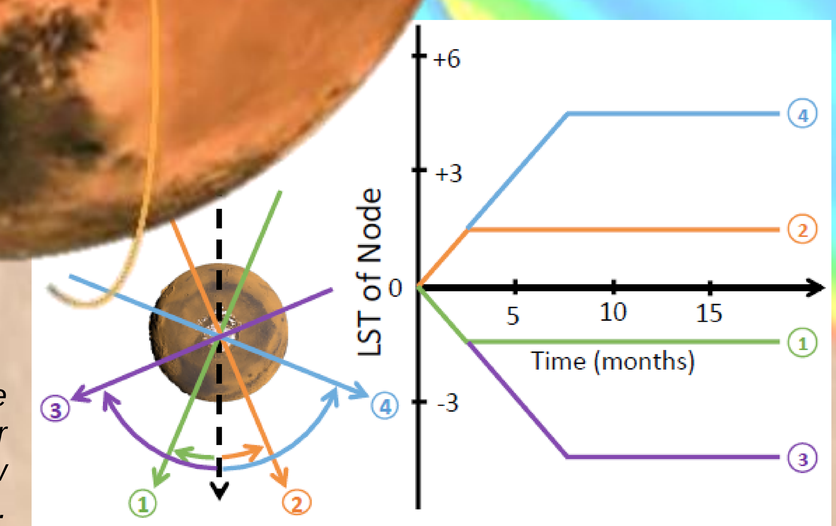


Fig. 4: After deployment the CubeSats drift to their desired nodes within a few months.

Goal 2: Globally Characterize Martian Weather

Goal 2 addresses improving understanding of short-term processes that form martian weather. One issue that limits progress in this area is the lack of coverage of observations at multiple local times. Numerous short-term atmospheric and surface processes are poorly characterized:

- **The inhomogeneous vertical distribution of atmospheric dust** that suggests convective activity triggered by solar heating of dust may play a crucial role in dust transport (Fig. 2) [4]. Observations performed several times over a single diurnal cycle could lead to a detailed understanding of these processes that are likely also driving the formation and growth of global dust events.
- **Forcing of semi-diurnal tides and higher order modes,** which reveal strong radiative influences of water ice clouds and affect the general atmospheric circulation [5]. The measurements would provide simultaneous information on water vapor supply, cloud condensation, and their radiative effects over the course of a sol.
- **Diurnal H_2O and CO_2 frosts that may have a significant impact on the regolith structure** [6]. Surface observations at all latitudes would reveal the distribution, physical properties, and relationship with the regolith and active geomorphological landforms.
- **The vertical heterogeneity of the Martian near-surface layer** that could be addressed with much greater accuracy than currently possible. This could reveal the depth of permafrost, internal bedrock layering or surface dust fluxes.
- **The energy balance of the Martian surface** that could be evaluated with much higher accuracy. Viking orbiter observations suggest much greater diurnal variability than currently modeled and predicted [7], with potential implications on volatile and heat exchange between the surface and the atmosphere.

Most of these science objectives cannot be addressed with current missions or future missions in development. Current missions like MRO are in sun-synchronous orbits that allow only limited local time coverage. The ExoMars Trace Gas Orbiter (TGO), currently entering its science orbit, will drift through local times only over the course of several 10s of sols, aliasing diurnal and seasonal changes. It will be unable to observe transient phenomena, such as local dust storms, more than twice per sol. Furthermore, the TGO instrumentation, as well as the instrumentation of the Hope orbiter to be launched in 2020, will only allow nadir measurements with coarse vertical resolution in temperature and no vertical information on quantities like dust, water ice or water vapor. Characterizing such processes globally at timescales of less than a sol would also provide an improved basis for assimilating data into General Circulation Models. This has proven challenging because the Mars atmosphere exhibits more globally connected features than Earth, e.g. thermal tides and remote responses to aerosol forcing [8]. Model simulations of rapidly evolving processes are not well constrained by existing observations; having simultaneous global measurements at multiple local times would alleviate many of these difficulties. Assimilating near real-time atmospheric and surface data could pave the way towards forecasting martian weather in support of landing, aerocapture and surface operations of future manned and robotic missions.

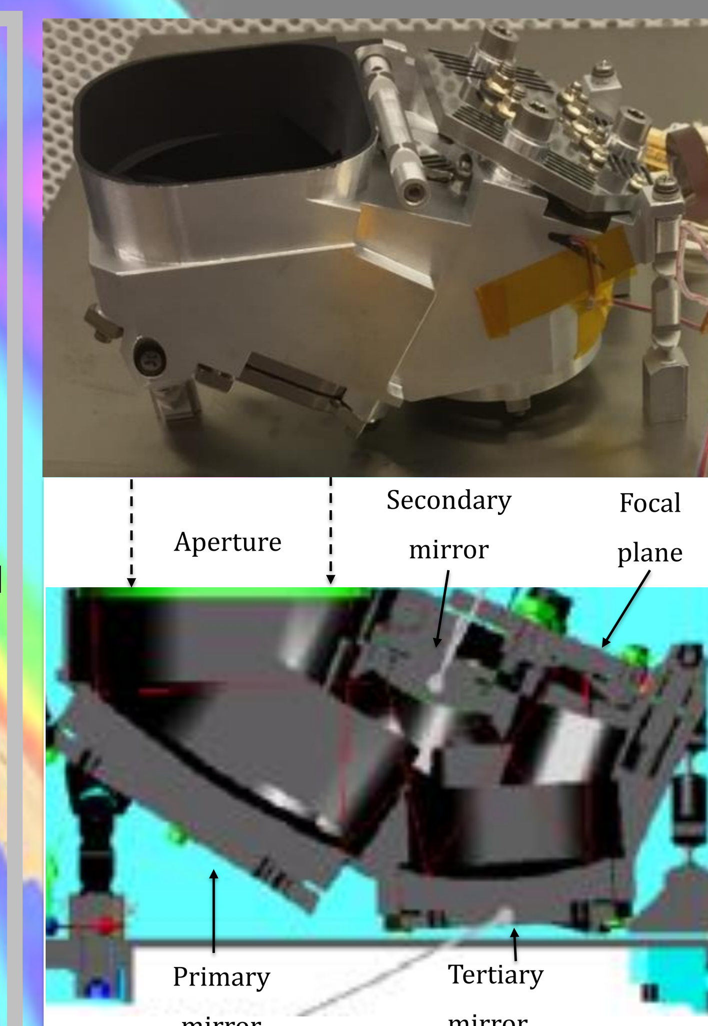
Mission Concept:

The proposed goals require global profile measurements of atmospheric temperature, dust, water ice and water vapor, as well as surface temperature, at multiple local times. We suggest a constellation of SmallSats or CubeSats in Mars orbit to perform these measurements (Fig. 4). Limb- and nadir radiometry measurements would require a low-altitude orbit of moderate to high inclination around Mars. Four satellites with a constant node spacing of 45° between orbits would ensure that atmospheric and surface observations over the same areas would be performed in regular local time intervals of 3 hours.

Satellites in a CubeSat form factor could reach their desired nodes under their own propulsion within a few month if deployed from Mars orbit (Fig. 4). If the satellites were to perform their own orbit insertion a larger form factor would likely be required. An ideal scenario would be the deployment of CubeSats from a large Mars orbiter in low Mars orbit. In this case the main orbiter could host an MCS-type instrument in its standard design [9,12] and also serve as a relay satellite for the CubeSats. This mission concept could be implemented during the decade of 2023-2032.

Instrumentation:

Measurements would be based on passive infrared radiometry in limb and nadir geometry as demonstrated by MCS [9] operating on MRO since 2006. Profiles of temperature, dust and water ice with 5 km vertical resolution have been retrieved from these measurements [10,11] together with atmospherically corrected surface temperature [6]. Eight spectral channels in the IR from 12-45 μm as well as a visible/near-IR channel would be used to fulfill the objectives (Fig. 3). Each channel would consist of a linear array of uncooled thermopile detectors, which instantaneously measures a radiance profile when vertically pointed at the limb. Most channels are heritage from MRO/MCS. MCS capabilities would be enhanced by adding a functional water vapor channel at far-infrared wavelengths. The MCS technology has high heritage. Deployment from a CubeSat would allow descoping the MCS actuators as the CubeSat itself could be used for pointing the instrument at the limb, nadir, and space. The design of the MCS telescope (Fig. 3) is very compact for the wavelength range it works in, fitting in an envelope of only 0.8 U.



Telescope/ Channel #	Bandpass cm^{-1}	Band Center - μm	Measurement Function
A1	595 - 615	16.5	Temperature 0 - 30 km
A2	615 - 645	15.9	Temperature 30 - 50 km; Pressure
A3	635 - 665	15.4	Temperature 50 - 90 km, Pressure
A4	820 - 870	11.8	Water ice extinction 0 - 90 km
A5	400 - 500	22.2	Dust extinction 0 - 90 km
A6	3300– 33000	1.65	High altitude hazes and particle size discrimination
B1	290 - 340	31.7	Dust and CO_2 ice extinction 0 - 90 km
B2	220 - 260	41.7	Water vapor 0 - 40 km
B3	231 - 243	42.2	Dust and Water ice extinction 0 - 30 km

Fig. 3: The MCS telescope design has high heritage and is very compact, fitting in only ~0.8U. The proposed measurement channels [12] are largely heritage from MRO/MCS [9].

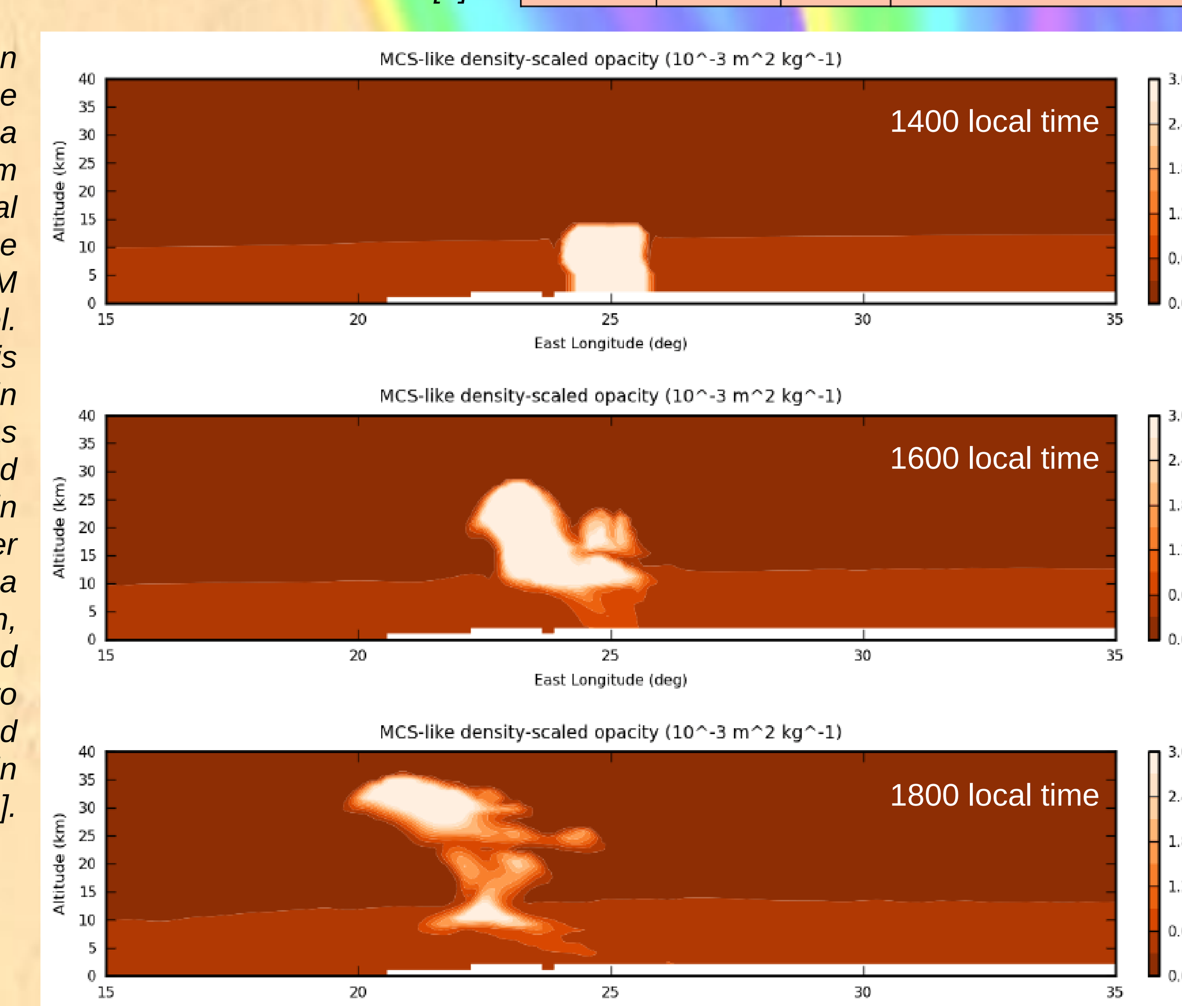


Fig. 2: Simulation of the development of a rocket dust storm at equatorial latitudes with the LMD-MMM mesoscale model. Dust is represented in shades of red as density scaled opacity at 22 μm in 10^{-3} m²/kg. Over the course of a martian afternoon, dust is lifted convectively up to 35-40 km and spreads out in layers. From [4].