MARS TRACE GAS MISSION:
Scientific Goals and Measurement Objectives

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Conclusion

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Mars is active today. Trace gases are a sensitive indicator of that activity, whether photochemical in the atmosphere or biogeochemical in the subsurface. A Trace Gas Mission emphasizing a broad survey of atmospheric composition, circulation and state, together with localization of active (sub)surface sources would characterize this modern activity and its implications for both climate and astrobiology.

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1. INTRODUCTION

The past decade has seen an explosion in the amount of spacecraft data from Mars. Data from Mars Pathfinder, Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Exploration Rovers, Mars Reconnaissance Orbiter, and Phoenix Lander, added to the earlier Mariner 9 and Viking data, can specify the surface and atmosphere of Mars in some detail. With the data now in hand, it is possible to present a reasonably complete first view of the current martian climate (e.g., Smith, 2008). However, there is still much that we do not understand and there are areas that require further observations.

Chief among these is the present lack of knowledge about the inventory of trace gases in the martian atmosphere. Recent observations of trace gases, notably methane, in the martian atmosphere (Krasnopolsky et al., 2004; Formisano et al., 2004; Mumma et al., 2009) have reinforced the importance of atmospheric composition as a window into underlying geological and biological processes. As first suggested in the 1960s, the most effective first approach for detecting the presence of biological or intrusive volcanic activity is to survey atmospheric composition for disequilibrium (Lederberg, 1965; Lovelock, 1965; Hitchcock and Lovelock 1967; Lovelock 1975). For example, the presence of gases such as methane in an oxidizing atmosphere could be direct evidence of life (Lovelock, 1965). However, geological and photochemical processes can also introduce disequilibrium into planetary atmospheres (Des Marais et al., 2002). Thus, the recent detections of martian atmospheric methane, and suggestions of its spatial and temporal distribution, have stimulated numerous hypotheses about the nature of the methanogenic sources, their magnitude, and locale.

The discovery of either current geological activity or extant biological processes would have profound implications for astrobiology and the Mars Exploration Program. While the case involving active microbiology is clear, identifying the locations of active geological processes would also be profound. Such places would be obvious targets for future exploration, particularly if water is likely to be found there. If these environments are not inhabited, a fundamental notion that, where there is liquid water, there is life, would be challenged.

A precise and global survey of the martian atmosphere to determine the underlying control of atmospheric composition is both scientifically timely and tractable. Such a mission should be designed to 1) Quantify the sources of trace chemical species to the martian atmosphere, 2) Localize these sources and their variability, and 3) Determine the lifetime of these species within the atmosphere. To accomplish these goals, the measurements must be obtained within the context of a broader atmospheric science mission. New observations of the atmospheric state including wind velocity and improved mapping of temperatures and aerosols over all local times are necessary to provide sufficient constraints on the atmospheric transport and photochemistry.

These science goals could be addressed by an orbiter at Mars (which we call the Trace Gas Mission, or TGM) carrying a capable suite of instruments specifically designed to observe the atmosphere of Mars. These should include remote sensing instrumentation with extremely high sensitivity to a broad suite of important trace gases, combined with nearly continuous spatial mapping of key minor constituents and of atmospheric state including vertical profiles of atmospheric temperature and aerosol abundances.

2. SCIENCE OBJECTIVES

The main science drivers for the TGM are a new and comprehensive view of **Atmospheric Composition** to seek evidence for the present habitability of Mars, and a vastly improved characterization of the present **Atmospheric State** to provide new insight into processes that control the martian weather and climate.

2.1 Atmospheric Composition

Trace Gas Inventory

The overarching goal of the Atmospheric Composition objective is to seek atmospheric evidence for present habitability and life through a sensitive and comprehensive survey of the abundance and temporal and seasonal distribution of atmospheric species and isotopologues. It has long been understood that the presence of life on a planet could modify the atmosphere in such a fashion that this "disequilibrium" condition could be detected by remote sensing. Moreover, active abiogenic geological processes also will modify the environment in which these processes occur. The atmospheric signatures of active processes that might be present and at what abundances they exist are largely unknown. Thus, the recommended approach is to search for a diversity of signature molecules with high measurement sensitivity in order to characterize the variations of known minor gases over a broad range of temporal and spatial scales and to improve by an order of magnitude or more the abundance limits of key gases not yet detected.

Measurements of atmospheric composition enable a comprehensive study of the coupled volatile environment of the Mars atmosphere, surface, and subsurface. Time and spatially dependent exchanges among the photochemically active atmosphere, surface ice of the polar caps, and potential subsurface sources (water vapor in adsorbed or permafrost state, methane from biogenic or geochemical sources) remain poorly constrained due to the limited breadth and abundance thresholds of existing measurements. Hence, TGM atmospheric observations should include a baseline set of molecular species necessary to isolate the key photochemical, transport, condensation, and biogenic-geochemical processes that control the current chemical state of the Mars atmosphere. In many cases these observations will require exceptional sensitivities to trace abundances relative to prior mission capabilities. Most notably, detection-mapping capability for atmospheric methane presents a core requirement due to its potential as a biogenic marker. Key atmospheric priorities are identified for photochemistry (H_2O_2, O_3, CO, H_2O), transport (CO, H_2O), isotopic fractionation (isotopomers of H_2O and CO_2), and surface-subsurface sources (CH_4 and H_2O). Additional targets of interest include HO_2, NO_x, and sulfur/carbon/ chlorine components associated with potential subsurface sources.

A key objective of the TGM investigation would be to follow up on the reported observations of methane in the martian atmosphere. Reports have suggested a seasonal variability in the CH_4 abundance and meridional and longitudinal variability, implying that the distribution of CH_4 could reveal the location of its source. However, current martian atmospheric photochemical models indicate that its lifetime is ~250 Mars years, which is so much longer than atmospheric transport timescales that the expectation is that CH_4 should be well-mixed throughout the atmosphere. If the reported spatial variability is true, then some atmospheric chemical processes (possibly dust-related), or exchange with the surface/cryosphere have been seriously underestimated in the current models. On the other hand, if observations with significantly higher precision show that CH_4 is well-mixed, then its distribution will not be a useful guide to locations of active processes. Thus, it is necessary to map co-generated species that have much shorter atmospheric lifetimes and therefore could be tracers leading back to source zones.

Detection and localization (if sufficiently abundant) of nitrogen/sulfur/carbon/chlorine-containing compounds can be important for localizing the methane source as several candidate methanogenic processes will cogenerate such species as discussed just above. However, while the detection of methane raises the possibility that one active subsurface process exists, there is the possibility that other, different active subsurface processes exist too, which introduce to the atmosphere some of these other trace gases. It is important that the TGM investigation be defined in the broadest terms to encompass any atmospheric evidence for one or more subsurface active processes.

Photochemistry

Mars photochemistry exhibits similarities to the terrestrial mesosphere in that HO_x radicals (H_2O_2, HO_2, OH, and H) associated with water vapor photolysis exert catalytic control over the trace specie families of O_x (O_2, O_3, and O), NO_x (NO_2, NO), and CO. In the case of Mars, these trace oxygen, nitrogen and carbon constituents are produced through photodissociation of the bulk CO_2/N_2 atmosphere. Loss and partitioning rates are dominated by reactions with the HO_x radicals HO_2, OH, and H; for which H_2O_2 serves as a short-lived (1000 seconds) reservoir (i.e., 2xOH). This link with HO_x chemistry leads to a fairly direct correspondence of short-lived trace gas species with the variable distribution of atmospheric water vapor in space and time. Long-lived photochemical products (CO, O_2, H_2) should exhibit much weaker spatial and temporal variations in the lower atmosphere, associated with transport and condensation effects. Existing observations of Mars CO, O_2, O_3, and H_2O_2 indicate the activity of homogeneous (gas-phase) photochemistry on Mars, but the data are insufficient to define the roles of heterogeneous, transport and non-equilibrium processes. These include heterogeneous loss of HO_x on ice clouds, HO_x production on charged dust particles, condensation and transport enrichment of species, and subsurface sources/reservoirs. A much more detailed characterization of the spatial/temporal distributions of key photochemical constituents than currently supported by existing measurements is required to separate and so identify these processes.

Isotopic Ratios

Measurements of hydrogen, oxygen, and carbon isotopic abundance in the martian atmosphere will allow new and important constraints to be placed on atmospheric chemistry, meteorology and interactions between the atmosphere and surface. Measurements of these isotopologues of CO_2 and water vapor in the lower atmosphere of Mars would provide a boundary condition for aiding in the interpretation of the aeronomy measurements in the upper atmosphere planned for the MAVEN Scout mission. Currently, knowledge of the isotopic composition of present day Mars is limited to lowprecision Viking analyses and Earth-based spectroscopic observations of D/H ratio of martian atmospheric water vapor and the ratio of D to H atom abundance in the exosphere. Additional, though less direct constraints are provided by measurements of ancient martian volatiles in the SNC meteorites. While these measurements are significant constraints on models of long-term atmospheric evolution, the generally poor precision and lack of knowledge of the vertical and latitudinal isotopic variations of atmospheric gases limits their usefulness for answering specific questions about the internal dynamics of the martian atmosphere and its interactions with the surface. Likewise for carbon, measurement of $^{13}C/^{12}C$ in atmospheric CO_2 will allow the anomalous observations of this ratio in SNC meteorites to be placed in the context of a well-mixed and large martian carbon pool. Finally, latitudinally resolved observations of oxygen isotopes in CO_2 when combined with the carbon isotope measurements will provide new insight into the sublimation and condensation of CO_2 in polar regions.

2.2 Atmospheric State

The Atmospheric State objective seeks to provide new insight into climate processes responsible for seasonal and interannual change. This will be accomplished by both providing new observations that constrain and validate models of atmospheric dynamics and state, and by extending the present record of martian climatology to characterize interannual variability and long-term trends of the atmospheric state, circulation, and cycles of dust, water, and carbon dioxide. New observations would include the first-ever direct observations of vertically resolved wind velocity over the globe on a daily basis, and broad coverage of the diurnal cycle of temperatures, winds, aerosol optical depth, and gas abundances. With these observations and the improved transport and climate models that will result from them, it will be possible to better describe surface-atmospheric interactions key to many climate processes, and may be possible to trace spatially varying minor atmospheric constituents (including water vapor) to localized source areas.

Dynamics, Transport, and Winds

The winds on Mars transport and mix aerosols and all of the minor atmospheric gaseous constituents, and they are a primary player in all surface-atmosphere interactions and exchanges on the planet. If there are local and/or transient sources of gases such as methane and SO_2 on Mars, then the winds are critical in determining the distribution of these gases in the atmosphere. Despite the importance of winds on Mars, at present there are remarkably very few direct observations of them. A primary objective of TGM will be to obtain good direct wind measurements for the first time. When combined with good measurements of the atmospheric temperatures and the dust and water abundances, this will enable, for the first time, a complete characterization of the general circulation of Mars. Most importantly here, wind measurements throughout the lower atmosphere will enable the transport of atmospheric constituents to be directly investigated.

The determination of transport and its inverse, in which trace species are tracked back to their sources, is best done using atmospheric circulation models. A necessary step is to validate the model predictions by comparison with observed winds and with the transported trace gases themselves. However, measurement and model limitations can also be mitigated through methods of data assimilation in which a blend of model predictions and direct observations is produced, essentially applying information-weighted corrections systematically to the model predictions as a function of time. In either case, the analysis works best when a suite of tracers with different life cycles and spatial variations is used. Gases with lifetimes of months to a few years are most diagnostic; shorter lifetimes will localize the tracer, while long lifetimes will produce uniformly mixed distributions that are no longer independent. One exception to the latter is that non-condensable inert gases (e.g., argon or CO) can reveal seasonal transport given the massive condensation/sublimation of up to 30% of the martian atmosphere in the polar regions. For transport purposes, water vapor, carbon dioxide, ozone, methane and their isotopes, together with some shorter lived, higher order hydrocarbons, can provide the variety of trace gases needed to test and improve model predictions and our basic understanding of the physical processes involved in their origin, loss and transport. A TGM can map and characterize a suite of tracers to allow the modeling of transport.

Climate Characterization

An initial assessment of the current martian climatology has been obtained by data returned from Viking, Mars Global Surveyor (MGS), Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter (MRO). Although much progress has been made, knowledge of the current climatology is limited by lack of observations in several key areas. Most importantly, there are currently no missions planned after Mars Express and MRO capable of global-scale monitoring of the atmospheric state. This is a serious shortfall. A long baseline of observations is crucial to understanding the current climate and the physical mechanisms that govern it, both to be able to model past climates, and to successfully predict the current atmospheric state for future robotic and manned landings.

Other aspects of the current climate not well sampled so far by observations are diurnal variations (for example, both MGS and MRO provide observations only at mid-afternoon and early morning local times), direct measurements of wind velocity, and the vertical distribution of aerosols and water vapor, especially in the lowest scale height of atmosphere. Full coverage of the diurnal cycle would greatly help the identification of wavemodes and the modeling of the water cycle including condensate clouds. The addition of wind observations would be an essentially new observation that would provide important new constraints for circulation models. Information on the vertical distribution of aerosols would greatly improve both the modeling of heating rates and the knowledge of circulation patterns through tracer motions, in addition to characterizing possible roles in photochemical production and loss.

2.3 Mission Support: Telecommunications Relay and Near-Real Time Monitoring

The presence of TGM in orbit around Mars would provide key telecommunications infrastructure over its planned lifetime supporting the relay of science data from, and commands to, landed assets. TGM would also provide telecommunications coverage of critical events such as Entry/Descent/Landing, Mars ascent vehicle launches, and Mars Orbit Insertion for other missions. Real-time monitoring of the atmospheric state can also play an important role in reducing risks associated with future spacecraft entry, landing and surface operation. Thus, these capabilities would add significantly to the science return and robustness of all future missions to Mars during TGM operations (also see Edwards et al., 2009).

3. SCIENCE MEASUREMENT GOALS

The science objectives outlined above require vertically resolved observations of atmospheric composition (trace gas abundance, isotopic ratios) and atmospheric state parameters (atmospheric temperature, wind velocity, aerosol optical depth, and water vapor abundance) with global coverage and a rapid change of observed local time during the course of the mission. For the atmospheric state, nearly global coverage, obtained with near-continuous (~85% or better) observations at least every 5°–10° of latitude along the orbit track is required so that phenomena such as regional-scale dust storms and the polar vortex are adequately resolved. A lifetime of at least one martian year is necessary to observe the annual cycle, with the possibility of additional martian years highly desirable in order to assess interannual variations.

What atmospheric signatures of active processes that might be present and at what abundances are unknown. Therefore, the measurement requirement for atmospheric composition is to sensitively detect a diversity of molecules over broad temporal and spatial scales. Molecules diagnostic of active geological and biogenic processes include sulfur, nitrogen, and reduced carbon species. For the purpose of maximum understanding of signatures present in the atmosphere and their seasonal abundance, a detection threshold of at least a few parts per trillion for a zonal average over 5° of latitude is necessary to significantly exceed current observations. The table below gives a summary of the measurement goals.

Table 1. Summary of science measurement goals.

Quantity	*Sensitivity*	*Vert. range*	*Vertical res.*
Trace Gases: Nature of Source			
Methane	50 pptv	0–60 km	5 km
Other species†	<50 pptv	——	——
† such as C_2H_6, N_2O, H_2CO, NH_3, HCN, SO_2, OCS, HCl. Other exotic species with very weak spectral lines may have higher limits.			
Trace Gases: Photochemistry			
H_2O, CO	10 ppbv, 1 ppmv	0–60 km	5 km
O_3, H_2O_2	1 ppbv, 100 pptv	0–40 km	5 km
Trace Gases: Isotopic Measurements			
D/H (in H_2O)	5% precision, 10% accuracy	0–40 km	5 km
$^{13}C/^{14}C$ (in CO_2)	0.5% precision, 2% accuracy	0–20 km	5 km
$^{16}O/^{18}O$ (in CO_2, H_2O)	0.5% precision, 2% accuracy	0–20 km	5 km
$^{17}O/^{18}O$ (in CO_2, H_2O)	0.5% precision, 2% accuracy	0–20 km	5 km
Atmospheric State			
Temperature	2 K precision, 2 K accuracy	0–80 km	5 km
Wind Velocity (2-D)	10 m/sec precision	5–80 km	10 km
Aerosol Optical Depth	0.05 precision at vis. wavelen.	0–60 km	5 km
Water Vapor	10% precision, 10% accuracy	0–60 km	5 km

4. MISSION CONCEPT

To achieve the objectives outlined above requires a mission that: 1) has instruments capable of sensitive detection of broad suites of atmospheric trace gases and their isotopes; 2) provides the needed measurements of atmospheric state (temperature, aerosol loading, winds, as a function of height); 3) maps key species in order to derive possible local sources; and 4) provides both diurnal and seasonal coverage in order to understand the nature of the spatial and temporal variations of the observed species. Thus, the observations should span both the diurnal cycle and at least one full Mars year.

To achieve the desired time-space coverage will require a moderately inclined, near-circular orbit, probably at the 400 km altitude of many previous Mars missions. The Mars Science Orbiter Science Definition Team (MSO SDT) developed a straw-man payload of 5-6 instruments, including a mix of nadir, limb, and solar occultation viewing modes. In any case, the instruments should be chosen in an open (AO) competition.

This orbiter should have the extended lifetime need to provide relay support and critical event coverage for future missions. The SDT estimated that a long-lived mission combining trace gas detection, survey and mapping capabilities with telecommunications and other mission support is a MRO (New Frontiers) class mission (~$750M).

5. CONCLUSION

Mars is active today. Trace gases are a sensitive indicator of that activity, whether photochemical in the atmosphere or biogeochemical in the subsurface. A Trace Gas Mission emphasizing a broad survey of atmospheric composition, circulation and state, together with localization of active (sub)surface sources would characterize this modern activity and its implications for both climate and astrobiology.

REFERENCES:

Des Marais DJ, Harwit MO, Jucks KW, Kasting JF, Lin DNC, et al. 2002. Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. *Astrobiology* 2: 153-81

Edwards, C. D., Jr., W. B. Banerdt, D. W. Beaty, L. K. Tamppari, and R. W. Zurek (2009). Relay Orbiters for enhancing and enabling Mars in situ exploration, 7 p. Decadal Survey white paper.

Formisano V, Atreya S, Encrenaz T, Ignatiev N, Giuranna M. 2004. Detection of methane in the atmosphere of Mars. *Science* 306: 1758-61

Hitchcock, D.R., and Lovelock, J.E., 1967. Life detection by atmospheric analysis. *Icarus*, **7**, 149-159.

Krasnopolsky VA, Maillard JP, Owen TC. 2004. Detection of methane in the martian atmosphere: evidence for life? *Icarus* 172: 537-47

Lederberg J. 1965. Signs of life: criterion-system of exobiology. *Nature* 207: 9-13

Lovelock JE. 1965. A physical basis for life detection experiments. *Nature* 207: 568-70

Lovelock JE. 1975. Thermodynamics and the recognition of alien biospheres, *Proc. Roy. Soc. London B*, **189**, 167-181.

Mumma MJ, Villanueva GL, Novak RE, Hewagama T, Bonev BP, DiSanti MA, Mandell AM, Smith MD. 2009. Strong release of methane on Mars in Northern Summer 2003. *Science*, 323: 1041-1045.

Smith MD. 2008. Spacecraft observations of the martian atmosphere. *Annu. Rev. Earth Planet. Sci.*, 36: 191-219.