Mars Polar Science for the Next Decade

Abstract:

In 1966, Leighton and Murray used polar energy balance calculations to predict that the Mars seasonal polar caps were composed of CO_2 ice, not H_2O ice as had been the common belief for hundreds of years. Over four decades later, the pursuit of detailed scientific understanding of the polar energy balance continues to be integral to elucidating the mysteries of Mars and its polar regions. Twenty-five percent of the Mars atmosphere is cycled through the seasonal caps each year, condensing into CO_2 snow and ice on the autumn/winter hemisphere and subliming on the spring/summer hemisphere. We have learned that the north and south permanent caps have different (at least surficial) compositions and exhibit regionally different seasonal processes. At present, continued research in this area is significantly impeded by the scarcity or lack of observations at appropriate spatial and temporal resolutions, and fundamental gaps in the understanding of the properties and behavior of CO_2 ice that is contaminated by water ice and/or dust under Mars conditions - knowledge which is fundamental to continued progress toward understanding the climate and its geologic implications throughout current, prior, and future epochs of Mars history. This situation could be much improved by a mechanism to fund inter-disciplinary Mars studies that involve equal measures of numerical modeling, spacecraft data analysis, and/or laboratory work. A multi-pronged approach is recommended for the coming decade: (1) increase the emphasis within NASA's Research and Analysis programs to specifically support CO_2 ice laboratory experimentation and inter-disciplinary investigations involving multiple techniques (any well-justified combination of modeling, data analysis, and/or lab experimentation); (2) continue to monitor polar processes with orbital assets that can differentiate between surface volatiles; (3) deploy spacecraft instrumentation that will assess the long-term stability of the south polar residual cap of Mars and the density of both the seasonal and residual CO_2 ices as a function of both space and time; and (4) deploy spacecraft instrumentation that will constrain CO_2 ice and snow formation and modification processes.

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Preamble:

The seasonal polar caps of Mars consist primarily of CO_2 that condenses from the atmosphere to form surface ice at high latitudes following the autumnal equinox in both hemispheres. The seasonal caps are prominent features on Mars that were first viewed by Herschel in 1784. They extend equatorward as far as 40º S in the southern hemisphere and 55º N in the northern hemisphere. Approximately 25% of the Martian atmosphere is cycled annually into and out of the seasonal caps. Consequently, the seasonal CO_2 cycle plays an important role in the planet's atmospheric general circulation. Questions about the seasonal caps that remain unresolved concern local cap properties (e.g., column mass, density, thickness, grain size, dust and water ice fraction), energy-balance terms (e.g. wavelength dependent albedo and emissivity) and CO_2 condensation mechanisms. The rate of seasonal deposition and sublimation of CO_2 ice is determined by the local energy balance, which depends on solar insolation, atmospheric properties (such as dust optical depth), emissivity and albedo of the surface, advection of energy by the atmosphere and energy storage within the regolith. The pursuit of detailed knowledge regarding the polar energy balance continues to be an important aspect of understanding Mars and its polar regions. Without the understanding of the present-day Mars processes and climate, especially in the polar regions, it will be difficult to accurately extrapolate to past climates when Mars may have been a warmer, wetter planet.

This white paper is intended to be a consensus of many of the active members of the Mars polar science community, and is the culmination of discussions held at the 3rd International Mars Polar Energy Balance and CO_2 Cycle workshop (MPEB2009) held in Seattle, WA, 21-24 July 2009. The attendees represented both North America and Europe.

The limited access of landers to areas of Mars that experience polar conditions (due in part to significant technical hurdles) necessitates the continued monitoring of the polar caps from orbital platforms throughout the next decade. Even so, some sorely-needed measurements, such as surface air pressure over several seasonal cycles at a high accuracy and precision, can only be obtained by a landed mission. Furthermore, all such observations must be correctly interpreted, a task which frequently requires detailed knowledge of material properties that can currently only be obtained via CO_2 ice experimentation and measurement in a laboratory setting. These sets of information will provide a more robust basis (than exists today) for the design of landed missions in the farther future.

1. Four major questions and investigations within Mars Polar Energy Balance science.

Question 1: What are the detailed spectral and physical properties of CO_2 ice under Mars conditions (including plausible contaminants)?

Investigation: Determine the above CO_2 ice properties through laboratory experiments under Mars conditions.

The topical sessions at MPEB2009 were wide-ranging, including discussions of the stability of the Mars south polar residual cap, the behavior of the seasonal polar caps, the interactions of the polar caps with the atmosphere, and the thermal effects of buried H_2O ice on the net accumulation of seasonal CO_2 ice. Throughout the workshop, an overarching deficiency became apparent – the scarcity or lack of laboratory experiments regarding the physical and spectral properties of CO_2 ice (pure and as a mixture with dust and H_2O ice) under Mars conditions. Without further work in this area, numerical models will continue to have poorly constrained parameterizations of physical processes important to the polar regions, and observational data of the polar regions will continue to be loosely interpreted or even misinterpreted due to a lack of detailed understanding of the material being observed.

Question 2: What are the densities, column mass and areal coverage of the CO_2 ice that composes the seasonal and residual polar caps?

Investigation: Measure the spatial and temporal evolution (thickness) of the seasonal polar caps with centimeter vertical resolution sampled at approximately every 10º of L_s.

Investigation: Measure the topography of the south polar residual cap at 20 meter (horizontal) and centimeter (vertical) resolutions.

Investigation: Measure the column mass abundance of the CO_2 ice in the seasonal and residual polar caps with accuracy of 50 kg/m^2 sampled at approximately every 10º of L_s.

Surface CO_2 ice emplacement can occur either as direct deposition onto the surface or as precipitation (snow) from the atmosphere aloft. The time evolution of these two modes of ice emplacement and subsequent grain growth primarily determines the seasonal cap density. Spatial and temporal density variations of the seasonal CO_2 ice are expected, but cannot be easily measured with present day observations. For example, an estimate of the volumetric density of seasonal CO_2 ice has been determined by combining MOLA altimetry (cm precision over ~120 m footprints) (e.g., Aharonson et al., 2004), gravity measurements (radio science) (Smith et al., 2001), and nuclear spectroscopy (e.g., Feldman et al., 2003; Litvak et al., 2007; Prettyman et al., 2009). Unexpectedly, the results are consistently much lower than the density of solid CO_2 ice, and may indicate either measurement bias or the effects of physical processes that are currently not understood. Similar results were obtained for the density of the residual polar ice. To determine CO_2 ice density as a function of space and time, we recommend two specific measurements: vertical changes in the cap height (and thus depth, given the substrate topography) during the fall, winter, and spring seasons, and a simultaneous determination of the CO_2 ice column abundance. The changes in elevation could be monitored by either a laser altimeter or by interferometric synthetic-aperture radar (InSAR). The second measurement could be accomplished with a collimated thermal-neutron detector. Since thermal neutrons are highly sensitive to the column abundance of CO_2 ice on the surface, and since thermal neutrons are readily absorbed by thin layers of material (e.g., Cd or Gd sheets), it would be possible to build a compact CO_2 ice imaging system with high spatial resolution (e.g., able to resolve spatial variations in the cap on a scale of 50-100 km), close to an order of magnitude improvement over that presently achieved by Mars Odyssey instrumentation (600 km resolution) (Boynton et al., 2002). Absorption of thermal neutrons by noncondensable gas (N2 and Ar) would be corrected using microwave data (using CO as a proxy for Ar and N2, see Question 4) or using measurements of epithermal neutrons. The column abundances would be determined to better than 50 kg/m^2, and coupled with thickness measurements accurate to 0.01m would enable the determination of density to within 3.3% (for a 1m thick solid slab), allowing testing of different theories on the physical form of the ice (e.g., snow vs. slab-ice vs. hoar frost) and how ice properties change with time (e.g., compaction, dust loading). Determining the thickness of the residual CO_2 ice cap to the nearest centimeter may also assist in the assessment of long term climate change, which is primarily addressed by Question 3.

Question 3: At the present day obliquity, is Mars currently undergoing climate change, and what effect does this have on polar processes and the CO_2 cycle?

Investigation: Determine the long-term stability of the south polar residual cap by establishing long-term measurements of the surface air pressure capable of detecting absolute changes of 4 Pascals per Mars decade.

It has been repeatedly suggested that Mars is currently undergoing climate change, based on observations of the south polar residual cap (SPRC) (e.g., Malin et al., 2001; Thomas et al., 2005). Observations of hectometer-scale CO_2 ice topographic features that resemble Swiss cheese show that the "holes" are growing larger, suggesting that the residual CO_2 ice may be experiencing net sublimation (e.g., Malin et al., 2001). Where the subliming CO_2 ice goes is a question of significant debate. If the CO_2 ice component of the SPRC is subliming away, then the CO_2 is going back into the atmosphere, thus raising the overall surface pressure by a few Pa per Mars decade (Haberle, 2009). However, other studies suggest that much of that CO_2 may be recondensing either along the SPRC edge (e.g., Winfree & Titus, 2006; Winfree & Titus, 2007) or on the flat surfaces adjacent to the Swiss cheese formations (Byrne and Zuber, 2006). Highly accurate and precise monitoring of the surface air pressure over long periods of time (many Mars-years) would directly address these issues. Note that the surface pressure constraint on the polar sublimation can be made by a lander anywhere on Mars.

Question 4: What is the nature of CO_2 deposition (e.g., snow or direct frosting, continuous or sporadic) and sublimation (e.g., at some depth or at the ice surface, contribution of contaminant load) in space and time?

Investigation: Determine the mixing ratios of non-condensible gases within the polar night and during the polar sublimation phase.

Mars Odyssey Gamma Ray Spectrometer (GRS) and Neutron Spectrometer (NS) data have shown that the wintertime atmosphere in the polar regions can become strongly enhanced with non-condensible gases (and are depleted in the springtime). This affects CO_2 condensation on the ground and in the atmosphere by changing the frost point, thus affecting the basic thermal structure of the atmosphere (and thereby affecting atmospheric circulation on a global scale). Because non-condensible gases are passive tracers, their time-dependent distribution can provide a great deal of information about the large-scale atmospheric circulation. It is thus very important that improved measurements of the enhancement/depletion of these non-condensible gases be made by future spacecraft. The GRS and NS Argon data have very low resolution in both space and time. Observation of trace gases other than N2 and Ar may be feasible with spatial resolution higher than can be achieved by GRS or NS. Carbon monoxide is an obvious candidate because it can be measured very accurately at microwave wavelengths, enabling full coverage of the high latitude atmosphere, including regions in the polar night.

Investigation: Measure and monitor clouds in the polar night, ground fogs, and CO_2 precipitation (snow).

Many of the physical expressions of the atmospheric portion of the polar energy balance on Mars occur on relatively small scales and are effectively unobservable by current passive spacecraft imagers (due largely to a lack of illumination or contrast, e.g. during the polar night). However, an active imaging instrument on an orbiting platform would enable a pioneering survey of these phenomena. An imaging LIDAR instrument, with lasers tuned to the continuum and spectral features of H_2O and CO_2 ices would allow observations of changes in H_2O and CO_2 discrimination in the snow pack and in the atmospheric clouds. Grain sizes, shapes, and cloud thicknesses would also be accessible. Nocturnal cloud surveys elsewhere on the planet (also poorly observable at the present time) would also be accessible to such an instrument.

2. Recommendations

Recommendation 1: Create and fund a new long-term NASA R&A program, the Mars Polar Research Program (MPRP).

Motivation: The motivation for such a new program is to provide a research funding option that can support inter-disciplinary studies that involve equal measures of numerical modeling, data analysis, and/or laboratory work. The current NASA Mars R&A programs, the Mars Data Analysis Program (MDAP) and the Mars Fundamental Research Program (MFRP), do not support this flexibility. MDAP overwhelmingly funds projects in which observational data analysis is clearly the dominant investigative technique, and the Mars Fundamental Research Program only funds projects that do not have a significant observational data analysis component.

Implementation: While a separate NASA Mars R&A program for polar science is strongly preferred, we recognize that such a change may not be possible in a timely fashion and so suggest that, at a minimum:
1) New polar science sub-panels should be added to both the Mars Fundamental Research Program and the Mars Data Analysis Program.
2) Specific emphasis on and support for CO_2 ice laboratory experimentation (under Mars conditions) should be provided for.

Recommendation 2: Continued comprehensive monitoring of Mars' polar regions with orbital assets.

Motivation: The extension of the relatively continuous observational record started by the Mars Global Surveyor spacecraft in 1997, and continued by Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter, is scientifically invaluable. Such measurements will enable researchers to search for interannual variations of the Mars climate (and for what causes them).

Implementation: The instrumentation necessary to continue the relatively continuous observational record started by the Mars Global Surveyor spacecraft must include the ability to determine surface and atmospheric temperatures, to differentiate between ices of different composition, to observe larger-scale weather phenomena (e.g., cap-edge dust storms), and to measure surface albedo and emissivity.

Recommendation 3: Obtain observations of Mars from orbit at a wide range of local times, while preserving an orbital inclination of between 85° and 95° to ensure polar coverage.

Motivation: With the notable exception of the Mars Express spacecraft, most observational data from orbit since 1997 have been acquired during the afternoon and the pre-dawn night. Observations at other times (e.g., mid-morning) would provide useful insights into the diurnal cycle of Mars polar phenomena, (e.g., cloud formation and thermal inertia effects).

Implementation: Place a spacecraft with a suitable payload into an orbit about Mars similar to that of the Mars Reconnaissance Orbiter, but allow the spacecraft to precess so that the nadir solar time changes throughout the mission.

Recommendation 4: All future landers and rovers destined for the surface of Mars should each be equipped with an air pressure sensor that is accurate, precise, and stable, and that records measurements of Martian air pressure for as long and as often as possible, up to 4 times equi-spaced through a sol.

Motivation: To ascertain whether Mars is currently undergoing a significant climatic shift (see Question 3, above). Such a determination requires a long temporal baseline (many Mars-years), and accurate and precise (capable of resolving a change as small as 4 Pa per Mars decade) absolute surface air pressure measurements. This cannot be done from an orbital platform.

Implementation: Equip each future lander and rover destined for the surface of Mars with an air pressure sensor that is accurate, precise, and stable, and that records measurements of Martian air pressure for as long and as often as possible.

Recommendation 5: We recommend that an orbital instrument package be sent to Mars specifically to determine formation processes and densities of seasonal CO_2 ice and snow.

Motivation: The Martian polar night still holds many mysteries, particularly with respect to the phenomena associated with CO_2 phase change. These questions include the thickness of the seasonal ice as a function of space and time, the formation of “cold spots” deep inside the polar night, possible convective CO_2 clouds, the enhancement of non-condensable atmospheric constituents, and the genesis of the cold and dark seasonal ice that composes the south polar “cryptic” region.

Implementation: The following orbital instrument combinations are suggested payloads that would be capable of answering questions about the nature of Martian CO_2 ice processes through synergy. These packages are meant to be relatively inexpensive and lightweight to facilitate their inclusion as an add-on to an existing mission concept or as a stand-alone Discovery-class mission. Conceptually, these two packages could be combined into a single polar science orbiter.

CO_2 Density Instrument Package - laser altimeter or interferometric synthetic aperture radar (InSAR), high-resolution thermal neutron imager, microwave atmospheric sounder, and high-precision radio science (ultra-stable oscillator required)

CO_2 Phase Change and Polar Night Instrument Package - Microwave atmospheric sounder, imaging LIDAR, and high-precision radio science (ultra-stable oscillator required)

3. Opportunistic Science

The recommendations presented in this paper, while focused on understanding the Mars polar energy balance and the CO_2 cycle, would result in knowledge and understanding that benefit other aspects of Mars research.

Recommendation 2 would also result in continued quasi-comprehensive observations of the entire planet, information that is important to understanding how the Mars climate system operates and varies over time, and build up more complete observations of geological features and compositions. Recommendation 3 would additionally result in global observations of Mars' atmosphere and surface at a wide variety of local times, a feat that a NASA orbiting spacecraft has not done since the Viking missions decades ago. Recommendation 4 would also provide information to further investigate atmospheric tides, frontal passages, and dust devil frequencies, and is completely consistent with recommendations by Hecht et al. 2009. Recommendation 5 would additionally provide important information about atmospheric composition, structure, and phenomena outside the polar regions.

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