PERSPECTIVES: PLANETARY SCIENCE

Global Change on Mars?

David A. Paige

Since NASA's Mars Global Surveyor (MGS) orbiter arrived at Mars in 1997, it has returned over three terabits of scientific data that are revolutionizing our view of the planet. For example, surface features have been interpreted as evidence of the recent presence of liquid water. Two reports in this issue (*1*, *2*) use MGS Mars Orbiter Laser Altimeter (MOLA) and Mars Orbiter Camera (MOC) observations to study Mars' present-day carbon dioxide cycle and the dynamic behavior of the martian polar caps. The results provide evidence for a substantial interannual variability that could have global-scale consequences for the stability of the martian environment.

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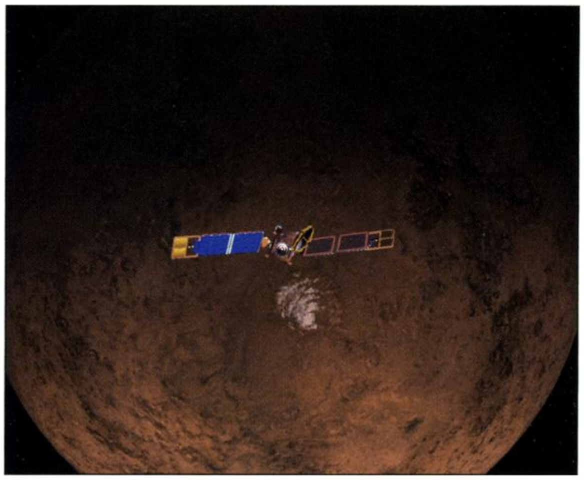
The martian atmosphere is composed primarily of carbon dioxide gas with a surface pressure of about 6 mbar—less than 1/100 that of Earth's atmosphere. In 1966, Leighton and Murray showed that temperatures on Mars are too low to permit the redistribution of substantial quantities of water ice over seasonal time scales. However, solid CO_2 deposits should condense in the polar regions during the cold fall and winter and then sublimate during spring and summer (*3*). The seasonal polar cap boundaries predicted by their early model calculations were in good agreement with telescopic observations and suggested a ~20% seasonal variation in CO_2 pressure in the martian atmosphere due to the condensation and sublimation of CO_2 planet wide.

Leighton and Murray were also the first to point out that the present surface pressure on Mars may not be an accident but rather the direct consequence of a residual or "permanent" deposit of CO_2 at one of the martian poles, in vapor equilibrium with CO_2 gas in the atmosphere. Their hypothesis implies that as long as there is enough CO_2 in the cap-atmosphere system to sustain a permanent CO_2 deposit, anything that affects the temperature of the permanent deposit (such as the amount of sunlight it receives or its solar reflectivity) will change its equilibrium vapor pressure and hence the mass of the martian atmosphere.

Given the exponential dependence of vapor pressure on temperature, the implications for the martian climate are dramatic. Dynamical calculations show that Mars has experienced quasi-periodic variations in the eccentricity of its orbit and the tilt of its spin axis that are much larger than those for Earth, resulting in factor-of-two variations in the total sunlight incident at the martian poles (*4*). The large amplitudes predicted for astronomically driven climate cycles on Mars and the sensitive coupling between its polar caps and its atmosphere have led many to believe that global change may be a routine occurrence on our neighboring planet.

Since the publication of their classic paper, many of Leighton and Murray's original notions regarding the behavior of martian volatiles have been supported by observations—but not necessarily in ways that were anticipated.



NASA's MGS orbiter observes Mars' south residual polar cap.

In 1973, after Mariner 9 sent back the first detailed images of Mars' north and south residual polar caps, Murray and Malin (*5*) proposed that the larger north residual polar cap was the most likely location of the atmosphere-buffering permanent deposit of solid CO_2. However, in 1976, Viking Thermal Mapper and Mars Atmospheric Water detector observations showed that the north residual polar cap was far too hot during the summer to contain solid CO_2 and, instead, was composed of water ice (*6*). Later Viking observations showed that the smaller south residual polar cap did remain cold enough throughout the summer to be consistent with the existence of a residual deposit of solid CO_2 (*7*). However, the relatively small geographic extent of the deposit, and conflicting data regarding its interannual stability (*8*, *9*), raised concerns regarding its ability to support a substantially larger atmospheric mass.

From its low polar orbit, MGS (see the figure) is observing Mars with uniform global coverage and unprecedented spatial resolution. These observations herald a new era in the study of Mars in which older "billiard ball" models of the planet are infused with hefty doses of reality. In no area is this more true than in studies involving the topography of the martian surface, where the MOLA instrument is accumulating a global data set of unparalleled completeness and quality.

On page 2141, Smith *et al.* (*1*) use the MOLA data acquired thus far to determine temporal changes in the shape of the planet due to the condensation and sublimation of seasonal carbon dioxide deposits. The noise level of these determinations of ±10 cm is relatively large. Nevertheless, the ~1-m seasonal amplitudes of the topographic changes that are observed in the polar regions are generally consistent with those expected from observations and models of the advancing and retreating seasonal polar caps. The results also show that the density of the seasonal deposits is on the order of 1 g cm^{-3}. This represents some of the best evidence to date that seasonal CO_2 deposits on Mars are less like fluffy, low-density snow or frost and more like higher density ice.

One aspect of the new MOLA results does not yet make sense. The maximum depth of accumulated seasonal CO_2 deposits at the north and south poles appears to be equal. Models and heat balance observations predict that because of the eccentricity of Mars' orbit, about 30% more solid CO_2 should accumulate during the longer southern fall and winter seasons at the south pole than during the shorter fall and winter seasons at the north pole (*10*).

On page 2146, Malin *et al.* (*2*) present high-resolution MOC images of what could be termed "ground zero" for the martian CO_2 cycle—the surface of the south residual polar cap. Earlier MOC images of the south residual cap revealed enigmatic scarp and pit textures not seen anywhere else in the solar system (*11*). New high-resolution images of the same areas of the cap, obtained one Mars year apart, show startling changes in morphology. The walls of scarps and pits on the cap appear to have retreated

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by 1 to 3 m and are interpreted to be the result of the sublimation of residual solid CO_2. Malin *et al.* estimate that if these observed annual scarp retreat rates were interpreted as an actual net loss of solid CO_2 from the south residual polar cap, the mass of the martian atmosphere would be increasing at a rate of about 1% per martian decade.

Are the large-scale changes in the current state of the martian atmosphere and the south polar cap suggested by these new observations reasonable? At least three considerations suggest that the answer may be yes. First, the mass of the atmosphere is extremely sensitive to the equilibrium vapor pressure of a permanent CO_2 deposit. In Leighton and Murray's model, a 1% change in the mass of the martian atmosphere would only require a 0.1% change in the long-term solar reflectance of a residual CO_2 deposit. Given this sensitivity, it may not be unreasonable to expect that interannual or longer term variations in the south residual polar cap's radiative properties might cause it to not be in precise vapor equilibrium with the present atmosphere.

Second, most previous measurements of the annual CO_2 cycle have been interpreted as consistent with annual repeatability, but the uncertainties in these measurements cannot preclude interannual variations in the mass of the martian atmosphere and south polar cap of the magnitudes suggested by Malin *et al.* Surface pressure measurements made by Viking Lander 1 over four Mars years show interannual differences on the order of 0.65% (*12*). Annual radiation budget measurements made by the Viking orbiters indicate a net annual imbalance at the south residual cap of -2 ± 5 W m^{-2}. This would correspond to a net annual gain or loss of about 20 ± 50 cm of CO_2 over the course of the year (*10*).

Third, comparisons between previously obtained images by the Mariner 9 and Viking orbiters have already shown large-scale changes in the extent of the bright south residual polar cap (*13*). The new MOC images may thus represent higher resolution views of previously observed interannual variations. Interestingly, the south residual cap observed by Viking appeared to contain more solid CO_2 than the one observed by Mariner 9 three Mars years earlier (*13*), implying that interannual changes can take place in both directions.

The suggestion that the martian carbon dioxide cycle may change from one year to the next adds an exciting new dimension to our study of the planet. During the next decade, we hope to see a quickening of the pace and a broadening of the scope of our exploration of the Red Planet. We hope to see additional long-term orbital observations of the present climate like those presented in these reports. Furthermore, landers and rovers in the polar regions and elsewhere on the planet should search for records of past climate change. From experience gained by studying the Earth's climate, we can anticipate that obtaining a deep understanding of martian climate processes and climate history will be a challenging endeavor. However, given what we are learning today, we have every reason to expect that the story that Mars has to tell us will be an interesting one.

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PERSPECTIVES: OCEAN CIRCULATION

Thin Walls Tell the Tale

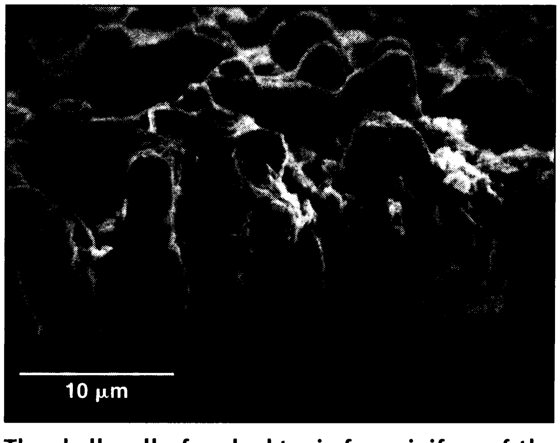
David Archer and Pamela Martin

Much of what we know about the oceans of the past has been gleaned from the microscopic shells of open-ocean plankton called foraminifera. We can reconstruct the temperature, chemistry, and circulation of the ocean from the distribution of species and their trace chemical makeup. On page 2152 of this issue, Broecker and Clark (*1*) show that foraminifera can tell us even more about the past. They use the thickness of their shell walls (see the figure) as an indicator of ocean chemistry and the carbon cycle.

The $CaCO_3$ shells dissolve and their walls get thinner when the concentration of carbonate ion, CO_3^{2-}, in seawater falls below the saturation value. Because the saturation value increases with increasing pressure, $CaCO_3$ is preserved on topographic highs such as mid-ocean ridges and completely dissolved in the deepest abyss. The concentration of CO_3^{2-} in seawater is intimately associated with pH and the concentration of dissolved CO_2 gas, and a reconstruction of deep ocean CO_3^{2-} can therefore provide clues about the circulation and carbon cycle of oceans past.

In today's ocean, convection in the North Atlantic carries high pH, high CO_3^{2-} waters into the abyss. The deep Pacific, in contrast, is unventilated, and its CO_3^{2-} concentration and pH are lower. Questions of ocean pH are at the heart of understanding the glacial/interglacial carbon dioxide concentration cycles of the atmosphere and hence the question of why there are ice ages at all. An increase in the pH of the whole ocean could explain the lowered glacial carbon dioxide concentrations during glacials (*2*).

A number of methods have been used to measure the extent of past $CaCO_3$ dissolution. One potential indicator is the bulk $CaCO_3$ concentration of the sediment, but changes in $CaCO_3$ also depend on changes in $CaCO_3$ production or dilution by clays. Another is the relative abundance of the more dissolution-resistant species of foraminifera (*3*, *4*). Both of these methods tend to be insensitive to the initial stages of dissolution, which are thought to occur even when the bottom waters above the sediment are supersaturated.



The shell wall of a planktonic foraminifera of the species *Orbulina universa*.

Broecker and Clark (*5*) have developed a dissolution index based on the size distribution of $CaCO_3$ pieces to track the breakup of large foraminifera shells into fragments. The abundance of fragments with diameters of more than 63-μm tracks overlying water CO_3^{2-} nicely today. However, Broecker and Clark's most dogged critic, Broecker and Clark (*6*), showed that the initial size distribution of $CaCO_3$ must have been differ-

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