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Mars: Northern Summer Ice Cap—Water Vapor Observations from Viking 2

Abstract. *Observations of the latitude dependence of water vapor made from the Viking 2 orbiter show peak abundances in the latitude band 70° to 80° north in the northern midsummer season (planetocentric longitude ~ 108°). Total column abundances in the polar regions require near-surface atmospheric temperatures in excess of 200°K, and are incompatible with the survival of a frozen carbon dioxide cap at martian pressures. The remnant (or residual) north polar cap, and the outlying patches of ice at lower latitudes, are thus predominantly water ice, whose thickness can be estimated to be between 1 meter and 1 kilometer.*

Over the past several years the subject of the fate of martian volatiles has received much attention. In particular, the question of whether the present thin CO_2 atmosphere with its purported small abundance of water vapor is the result of considerably less degassing than has occurred on the earth, or whether the planet has degassed to a similar extent and the volatiles are stored in the regolith material, has been debated at some length. Much of the background to this argument is summarized by Murray and Malin (*1*). It has been suggested that the bulk (CO_2) atmosphere is stabilized against variations in insolation by the presence of a reservoir of solid CO_2 located within the large residual northern polar cap.

We report here observations of the atmospheric water vapor at extreme northern latitudes, taken from the Viking 2 orbiter, within a few weeks of the northern summer solstice. The total vertical column vapor abundances poleward of 70°N latitude are the largest seen anywhere on the planet to date, and imply near-surface atmospheric temperatures in the polar region which are incompatible with the survival of a CO_2 ice cap. The remnant pole cap seen in the television images, and the outlying patches of ice covering the surface at lower latitudes, are thus predominantly water ice.

Observations. During the first 2 weeks after orbit insertion of the Viking 2 spacecraft (7 August 1976), observations were made by the Mars atmospheric water detector (MAWD) in support of the landing site selection procedure for the Viking 2 lander (*2*). These observations provided the first opportunity during the mission to view the extreme northern latitudes. Throughout the site selection and certification process, Viking 2 was in asynchronous orbit with a period of 27.4 hours, providing a survey of the northern hemisphere by drifting westward at a rate of 40° per revolution. During this phase of the orbiter's activities, MAWD made observations of two types on each of revs 7 through 15: the first of these were constant-longitude swaths from the polar region to about 20°N (the local time chosen for these swaths was approximately 1400 hours); the second set of observations comprised scans of constant latitude along the region 40° to 50°N, a total longitude coverage of about 80° being obtained on each revolution. In this way a complete survey of the nominal landing site latitude was obtained, each point being covered at several local times of day. Taken as a whole, these observations provided an adequate first-order description of the water vapor over the northern hemisphere in terms of its dependence on latitude, local time, and topography at this season (that is, about one martian month past the northern summer solstice).

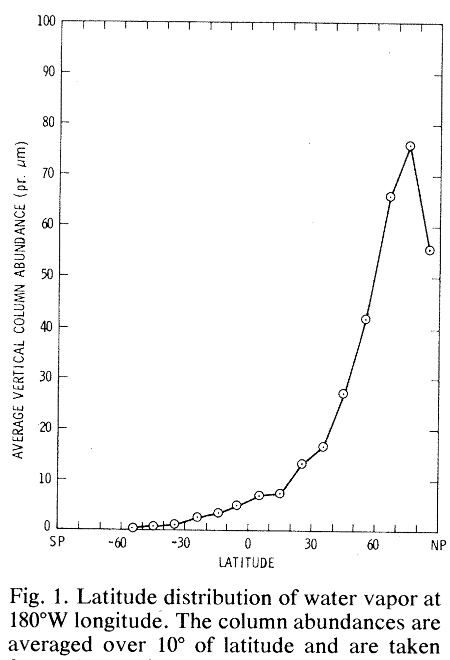

Fig. 1. Latitude distribution of water vapor at 180°W longitude. The column abundances are averaged over 10° of latitude and are taken from observations made between 1200 and 1400 hours local time. The season is northern summer (planetocentric longitude ~ 108°).

On rev 7, the constant-longitude swath scanned the 180°W meridian. The latitude dependence of vertical abundance derived from this sequence, averaged over 10° of latitude, is shown in Fig. 1. Individual measurements contributing to the averages plotted in Fig. 1 have an uncertainty (1 standard deviation) of 10 to 15 percent, depending on the local surface albedo; the corresponding uncertainty in the mean abundance for each latitude band (derived from some 10 to 20 individual records) is ± 4 percent. Included in Fig. 1 are the midday averages determined from the southern hemisphere mapping (*3*) carried out from the Viking 1 orbiter during approximately the same time period; the latter measurements overlap those from the Viking 2 orbiter at 20°N, and the composite result illustrates the strong latitude dependence of the vapor from the extreme winter latitudes—less than 1 precipitable micrometer (pr μm)—to the edge of the summer cap, covering a range of abundances of almost three orders of magnitude. There is a marked increase at about 40°N, the maximum being reached in the polar region at 70° to 80°N. Similar distributions were observed at each of the longitudes scanned, although the values were somewhat smaller than those at 180°W.

As a result of the large abundances observed in the polar region during the initial site certification phase, a set of box scans coupled with an imaging sequence was inserted on rev 22. This was done in order to obtain more detailed data for the polar latitudes before any major change in the atmospheric or surface conditions in that region occurred (*4*). Figure 2 shows the mosaic of seven television images taken on rev 22; water vapor scans were taken before, during, and after the imaging sequence, and hence cover a larger range of longitudes in the vicinity of the cap. In general terms, the data show large areas, coin-

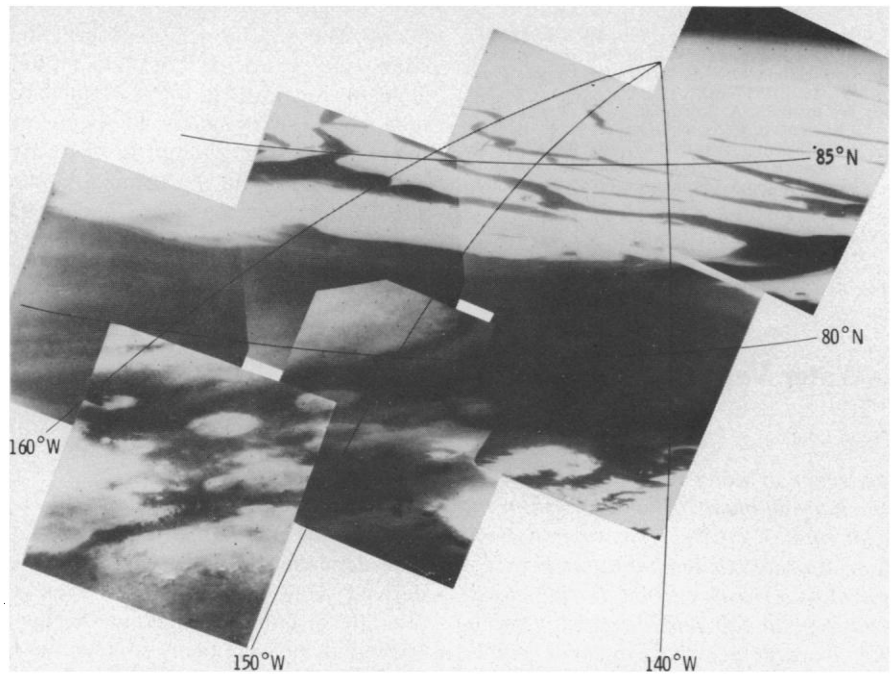

Fig. 2. Mosaic of seven TV images of the northern polar region taken from the Viking 2 orbiter on rev 22. The central residual ice cap extending down to 82°N latitude and the surrounding dark region with fragmented patches of ice and cloud cover can be seen.

ciding with the dark band around the residual cap and including the outlying ice patches, over which the column water vapor abundances are in the range 60 to 80 pr μm. Toward the center of the cap itself the values drop to about 30 to 40 pr μm.

Discussion. In order to determine the degree of saturation of the atmosphere, it is necessary to know the vertical profiles of both the vapor mixing ratio and the temperature. Neither of these is available from the data in hand; however, a lower bound on the atmospheric temperature near the surface can be set by assuming a scale height for the vapor equal to that of the bulk atmosphere (~ 11 km) and an isothermal vertical temperature profile. Even under these unlikely conditions, to avoid saturation the surface atmospheric temperature must be in excess of 204°K. A more realistic estimate can be made as follows: the atmospheric temperature at an altitude of 20 to 25 km (that is, two scale heights above the surface) at equatorial and middle latitudes is approximately 180°K (*5*), and we assume, conservatively, that this applies to the polar region also. The minimum atmospheric temperatures correspond to saturation at all levels and, assuming a single lapse rate of temperature, are compatible with the observed vapor abundance if the lapse rate is not less than ~ 1.5°K km^{-1}. It should be noted that this implies a *stable* atmosphere and that the near-surface atmospheric temperature must exceed 205°K over the central ice cap and 210°K in the dark region surrounding it. Independent observations of the actual surface temperatures in the polar region confirm this result (*6*). Clearly, any other distribution of the water vapor with altitude (for example, the use of a scale height significantly smaller than that of the bulk atmosphere) would result in yet higher temperatures. Furthermore, the agreement between the near-surface atmospheric temperatures derived from the water vapor observations and the temperature of the surface itself indicates that the atmosphere is, in fact, close to saturation over the entire polar region at this season.

It is thus difficult to reconcile the observed amounts of water vapor with the survival of a CO_2 ice cap (which at martian atmospheric pressure requires a temperature of 150°K). The summer residual ice cap (above 82°N) and the fragmented patches of ice remaining in the band 70° to 80°N are, therefore, water ice.

The thickness of the polar ice can be estimated from the scale of surface roughness, which the thickness must exceed in order to produce features visible in the orbital photography as extended areas of high albedo. For the outlying ice-covered region, the roughness scale must lie somewhere between the average size of boulders (perhaps ~ 1 m) and the depth of the smallest craters whose rims protrude above the ice surface (on the assumption that these are ice-filled). Using the rule of thumb that the average crater diameter-to-depth ratio is 6 : 1, this yields an estimate for the maximum thickness of the peripheral polar ice of the order of 1 or 2 km. The maximum thickness of the ice forming the continuous cover of the central residual polar cap is presumably equal to or greater than this.

If the vapor in the polar region were condensed onto the surface, its thickness (~ 0.1 mm) would be insufficient to produce any detectable change in the surface albedo. Indeed, the total planetwide vapor at the seasonal maximum (which is equivalent to ~ 1 km^3 of ice), condensed on the surface above 70°N latitude, would produce a layer less than 1 mm thick.

Considering the average martian surface temperature, the prevailing water vapor budget is entirely consistent with the possibility that there is a large reservoir of water ice within the planetary regolith. Furthermore, there must be a permafrost layer (that is, permanent over periods greater than a martian year) at the depth where the diurnal and seasonal thermal waves at no time during the year raise the temperature above the mean frost-point temperature; that is, the surface of the permafrost does not contribute to the annual cycling of vapor between the regolith and the atmosphere. Superimposed on the permafrost layer is a region of *seasonal* permafrost ("tempofrost") which, during the cold season, remains at or below the mean frost-point temperature. Observations of the seasonal variation of surface temperature (*7*) show that the seasonal permafrost boundary in the winter hemisphere includes the surface at all except the equatorial latitudes. At the onset of spring and summer the seasonal permafrost boundary at the surface recedes toward the pole, with the release of vapor to the atmosphere. The residual water ice seen in the (northern) polar region marks the boundary of the intersection of the true permafrost with the planetary surface.

It will be a matter of some interest, in the context of martian climatic changes, to attempt to determine from the future observations whether the polar reservoir of ice acts as a net source or sink (over periods greater than a martian year) for the atmospheric vapor during this phase of the present epoch.

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Martian North Pole Summer Temperatures: Dirty Water Ice

Abstract. *Broadband thermal and reflectance observations of the martian north polar region in late summer yield temperatures for the residual polar cap near 205 K with albedos near 43 percent. The residual cap and several outlying smaller deposits are water ice with included dirt; there is no evidence for any permanent carbon dioxide polar cap.*

Observations of the martian south polar cap obtained by Mariner 7 conclusively demonstrated that the seasonal polar caps were composed predominantly of solid CO_2 (*1*). Whether the residual polar caps are composed of H_2O, CO_2, or a combination of them has been the subject of continued debate [for example, see (*2–4*)]. The abundance of martian surface forms attributed to fluvial erosion is a strong indication that Mars previously had a more extensive atmosphere than it does now, and permanent deposits of solid CO_2 have been invoked as stores of material that could contribute to periodic reconstitution of such an atmosphere (*5*). A persistent CO_2 polar cap would also act as a permanent cold trap and strongly influence the transport of water vapor around the planet.

A conclusive test for the absence of solid CO_2 is observation of brightness temperatures appreciably greater than 148 K, the saturation temperature of CO_2 at the martian mean total surface pressure (6.1 mbar). Carbon dioxide can be "condensed" as carbon dioxide–water clathrate ($CO_2 \cdot 6H_2O$), with an effective CO_2 density of about 0.33 g cm^{-3}, at temperatures about 5 K higher than pure CO_2. Considering both the possibility of a clathrate and that the polar surface could be at low elevation (high pressure) (*6*), temperatures above 155 K are incompatible with condensed CO_2 at the martian surface. Conclusive observations were not made by Mariner 9 (*7*).

A major objective of the Viking thermal mapping investigation has been to measure the temperature of the residual north polar cap. The infrared thermal mapper (IRTM) measures the brightness temperature at 18 to 24 μm (T_{20}) and 10 to 13 μm (T_{11}) and the total reflected solar energy (expressed as apparent albedo) simultaneously in seven 5-mrad-diameter spots with three telescopes; the fourth telescope has three detectors each at 7 and 9 μm and one in the 15-μm CO_2 band (*8*).

While the second Viking spacecraft was searching for a suitable landing area, the orbiter infrared instruments made observations which, on several revolutions, extended into the north polar region. On 31 August 1976, coverage of nearly 180° of longitude was obtained with seven accompanying pictures of a portion of the polar cap.

The measurements of 20-μm brightness temperatures over the region of the imaging coverage are shown in Fig. 1. The major thermal boundaries clearly correspond to structure in the visual brightness. The large dark regions have T_{20} near 235 K, while the main portion of

Fig. 1. Contours of T_{20} for part of the 31 August 1976 observations. The circular field of a single IRTM detector has a diameter one-sixth the width of a single photograph. The light areas with temperatures near or below 220 K are water ice. The light areas in the lower left portion of the mosaic are almost entirely clouds with little actual brightness variation; the contrast between adjacent frames indicates the variation of image enhancement. At the center of the mosaic, the geometry at the time of the IRTM observations was: solar incidence angle 62°, viewing angle 70°, phase angle 49°, local time 1500 hours, and range 3200 km.