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# Cold Spots in the Martian Polar Regions: Evidence of Carbon Dioxide Depletion?

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**Regions of very low, rapidly varying brightness temperatures have been observed near the martian winter poles by several spacecraft. One possibility is that the $CO_2$ condensation temperature is lowered by depletion of $CO_2$ in the air at the surface. We estimate the rate at which this low-molecular-weight air would disperse into the high-molecular-weight air above and show that it is generally faster than the rate of supply. This dispersal could be prevented if there is a strong temperature inversion (warm air above colder air) near the surface. Without an inversion, the entire atmospheric column could become depleted. However, depleted columns take a long time to form, and they are inconsistent with the rapid fluctuations in the cold spot locations and temperatures. Because low-altitude temperature inversions cannot be ruled out by existing observations, $CO_2$ depletion is still a viable explanation for the martian cold spots.**
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## 1. INTRODUCTION

During the martian winter, surface and atmospheric temperatures fall to the frost point of $CO_2$ gas, and the atmosphere condenses to form the seasonal polar frost caps. The winters are short enough that the global $CO_2$ atmosphere is never fully depleted, which should prevent temperatures from falling below the nominal frost point anywhere on the surface. Given that the surface partial pressure is about 7 mbar, the temperature of this point should be near 148 K. It was thus a major surprise when the Viking Orbiter Infrared Thermal Mapper (IRTM) observed 20-$\mu$m brightness temperatures as low as 127 K in localized parts of the winter polar regions (Kieffer *et al.* 1977). Subsequent analysis of the IRTM data has shown that sub-148 K average temperatures persist throughout much of the winter for latitudes poleward of $\sim 70^\circ$ (Forget *et al.* 1995). Often referred to as "cold spots," these features vary on time scales of days and weeks and on spatial scales of hundreds of kilometers, ultimately disappearing with the arrival of spring. Some cold spots were observed to fluctuate by 10 K or more in a few days while remaining in a fixed location; such cold spots seem to be well correlated with surface features like the permanent polar boundaries and isolated craters (Forget *et al.* 1995, Hansen 1998). Cold spots have also been retrospectively identified in Mariner 9 interferometer spectrometer (IRIS) data (Forget *et al.* 1995). The Mars Global Surveyor Thermal Emission Spectrometer (TES) is now detecting 20-$\mu$m brightness temperatures as low as 115 K (Kieffer *et al.* 1998).

Kieffer *et al.* (1976a) and later authors proposed several hypotheses to explain the cold spots: the presence of ground $CO_2$ frost or snowfall with emissivities less than one (Forget *et al.* 1995, 1998, Hansen 1998, Kieffer *et al.* 1998), obscuration by high-altitude, low-temperature clouds (Kieffer *et al.* 1977, Hansen 1998, Forget *et al.* 1995, 1998), elevation of the surface, the presence of cyclonic low-pressure zones, and the depletion of $CO_2$ in the near-surface atmosphere (Hess 1979). All but the first two hypotheses involve emission from a region of low $CO_2$ partial pressure at the ground, which lowers the frost point and brightness temperature. Because there has been little additional data since the Viking era, most efforts have been aimed at determining the physical plausibility of these hypotheses, particularly the first two. Recent altimetry data, which put the top of the north polar cap at −3 km (Zuber *et al.* 1998, Smith *et al.* 1999), immediately rule out the high surface elevation hypothesis as an explanation for the north (but not for the south) polar region.

## 2. THE $CO_2$ DEPLETION HYPOTHESIS

In the last hypothesis, the atmosphere above the surface becomes depleted in $CO_2$ as it condenses on the surface, resulting in the progressive enrichment of noncondensable gases ($N_2$, Ar, and $O_2$, and the other trace gases in their natural atmospheric ratios) while maintaining a constant total pressure. Thus the partial pressure of noncondensable gases increases and that of $CO_2$ decreases. For example, the atmosphere, which on average is 95.32% $CO_2$, would need to be about 20% $CO_2$ in the surface layer for the condensation temperature to be lowered to the typically observed temperature of 137 K (Kieffer *et al.* 1976a). Even more depletion would be needed to reach lower condensation temperatures.



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The atmosphere may not be capable of achieving such a depleted state since there will be some convection of the noncondensable gases (mean molar weight $m_d = 30.9$ g) back into the heavier surrounding atmosphere (mean molar weight $m_s = 43.5$ g). Hess (1979) assumed that a depleted gas layer could be maintained only under conditions of strong static stability (i.e., when there is no convection occurring). This assumption is not necessarily valid, since it might be possible to maintain a depleted layer that is also convecting: this would occur if the layer is created at a faster rate than it is convected away. Later in this paper we demonstrate that Hess' assumption is actually correct.

Hess also assumed that temperature increases with height no faster than about 2 K/km, and then showed that a depleted layer with 20% $CO_2$ would convect unless it were at least 100 km thick. This is essentially the entire atmosphere above the surface. Such an anomalous gas column would be highly susceptible to mixing with undepleted air from adjacent latitudes. Also, it would be hard to create and destroy such a column on a timescale of days, which is required to explain the higher frequency cold spots. Hess did not discuss the problem of time scales, but he did address the problem of mixing. He showed that the depleted column could be protected if the surface below it had several kilometers of elevation and was surrounded by a strong circumpolar vortex. However, the MOLA topography (Zuber *et al.* 1998) implies that the topography is low, at least in the north polar region.

In section 3, we show the validity of Hess's assumption that static stability is required for the maintenance of a depleted surface layer. Thus, unless there is a strong temperature inversion (i.e., almost discontinuous increase in temperature with height), the depletion must extend through the entire atmospheric column. In section 4, we give arguments that cast serious doubt on the feasibility of maintaining such a tall, depleted column. However, we demonstrate that a strong temperature inversion near the ground could sustain a thin depleted layer for the observed time scales. In section 5, we demonstrate that the IRTM data cannot rule out the presence of a tall, depleted column. Since these data also do not rule out a near-surface temperature inversion, we cannot rule out carbon dioxide depletion as an explanation for the cold spots.

## 3. REQUIREMENT OF STATIC STABILITY

We begin by demonstrating that static stability is indeed necessary for the maintenance of a depleted surface layer. The reason is that convection of the noncondensables, driven by the unstable molar weight gradient, would remove the noncondensables from the layer faster than they could be replenished. Consider a thin surface layer that is 20% $CO_2$. If diffusion of the noncondensables into the overlying atmosphere were the only way to remove these gases from the surface layer, then a depleted layer could build up on a short time scale (Kieffer *et al.* 1977). However, diffusion is not the only process, removing noncondensables. Since there should be both turbulent mixing and convection due to the gradient in molar weight. For an isothermal layer (no inversion) the latter flux (molecules $cm^{-2}$ $s^{-1}$) is (Ingersoll 1970)

$$F_C = 0.17 \Delta n D \left( \frac{g \Delta\rho}{v^2 \rho} \right)^{1/3},$$

where $\Delta n$ is the difference between the depleted gas concentration (molecules $cm^{-3}$) at the surface and that of the gas away from the surface, $D$ is the diffusion coefficient of the enriched gases in $CO_2$, $g$ is the acceleration of gravity on Mars, $v$ is the kinematic viscosity of $CO_2$, and $\Delta\rho/\rho$ is the difference between the density of the ambient gas and that of the gas at the surface divided by the density of the gas at the surface. Ingersoll obtained the above mass flux equation from Jakob (1949), who detailed the similarity between the equations of mass exchange and heat convection above a heated horizontal plate. Ingersoll combined Jakob's Eqs. (28-17), (28-6), (25-26), and (25-27), letting $T_s = T_0$. He then multiplied the final equation by a factor of $2^{4/3}$ since Jakob's equations are for convection between two heated plates instead of above a single plate. The dimensionless constant 0.17 is derived from experimental measurements of the heat flux (Jakob 1949).

The martian atmosphere contains 5% noncondensable gases composed mainly of $N_2$, Ar, and $O_2$. Since we are assuming a surface layer that is 80% noncondensables, $\Delta n = (0.80 - 0.05)n = 0.75n$, where $n = 3.2 \times 10^{17}$ $cm^{-3}$ is the total density. Since the pressure of the surface layer should be the same as the surroundings, it can be shown that $\Delta\rho/\rho = 0.3$. Using $\rho = 1.1 \times 10^{-3}$ g $cm^{-3}$, $v = 9.8 \times 10^{-3}$ Poise (scaled from data in the CRC tables), $D = 7.54$ $cm^2$ $s^{-1}$ (Kieffer *et al.* 1977), and $g = 370$ cm $s^{-2}$, we find

$$F_C = 3.2 \times 10^{19}\ cm^{-2}\ s^{-1}.$$

We now compare this convective flux of molecules away from the surface with the rate at which they could be resupplied. It will take 54 days for a blackbody at 137 K to radiate away the latent heat of condensation of the $CO_2$ in the atmospheric column above it. Since the scale height of the atmosphere is 7.4 km, the downward velocity $w$ of condensing $CO_2$ molecules is $\sim$0.14 cm $s^{-1}$. The noncondensable gases will be entrained in the downward-moving $CO_2$, and so the rate at which the depleted layer is created is

$$F_R = wnf = 2.2 \times 10^{15}\ cm^{-2}\ s^{-1},$$

where $f = 0.05$ is the molar fraction of the noncondensable gases in the background atmosphere. Since $F_R$ is considerably less than $F_C$, a thin 20% $CO_2$ surface layer is not maintainable if the atmosphere is convecting. In fact, only a layer enriched in noncondensables by 0.1% above normal is maintainable. Such a negligible enrichment will not alter the $CO_2$ condensation temperature by any significant amount. The addition of turbulent mixing, not considered in the above calculation, would only increase the upward flux. Like Hess (1979), we conclude that the depleted layer will be quickly diluted into the overlying atmosphere. Thus, unless the atmosphere has a strong near-surface temperature inversion (see below), the only way to maintain a layer depleted of $CO_2$ would be if the entire air column above the surface were similarly depleted.

## 4. NEED FOR INVERSIONS

Maintaining an entire column of depleted air would be difficult for several reasons. As mentioned by Hess (1979), a depleted column could be resupplied with $CO_2$ by advection from adjacent undepleted columns. This lateral influx of fresh air might be prevented if, like Earth, Mars has a polar night vortex that inhibits poleward transport. On Earth, the vortex results from sustained low pressures around the pole due to the low temperatures reached during the night (Salby 1996). However, since the ratio of temperature to molecular weight ($T/m$, which is inversely proportional to density) of the polar martian vortex core would be large (see below), it could be fundamentally different from the Earth's cold-core vortex. If $T/m$ inside the condensing region exceeds that of the outside latitudes, the dynamics above the martian poles would resemble a terrestrial hurricane, which is a warm-core structure. If so, the rapid convergence in the boundary layer would quickly dilute the depleted gas inside.

Saturated martian air at 6 mbar has a local density maximum (minimum of $T/m$) at 148 K and a local density minimum at 134 K (Kieffer *et al.* 1977). As $T$ decreases from above the frost point, $m$ is constant, so $T/m$ decreases. As $T$ continues to decrease below the frost point, $m$ initially decreases more rapidly than $T$, and $T/m$ increases. As $T$ decreases further, $m$ approaches a constant (that of the noncondensable gas), and $T/m$ decreases again. The maximum value of $T/m$ occurs at 134 K and is the same as normal martian air at 181 K. The value of $T/m$ above a 137 K cold spot (20% $CO_2$) would equal that of a gas with 95% $CO_2$ at a temperature of 180 K. This is approximately equal to the mid-winter temperatures observed near the edge of the low-brightness temperature zones in the northern polar region ($\sim$60°N) during the year following the Viking landings (Leovy 1985). However, it is probably warmer than equivalent temperatures (150 K) on the edge of the southern polar region ($\sim$70°S). Thus, to first order it appears that depleted columns above southern polar cold spots would behave as warm-core rather than cold-core structures. As such, they would be vulnerable to mixing with air from outside.

Even if the poles are isolated by a low-pressure vortex, it would be difficult for such a long-lived and large-spatial scale flow to produce the cold spots, which change quickly and are highly localized. For instance, Viking observed a decrease from $\sim$147 to $\sim$143 K in the 20-$\mu$m brightness temperature—corresponding to a halving of $CO_2$ partial pressure—over 12 days in an area just a few tens of kilometers in size (Forget *et al.* 1995). Assuming no exchange with adjacent air columns, it would take a little less than 2 months for a 143 K surface to deplete the $CO_2$ in the atmospheric column above it. Thus, even if $CO_2$ could be rapidly resupplied to depleted regions, it would be extremely difficult to re-deplete those regions soon afterward. This problem could be alleviated if depleted columns were able to move rapidly from one location to another. However, such moving columns would be vulnerable to mixing with adjacent undepleted columns. There is also no evidence for coherent, moving cold spots in the IRTM or IRIS data. And this could not explain the subclass of cold spots which fluctuate rapidly in brightness temperature (by 10 K or more in days) but are stationary and appear well correlated with underlying surface features and low-amplitude topography (Forget *et al.* 1995, Hansen 1998).

So a tall depleted column is vulnerable to mixing and cannot explain the observed rapid temperature variations. We now consider the more feasible possibility of a thin depleted layer. Based on the previous discussion of the behavior of $T/m$ with $T$, a thin depleted layer could only be maintained if the undepleted gas immediately above it were significantly warmer (e.g., the undepleted gas would have to be warmer than 180 K for a 137 K, 20% $CO_2$ surface layer). This is a realistic possibility, since air derived from lower latitudes could remain adequately warm for $\sim$2 days (the time scale for radiative cooling). This is longer than the 1/2 day required for the formation of a 100-m-thick depleted layer by condensation. We conclude that $CO_2$ depletion is possible if there are strong near-surface temperature inversions during the polar night.

## 5. TESTING THE $CO_2$ DEPLETION HYPOTHESIS WITH IRTM DATA

We now examine the IRTM data for evidence of tall, depleted columns or for strong near-surface temperature inversions. Figure 7 of Forget *et al.* (1995) contains more than 25,000 simultaneous 15- and 20-$\mu$m IRTM observations of both polar regions during fall and winter. The 20-$\mu$m ($T_{20}$) data are unaffected by gaseous absorption and measure the brightness temperature of the surface when the aerosol opacity is low. For the 95% atmosphere, the 15-$\mu$m ($T_{15}$) data measure atmospheric temperatures averaged over a broad range of altitudes with maximum sensitivity at the 25-km (0.6 mbar) level (Kieffer *et al.* 1977). In the figure of Forget *et al.*, $T_{15}$ is plotted against $T_{20}$. The cold spots are where $T_{20} < 148$ K.

In the cold spots, $T_{15}$ ranges from $\sim$175 down to 130 K. The lower limit is sharp ($\pm$1 K) and applies to all points, whether or not they are cold spots. The upper limit is softer, but it implies that warm atmospheric temperatures are sometimes found over the winter cold spots. These are consistent with a strong temperature inversion that could maintain $CO_2$-depleted air close to the surface. On the other hand, the $T_{15}$ data sample a broad layer at high altitude and do not give information about conditions close to the surface. Also, many of the cold spots do not have warm $T_{15}$ brightness temperatures. The IRTM data do not rule out the possibility of strong temperature inversions close to the surface.

Initially we hoped that the firm lower limit on $T_{15}$ at 130 K could be used to rule out the hypothesis of depleted $CO_2$ columns. The idea was that such columns could have temperatures at the 0.6-mbar level that are below the minimum possible temperatures in the normal martian atmosphere. If such temperatures were never seen, then such columns probably did not occur. We first verified that 130 K is the expected minimum $T_{15}$ brightness temperature, assuming the minimum corresponds to a saturated atmosphere, i.e., a moist adiabat starting at the Mars surface with a normal mixture of $CO_2$ and other gases. The formula for a moist adiabat when the condensing gas is a major constituent is taken from Eq. (3.8.3) of Gill (1982). We digitized the 15-$\mu$m IRTM weighting functions (Kieffer 1976b) and convolved them with the Planck function of the moist adiabat. This is the minimum brightness temperature one would expect to see, and for an airmass of 2.0 it is exactly 130 K (it is 132 K for an airmass of 1.0).

The difficulty comes when one tries to compute the minimum brightness temperature for a depleted atmospheric column. As long as pressure broadening is unimportant, the weighting functions are controlled by the amount of $CO_2$, which for a saturated atmosphere is controlled by temperature. Thus as $CO_2$ is removed from the atmosphere, the weighting functions move down to where the temperature is warmer. The result is that $T_{15}$ does not drop below 130 K. We cannot use the absence of lower brightness temperatures as evidence for the absence of depleted columns. Pressure broadening of the spectral lines could prevent the weighting functions from moving down in proportion to the $CO_2$ abundance. However, pressure broadening is relatively unimportant in the martian atmosphere, so the conclusion stands. The 130 K lower limit is mainly evidence that the martian atmosphere is not supersaturated (no temperatures below the frost point). It does not allow us to rule out depleted columns.

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