Thermal Infrared Properties of the Martian Atmosphere

3. Local Dust Clouds

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Prior to and during the Martian global dust storms in 1977, local dust clouds were identified from thermal observations. Local dust clouds appear up to 40 K cooler than the surrounding region in the daytime and appear warm at night. In contrast to their well-developed and consistent thermal signatures, local dust clouds exhibited little albedo contrast. Multiple observations of the same areas show that local dust clouds form and dissipate in a few days or less, and clouds were observed to move with velocities of from 14 to at least 32 m s⁻¹. Local dust clouds are common along the receding edge of the south polar cap (observed primarily for orbiter imaging) and in the restricted area -10° to -30°, 80° to 125°W (observed primarily by the infrared thermal mapper); several of the latter occurred over a ridge in Claritas Fossae, indicating strong topographic control. In their active growing stage, local dust clouds are probably about 8 km high and have relatively abrupt tops. The accumulation of dust from local clouds reached similar levels immediately prior to both global storms, supporting the hypothesis that such dust accumulations are responsible for triggering the global dust storms.

INTRODUCTION

Dust storms, ranging in size from local (10⁴ km²) to global, have been observed by Viking spacecraft during the course of their missions. Earth-based observers have long noted the presence of 'yellow' dust clouds; these occur in all seasons and in locations spanning the entire planet [Capen and Martin, 1971]. Major storms, usually global in nature, have been documented by Capen [1974], Capen and Martin [1972], and L. J. Martin [1974] and have been found to begin near Mars’ perihelion, when solar insolation is maximum in the southern mid-latitudes. Mariner 9 arrived during such a global storm in 1971 [Leovy et al., 1972] and was able to observe the varying stages of the storm as well as numerous local dust clouds. (For an extended discussion of historical observations and review of dust storm dynamical theories, see the work of Briggs et al. [1979].) Thus the Viking observations of storms came as no surprise. What they do provide is high-resolution imagery of dust activity by the Viking imaging system (VIS) [Briggs et al., 1979], in situ measurements [Pollack et al., 1979; Ryan and Henry, 1979; Tillman et al., 1979], and visual and thermal data from the infrared thermal mapper (IRTM), which detected and mapped storms with and without the aid of visual imaging. Also, the Viking experiments have extended observations to portions of the Martian year previously undocumented by spacecraft instrumentation.

Two major dust storms and numerous local dust clouds were observed from June 1976 (L₆85) to October 1977 (L₆342), the highest concentration of activity occurring during the Martian southern spring (January 1977 to June 1977, L₆180-270). The two global storms were observed near perihelion, although the first storm (L₆207) appeared earlier than expected from the historical record; the occurrence of two major storms in a single season, however, is not uncommon (Mars Scientific Model [Michaoux and Newburn, 1971]). Although observations of local dust clouds were made by Viking throughout the year, the majority of the storms occurred during spring in the southern hemisphere.

An increase in global atmospheric opacity prior to the onset of each of the global storms was observed from both orbiter IRTM observations [T. Z. Martin et al., 1979] and lander imaging [Pollack et al., 1977, 1979]. The occurrence of numerous local dust clouds prior to the global storms thus appears to be an important mechanism for injecting considerable quantities of dust into the atmosphere.

In this paper we describe the thermal and visual characteristics of the local dust clouds as detected by the Viking IRTM. Attention is given to documenting the occurrence of the local clouds in time and location on the planet, their thermal and visual properties, and the association of the clouds with local and regional surface features.

IRTM Data Description

The data presented in this paper were collected between June 1976 and October 1977 by the infrared thermal mappers aboard the two Viking orbiters. The IRTM is an infrared radiometer which collects data in six spectral bands; five thermal channels, centered at 20, 15, 11, 9, and 7 μm, and one visual channel which covers from 0.3 to 3.0 μm (see the work of T. Z. Martin et al. [1979] for an extended discussion of the IRTM characteristics as they relate to atmospheric studies). Brightness temperatures derived from the thermal channels are used extensively in this paper, the channel reference being given as $T_x$, where $x$ equals the wavelength in microns corresponding to the center of that channel (for example, a brightness temperature derived from the 7-μm channel will be referred to as $T_7$). A comprehensive description of the IRTM is given by Chase et al. [1978].

The Viking mission has produced an enormous quantity of IRTM data, an average of more than 1 hour of observation per spacecraft per day. Some selectivity among data sets was therefore necessary to search for local storm signatures. The search has concentrated on the time between the two global dust storms. Although considerable earlier IRTM data have been examined without detection of a dust storm, this examination neither was exhaustive nor did it include dust storms as an objective.

There are additional constraints on IRTM coverage of local and regional dust storms placed by Viking orbital parameters and viewing opportunities. A profile of the Viking orbiter
primary mission and IRTM operations have been described by Snyder [1977] and Kieffer et al. [1977], respectively. In the northern hemisphere, orbiter coverage during the period of the two dust storms was such that synoptic observations were not feasible. Synoptic coverage of the southern hemisphere was possible, and thus the detection of local dust clouds is biased toward this hemisphere.

The observations are not uniformly spaced in time, but an average of about one sequence per day obtained between the two global storms was examined. This study covers all longitudes reasonably uniformly, with special examination of areas where local dust storms were known to occur. The recognition of a dust cloud from the thermal data was based on two criteria: the presence of an unexpected area of thermal contrast in a region where such a contrast was not observed in previous mapping and a large variation in brightness temperature with wavelength.

**Dust Storm Observations**

The majority of local dust clouds and the two major global storms originated in the southern hemisphere between $L_2$170 and 290. The major global events corresponding to this time period are the rapid sublimation of the seasonal south polar cap, which produces a large mass flux of CO$_2$ into the atmosphere. Mars perihelion ($L_2$250), and peak solar insolation at southern mid-latitudes corresponding to the southern solstice ($L_2$270). Brightness temperatures in excess of 300 K were measured during this period for some areas of low thermal inertia. The local dust clouds observed in the southern hemisphere during this time by the orbiter imaging and/or the IRTM are represented in Figure 1 as a function of time and latitude. While a considerable number of local dust clouds have been identified, complete and continuous sampling at all longitudes, latitudes, and times was not possible; thus some occurrences have certainly not been recorded.

The local dust clouds are not uniformly distributed in latitude and season and can be conveniently grouped for purposes of discussion. In the southern hemisphere the clouds can be divided into two groups: those which occurred along the receding edge of the south polar cap prior to each global storm and those which occurred in a narrow tropical band in the period following the beginning of the first global storm. Only two local dust clouds have been observed in the northern hemisphere at $L_2$201 and $L_2$340 at $+42^\circ$ and $+22^\circ$, respectively, the occurrence of the second one being over the Viking Lander 1 site. The small number of northern storms observed may be due to the lack of synoptic coverage of the northern hemisphere during this period.

Numerous local dust clouds were observed by the VIS along the receding edge of the south polar cap throughout the southern spring [Briggs et al., 1979]. At $L_2$176, when two yellow dust clouds occurred in the Argyre basin ($-47^\circ$, 39$^\circ$W and $-48^\circ$, 31$^\circ$W), $T_{bc}$ ranged from 150 K over the CO$_2$ frost at $-55^\circ$ to 210 K at the latitude of the local clouds. The thermal characteristics of these clouds were difficult to ascertain because of the limited IRTM spatial resolution of these observations, the large temperature contrasts associated with the edges of frosted regions, and the similarity of surface and atmospheric temperatures.

The locations of the centers of the tropical dust clouds are shown in Figure 2. During the period between the two global storms, orbiter observations covering all longitudes were checked for evidence of local dust activity, but only in the region between 80$^\circ$ and 130$^\circ$ longitude was such evidence detected. This is the same longitude band in which the global dust storms were first detected. The fact that local dust clouds were not detected elsewhere in the southern hemisphere, except near the south polar cap edges as described above, was surprising because of the many historical observations of dust clouds in the Hellespontus ($-40^\circ$, 315$^\circ$W) and Noachis ($-40^\circ$, 345$^\circ$W) regions during the southern spring [L. J. Martin and W. A. Baum, 1969]. In 1977, local dust clouds formed repeatedly over particular locations: Solis Planum ($-20^\circ$, 90$^\circ$W) and Claritas Fossae ($-20^\circ$, 110$^\circ$W).

At $L_2$221.4 a small dust cloud was observed by the VIS in Solis Planum (Figure 3a), at a time when the atmosphere was still dust laden from the first global storm, which had begun only 1 month earlier. At $L_2$227.7 a larger, more sharply developed cloud was imaged over the same location (Figure 3b). Both images were taken at ~11.6 hours local time with violet

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![Diagram](image-url)  

Fig. 1. Time line of the occurrences of local dust clouds in the southern hemisphere. Time is given in both universal time and solar longitude. The receding edge of the south polar cap is shown as two lines at the approximate time that the cap becomes asymmetrical [see James et al., 1979].
Fig. 2. Southern hemisphere tropical local dust clouds during the southern spring. The black dots represent the location of the minimum temperatures associated with IRITM-detected local storms and show the solar longitude of the event. The corresponding thermal data for these clouds are presented in Table 1.
Fig. 3. 
(a) Local dust cloud over Solis Plenum at $L_s=221.4$ (VIS frame 201B22). (b) Dust cloud in the same location 10 days later at $L_s=227.7$ (VIS frame 211B24). The bright complex features in the upper portions of the pictures are Noctis Labyrinthus and the western extreme of Vallis Marineris. The bright 100-km circular feature south of their juncture is the crater Oudemans ($-10^\circ, 92^\circ W$). These features appear bright at this time because of low-lying dust.
filters and similar viewing geometry. The dust cloud at $L_227.7$ has an area of $\sim 3 \times 10^8$ km$^2$ and shadows suggesting heights of $\sim 10$ km. The IRTM observed a dust cloud in the same location on the preceding day ($L_227$) in a set of four observations which spanned a midday period of 5.1 hours. The spectral signature and behavior in time of this cloud were studied in detail.

The spectral signature of the Martian atmosphere as a function of season is discussed by T. Z. Martin et al. [1979]. In general, dust absorption has the greatest effect on $T_{9}$, somewhat less and similar on $T_{11}$ and $T_{26}$, and least on $T_{s}$. This was shown to agree with the Mariner 9 infrared interferometer spectrometer spectra, which noted broad absorption bands due to the dust near 480 cm$^{-1}$, within the 20-μm band, and between 900 and 1200 cm$^{-1}$, which is centered at 9 μm and extends toward the 11-μm band [Hanel et al., 1972]. The local dust clouds exhibit the same relative pattern, $T_{s}$ being the warmest and $T_{11}$ the coolest of the IRTM ‘surface’ temperatures at midday. Figure 4 shows these spectral differences for the $L_227$ dust cloud at 12.8 local hour. The shape of the cloud and the location of the thermal minimum are essentially the same for all of these four spectral bands. Because of the strong gradients of brightness temperature across the dust cloud the spectral changes can best be established by differencing the simultaneous individual measurements. Since $T_{9}$ and $T_{s}$ are measured by two offset triples of detectors in the same telescope, they cannot be directly differed but can be compared to either $T_{11}$ or $T_{26}$, which each have a full complement of seven detectors; $T_{11}$ is used here. In a $150 \times 300$ km area centered over the dust storm (selected as the area of the lowest temperatures), $T_{7}$, $T_{11}$, and $T_{26}$ were $+6.0$, $-3.4$, and $-1.5$ K relative to $T_{11}$, respectively, and 500 km to the southeast, off the edge of the dust cloud thermal depression, the corresponding spectral contrasts were $+9.8$, $-4.0$, and $-3.8$ K. $T_{9}$ $- T_{11}$, however, was as low as $-7$ K near the strongest temperature gradients on the east and south boundaries of the dust cloud. Over the next 4-hour period of general cooling the spectral contrast between the current center of the cloud and the region 500 km southeast,

$$ (T_{9} - T_{11})_{\text{cloud}} - (T_{9} - T_{11})_{\text{region}} $$

was essentially constant at 6.2 K for $T_{7} - T_{11}$, decreased from 0.6 to $-2.5$ K for $T_{9} - T_{11}$, and decreased from 2.3 to 1.5 K for $T_{26} - T_{11}$. The difference between $T_{26}$ and $T_{11}$ was less over-the-cloud than in the surrounding region at all times observed. There was in general a remarkable lack of spectral effect, apart from $T_{s}$, considering that the cloud had a 35 K thermal amplitude.

The other local clouds observed in the southern tropical latitudes had similar spectral differences. Table 1 presents the locations, observational geometry, minimum temperatures, and estimated velocities for these clouds. The absolute values
The series of four IRTM observations, spanning 5.1 hours, of the Solis Planum dust cloud allow study of the short-period thermal changes and apparent motion of a dust storm. The 20-μm brightness temperature maps for each of the four obser-

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Resolution = (0.0052 - range)/\(\cos e\). NA means not applicable.

of the spectral differences varied for each individual cloud. The variations appear to be due to actual variations in the infrared opacity of the clouds as well as to differing observational incidence and emission angles.

Fig. 5a

Fig. 5b

Fig. 5c

Fig. 5d

Fig. 5. Diurnal variation of \(L_{p227}\) dust cloud as seen in the 20-μm brightness temperature maps. Local time refers to a common point at 95°W longitude. See Table 1 for the geometry associated with each map.
Fig. 6. The 20-μm brightness temperature maps of the Claritas Fossae region. The data concerning the midpoint of the map are shown.
The pattern of wind streaks and model calculations [Leovy and Mintz, 1969] suggest, however, that westerly winds should be predominant at this season. The rapid occurrence and dissipation of local yellow clouds has been noted from earth-based observations [L. J. Martin and W. A. Baum, 1969], suggesting that the first explanation is reasonable. The thermal characteristics of the day 2 cloud are quite similar to those of the L227 dust cloud discussed above.

During the primary mission the Claritas Fossae region exhibited a noted albedo contrast, with a bright area centered at −20°, 107°W [Kieffer et al., 1977], the same location as that of the clouds on days 7 and 9. From the albedo maps alone on those 2 days it is difficult to detect any unusual brightness features. On day 2 the variation in visual brightness is evidenced by a 20% brightening over the area of the cloud. In general, the albedo signatures of the local dust clouds were difficult, if not impossible, to distinguish from the underlying surface. It should be noted that the images of dust clouds in Figure 3 are highly contrast enhanced.

The cloud on day 7 appears to be optically thinner than the day 2 cloud, as the spectral variations and the thermal contrast of the cloud in $T_{\text{m}}$ is less on day 7. The absence of a cloud on day 5 strongly suggests that the cloud on day 7 is a completely different cloud that has formed in the time between days 5 and 7. The cloud on day 9, however, may be the day 7 cloud slightly shifted to the east.

At $L_{\text{268}}$, over Claritas Fossae, the one example of a dust storm at night was found. The spectral signature was reversed from the daytime storms, with $T_{\text{i}}$ now cooler than $T_{\text{m}}$ by 13 K. This is what would be expected for temperature conditions at night, when the atmosphere and clouds are warmer than the surface.

**DISCUSSION**

The limited region of occurrence of local dust clouds in the southern tropical latitudes of Mars was one of the unexpected results of the Viking observations, as earth-based observations have commonly cited numerous other locations than the Claritas Fossae–Solis Planum region. Whether or not local dust clouds will cluster in one particular region each season is not clear. However, it is apparent that the dust clouds will occur preferentially in particular regions over many seasons. The surface characteristics of the Claritas Fossae–Solis Planum region provide some insight into why these clouds preferentially occur in such a region. Dramatic differences in albedo boundaries and wind streaks in this region between 1972 and 1976 suggest that significant redistribution of surface material has occurred in this region [Veverka et al., 1977]. Viking observations of this region from before and after the dust period also show that dramatic changes in surface albedo and color features have occurred. Thus in the context of the local dust clouds this region has a thin veneer of fine-grained material that is mobile owing to the common occurrence of winds that exceed threshold velocities.

There is a low thermal inertia region including the Tharsis plateau and extending west to the Elysium region and a relatively high thermal inertia region centered in Solis Planum (Figure 8). The minimum thermal inertia occurs on Arsia Mons, where diurnal temperature variations of approximately 150 K occur during the season of peak solar insolation, and a local maximum in Solis Planum, where diurnal variation is ~ 60 K. The gradient in thermal inertia appears to be greatest across the Claritas Fossae–Solis Planum region, where it fol-
Fig. 8. Thermal inertia map of the region of local dust storm occurrence. The contour intervals are in units of $10^{-4}$ cal cm$^{-2}$ s$^{-1/2}$ K$^{-1}$ [Kieffer et al., 1977].
allows the topographic gradient (see Figure 2), and the combination could produce strong slope winds. The Claritas Fossae ridge would act essentially as a barrier across these winds, causing strong local turbulence capable of raising the dust into the atmosphere.

The motion of the L$_{1227}$ local dust cloud and three other clouds, shown in Table 1, ranged from 14 to 32 m s$^{-1}$, based on the displacement of the brightness temperature isotherms. The direction of motion consistently aligned with prominent wind streaks on the surface. The orientations of the wind streaks are predominantly parallel to the regional slope, thus implying the presence of downslope winds. The variation of wind streak form and contrast across the dust storm period suggests that Claritas Fossae–Solis Planum is indeed a region of active aeolian processes.

Some general inferences may also be drawn about local dust cloud height and about the infrared opacity near the cloud top by using simultaneous observations of brightness temperature at several wavelengths.

An upper limit on the height of local dust clouds is placed by the absence of any noticeable change in $T_{\text{BB}}$ over the clouds. Measurements of $T_{\text{BB}}$ over the cloud shown in Figure 4 were about 30 K colder than the top of the local cloud measured in the other thermal bands. The average temperature at the 0.5-mbar level at this season, latitude, and local hour is 211 K [T. Z. Martin and H. H. Kieffer, 1979]. A contrast in $T_{\text{BB}}$ of 4 K, 4 times the noise level, would result if the lowest 15% of the $T_{\text{BB}}$ weighting function were to sense a source at 237 K, the approximate temperature of the top of the local dust cloud. This places an upper limit on the cloud height of approximately 17 km.

The appearance of vigorous activity exhibited by the local dust clouds in Viking orbiter imaging suggests that the lapse rate within the clouds is near adiabatic. A reliable estimate of absolute height based on cloud top temperature cannot be made because of the absence of information on the temperature difference across the boundary layer, or even the temperature of the surface where cloud shadowing may be important. However, assuming an adiabatic lapse rate (4.5 K km$^{-1}$) and no boundary layer yields a cloud height of about 8 km for the cloud observed at L$_{1227}$. The lowest temperatures occur about 250 km behind the apparent front of this cloud, so that just the assumption of a monotonic relation between temperature and height places the highest part of the cloud well away from the forward edge.

The general similarity of the 9-, 11-, and 20-$\mu$m brightness temperatures for the local dust cloud is surprising, since the opacity of the dust constituting the global pall varies considerably in this wavelength range [see T. Z. Martin et al., 1979]. This observation implies that the atmosphere has only a small temperature change over the altitude range including the first optical depth of the dust clouds at these three wavelengths.

Over the L$_{1227}$ dust cloud, the spectral contrast, excluding $T_{\text{BB}}$, is decreased from the surrounding region. T. Z. Martin et al. [1979] estimate the relative opacities of the global dust storms as $\tau_9 \sim 0.2\tau_2$ and $\tau_{11} \sim 0.6\tau_2$. Using these values (and ignoring any opacity above the cloud) yields $dT/d\tau_9 \sim 5$ K in the cloud top. Correcting for the global opacity by the crude estimate that one half of the regional spectral contrast is due to dust above the level of the top of the local cloud yields $dT/d\tau_2 \sim 3$ K. Assuming an adiabatic lapse rate implies an absorption coefficient in the 9-$\mu$m band of about 1 km$^{-1}$ (1.1 and 0.7 for these two above cases). The spectral contrast of this dust cloud is typical of those shown in Table 1, indicating that such an absorption coefficient is representative of dust clouds identified with the IRTM.

The contribution of dust into the atmosphere by the local clouds appears to be an important mechanism for triggering the major storms [Gierasch and Goody, 1973; Leovy et al., 1973]. While it appears that the initiation of the local dust clouds is tied to surface-related thermal and topographic conditions, the dust injected into the atmosphere by the local dust clouds is responsible for an increased diurnal temperature variation in the atmosphere [T. Z. Martin and H. H. Kieffer, 1979] which is the driving mechanism for the global dust storms [Leovy and Zurek, 1979].

The Viking observations have substantially increased the data base pertaining to dust clouds and storms on Mars. It remains to be determined from future Viking observations and/or future Mars missions whether the observations made during this year are typical of a Martian season or reflective of an anomalous year.

Acknowledgments. This research was supported by the National Aeronautics and Space Administration, Viking Project Office, and by NASA JPL contract 952088 to UCLA.

References


(Received May 4, 1978; revised July 31, 1978; accepted October 4, 1978.)