

An intercomparison of ground-based millimeter, MGS TES, and Viking atmospheric temperature measurements: Seasonal and interannual variability of temperatures and dust loading in the global Mars atmosphere

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Abstract. During the period October 1997 to September 1999 we obtained and analyzed over 100 millimeter-wave observations of Mars atmospheric CO line absorption for atmospheric temperature profiles. These measurements extend through one full Mars year (solar longitudes L_S of 190° in 1997 to 180° in 1999) and coincide with atmospheric temperature profile and dust column measurements from the Thermal Emission Spectrometer (TES) experiment on board the Mars Global Surveyor (MGS) spacecraft. A comparison of Mars atmospheric temperatures retrieved by these distinct methods provides the first opportunity to place the long-term (1982–1999) millimeter retrievals of Mars atmospheric temperatures within the context of contemporaneous, spatially mapped spacecraft observations. Profile comparisons of 0–30 km altitude atmospheric temperatures retrieved with the two techniques agree typically to within the 5 K calibration accuracy of the millimeter observations. At the 0.5 mbar pressure level (~25 km altitude) the 30°N/30°S average for TES infrared temperatures and the disk-averaged millimeter temperatures are also well correlated in their seasonal and dust-storm-related variations over the 1997–1999 period. This period includes the Noachis Terra regional dust storm, which led to very abrupt heating (~15 K at 0.5 mbar) of the global Mars atmosphere at $L_S=224^\circ$ in 1997 [Christensen *et al.*, 1998; Conrath *et al.*, this issue; Smith *et al.*, this issue]. Much colder (10–20 K) global atmospheric temperatures were observed during the 1997 versus 1977 perihelion periods ($L_S=200^\circ$ – 330°), consistent with the much (2 to 8 times) lower global dust loading of the atmosphere during the 1997 perihelion dust storm season versus the Viking period of the 1977a,b storms. The 1998–1999 Mars atmosphere revealed by both the millimeter and TES observations is also 10–15 K colder than presented by the Viking climatology during the aphelion season ($L_S=0^\circ$ – 180° , northern spring/summer) of Mars. We reassess the observational basis of the Viking dusty-warm climatology for this season to conclude that the global aphelion atmosphere of Mars is colder, less dusty, and cloudier than indicated by the established Viking climatology even for the Viking period. We also conclude that Mars atmospheric temperatures exhibit their most significant interannual variations during the perihelion dust storm season (10–20 K for $L_S=200^\circ$ – 340°) and during the post-aphelion northern summer season (5–10 K for $L_S=100^\circ$ – 200°).

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1. Introduction

The successful orbit insertion of Mars Global Surveyor (MGS) in early September of 1997 marked the beginning of the most significant spacecraft exploration of Mars since the Viking orbiter observations in the late 1970s. One of the unique aspects of the MGS mission is its use of aerobraking to obtain the circular, fixed local-time orbit for mapping operations. In support of this MGS aerobraking, a coordinated program of Mars atmospheric monitoring was developed to provide quantitative, real-time assessment of atmospheric density variations at the altitudes of aerobraking. This program

included a broad range of spacecraft and ground-based observations as well as several modeling efforts [Keating *et al.*, 1998]. The following analysis presents an intercomparison between two of the aerobraking observational data sets, both pertaining to Mars atmospheric temperatures over the 0–30 km altitude range for the period October 1997 through September 1999. The specific concern of this comparison is the degree to which the global average behaviors of temperatures and dust loading in the lower Mars atmosphere are described by a relatively dusty, warm model based largely on Viking lander measurements [e.g., Haberle *et al.*, 1993, 1997; Schofield *et al.*, 1997] or the colder, less dusty behavior determined from 1980s and 1990s ground-based observations [Clancy *et al.*, 1990, 1996]. The broader implications of these divergent climate descriptions include fundamental issues of dust-ice aerosol interactions, interannual and seasonal variability, photochemistry, and meridional transport of water and dust in the current Mars climate system [Clancy *et al.*, 1996; Clancy and Nair, 1996].

The relevant MGS data set is provided by the Thermal Emission Spectrometer (TES) [Christensen *et al.*, 1992], which measures spectrally resolved brightness temperatures across the 15 μm CO₂ absorption/emission band. Radiance in the CO₂ band are inverted to profile Mars atmospheric temperatures in both nadir and limb pointing geometries [Christensen *et al.*, 1992, 1998; Conrath *et al.*, this issue]. While the TES limb observations allow temperature retrievals to higher altitudes (~ 60 km), they provide much reduced temporal and spatial coverage (during the aerobraking period) as compared to the TES nadir observations. Consequently, the current comparison employs only the TES nadir temperature profiling over the 0–30 km altitude range. Christensen *et al.* [1998], Smith *et al.* [this issue], Conrath *et al.* [this issue] and J. C. Pearl *et al.* (Mars water ice clouds: Observations by the Thermal Emission Spectrometer (TES) during the first Martian year, submitted to *Journal of Geophysical Research*, 1999) present the broader range of the TES atmospheric results from the initial aerobraking operations, including nadir and limb measurements of atmospheric temperatures and aerosols.

The second comparison data set is provided by ground-based millimeter CO line retrievals of disk-averaged Mars atmospheric temperature profiles over the 0–80 km altitude region, as observed from Kitt Peak, Arizona (National Radio Astronomy Observatory (NRAO) 12 m telescope for millimeter spectroscopic studies, operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation). This technique employs the optically thick line opacities from rotational transitions of CO in its ground vibrational state at millimeter to submillimeter wavelengths, to sound atmospheric temperatures in essentially the same manner as infrared CO₂ remote soundings are employed. Significant differences, relative to the infrared radiation, include the linear temperature dependence of

emission, the separation of individual rotational lines, and the negligible role of aerosol scattering/absorption at millimeter wavelengths. Because of the small angular size of Mars (4''–20'') and the diffraction limited resolution of millimeter telescopic observations ($\sim 15''$ –60''), millimeter temperature retrievals typically yield low- to midlatitude, dayside averages for the Mars atmosphere. The altitude range sounded extends from the surface to as high as 80 km, depending on the rotational transition observed and the signal-to-noise ratios obtained. A more detailed description of the method and prior results have been published elsewhere [Clancy *et al.*, 1983, 1990, 1996; Clancy and Sandor, 1998].

2. Comparison Goals

The distinct differences in the TES and millimeter spatial resolutions and latitude/longitude sampling versus time (diurnal, daily, and seasonal) are significant obstacles to a detailed statistical comparison of these temperature retrievals. Fortunately, such precise comparisons are not required to obtain important results. This is because the Mars atmospheric issues raised by these millimeter retrievals correspond to large temperature differences with respect to the Viking climatology (15–20 K) and so can be addressed with millimeter-TES comparisons of relatively modest accuracy (e.g., 3–5 K). Our first comparison goal is to determine the average thermal state of the global Mars atmosphere as described by the millimeter and TES temperature retrievals. The specific measurement issue is the 15–20 K offset between the 1982–1999 ground-based millimeter and the 1976 Viking and 1997 Pathfinder descent profile retrievals of Mars atmospheric temperatures over the 0–50 km altitude range. The warmer Viking and Pathfinder entry profiles are very limited in temporal and spatial coverage (three profile measurements at 19°, 22°, and 44° N, for $L_S=96^\circ$, 117°, and 143° respectively), but have been interpreted as typical of minimum atmospheric dust loading and hence minimum atmospheric temperatures. The Viking model of Mars climate is based on these entry profiles and seasonally extended Viking observations (e.g., the 15 μm IRTM maps [Martin, 1981] and the lander dust opacity determinations [Colburn *et al.*, 1989]) of a relatively warm Mars atmosphere, in which vertically extended dust loading equivalent to column visible opacities of ≥ 0.5 characterizes Mars low- to midlatitudes in all seasons [e.g., Pollack *et al.*, 1979; Haberle *et al.*, 1997]. The Pathfinder imaging [Smith *et al.*, 1997; Smith and Lemon, 1999] and descent entry teams [Schofield *et al.*, 1997] conclude that the millimeter temperatures are biased 15–20 K cold and that dusty, warm conditions are a constant condition of the current Mars climate, although the presence of a deep temperature inversion in the lower scale height suggests some distinction from the Viking description [Magalhães *et al.*, 1999; Colaprete *et al.*, 1999; see also Titov *et al.*, 1999].

However, the Viking model of the Mars atmosphere

may be inaccurate even for the Viking period. *Wilson and Richardson* [2000] present evidence for a positive bias in the Viking IRTM $15\ \mu\text{m}$ radiances due to an unaccounted contribution from surface emission. We refer readers to *Wilson and Richardson* [2000] for a complete description of the differences and origins of the corrected versus uncorrected IRTM temperatures, but the correction stems from an apparent out-of-band leak in the Viking IRTM $15\ \mu\text{m}$ channel filter response, which leads to substantial contribution from diurnal and latitude-dependent Mars surface emission. An important consequence of this correction is that Mars atmospheric temperatures during the Viking period become more comparable to the millimeter record of Mars atmospheric temperatures over the past 10 years [see also *Richardson*, 1998]. The presented millimeter-TES comparison provides the first opportunity to verify the 5 K absolute accuracy of the millimeter retrievals [*Clancy et al.*, 1996], and so establish a baseline for the thermal and aerosol conditions of the Mars atmosphere versus solar longitude (L_S) over the 1990s. In our comparison of these conditions to the Viking and Mariner 9 periods, we consider how the corrected Viking IRTM $15\ \mu\text{m}$ temperatures and a review of IRTM $9\ \mu\text{m}$ dust opacities [*Martin*, 1986] may support a colder and less dusty (in

terms of background dust loading) model of the Viking period atmosphere which compares more closely with currently observed conditions. This also allows a more accurate definition of interannual variations implied by the remaining differences between the Viking and current periods.

The second comparison goal is an assessment of the spatial scale of temporal variations that have been observed in the long-term millimeter measurements. This includes a very repeatable 20–30 K orbital variation in Mars disk-averaged atmospheric temperatures, which is roughly twice that exhibited by the warm, dusty Viking-based model of the low- to midlatitude Mars atmosphere. Additionally, very rapid (approximately a few days) temperature increases of 10–20 K have been observed in all Mars southern summer seasons observed [e.g., *Clancy et al.*, 1994], and within many northern summer seasons as well [*Clancy*, 1996]. Both kinds of atmospheric temperature increases exhibit specific temporal and altitude dependencies, which have been attributed to global-scale dust heating and dust-ice aerosol interactions within the Mars atmosphere. A key uncertainty in this interpretation is the degree to which such variations in disk-averaged measurements represent globally coherent variations of atmospheric

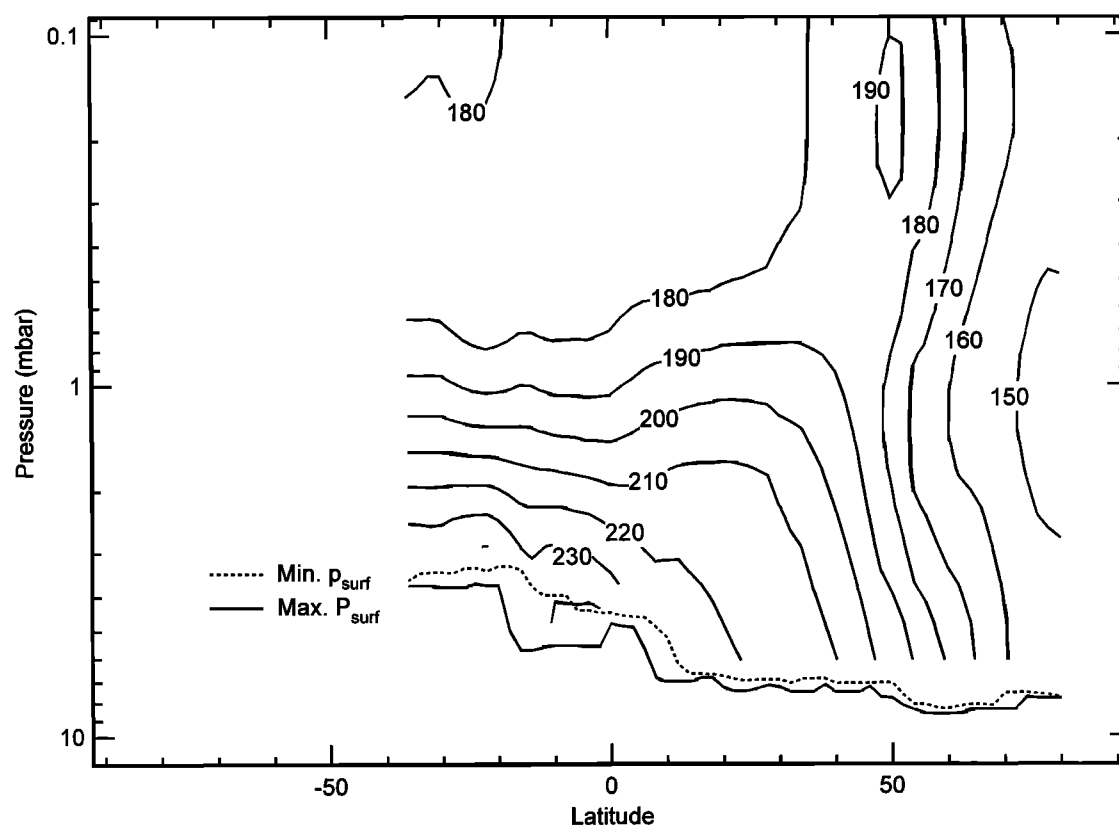


Figure 1. Latitude-pressure contour of Mars atmospheric temperatures as retrieved from TES observations in October 1997 ($L_S=205^\circ$, orbit 28, longitudes 29° – 50° W). The altitude range corresponding to the 7–0.1 mbar pressure range is roughly 0–30 km. Such TES latitudinal cross sections are averaged according to the latitudinal weighting of the millimeter whole-disk measurements to provide the TES-millimeter profile comparisons of Figures 2–5 and 7–8.

temperatures on Mars. For example, do perihelion 15 K increases in disk-averaged temperatures at 10–50 km altitudes correspond to latitude-independent 15 K temperature increases over low- to midlatitudes? Or do they represent a weighted average of much larger temperature increases in the northern hemisphere middle atmosphere which are compensated in the disk average by temperature decreases in the southern hemisphere middle atmosphere? The TES mapping observations are ideally suited to placing the long-term millimeter record of Mars atmospheric temperature variations in a physically interpretable context.

3. Temperature Comparisons

3.1. Perihelion Temperature Profiles (0–30 km altitudes)

Millimeter-TES comparisons of temperature profiles (0–30 km altitudes) are presented for six observational periods extending from $L_S=205^\circ$ – 214° in 1997 to $L_S=141^\circ$ – 144° in 1999. Three perihelion periods are selected to present southern spring/summer conditions before ($L_S=205^\circ$ – 214°), during ($L_S=226^\circ$ – 227°), and after ($L_S=300^\circ$ – 308°) the 1997 Noachis Terra regional dust storm (beginning at $L_S=224^\circ$) [Smith et al., 1999]. We also present three aphelion comparisons for the northern spring/summer season ($L_S=28^\circ$ – 34° , 108° – 112° , and 141° – 144°), which allow seasonally equivalent comparisons to the Viking [Seiff and Kirk, 1977] and the Pathfinder [Magalhães et al., 1999] descent profile measurements. As the $L_S=40^\circ$ – 100° seasonal range was not observed by TES, we include a millimeter profile comparison to MGS (D. P. Hinson, private communication; see also Hinson et al. [1999]) and Viking [Lindal et al.,

1979] radio occultation profiles obtained over $L_S=74^\circ$ – 77° . Uncorrected Viking IRTM $15\ \mu\text{m}$ measurements of global (dayside) atmospheric temperatures near the 0.5 mbar pressure level (~ 25 km altitude) are indicated to demonstrate the seasonal behavior of the Viking-based climatology. Corrected IRTM values of atmospheric temperature are included to indicate the significance of the revision proposed by Wilson and Richardson [2000] for this key Viking atmospheric measurement.

Each of the TES-millimeter profile comparisons incorporate our best efforts to construct latitudinal averages of the spatially resolved TES temperatures, which correspond most directly to the latitudinal weighting of the disk-averaged, ground-based measurements. The longitudinal and local time coverage of the TES and millimeter observations are distinct in sampling, and often separated in specific coverage. The millimeter whole-disk measurements average over a wide range of longitudes and dayside local times in each observation, where the sub-earth longitude cycles within a 1 month period. During the aerobraking phase, the TES latitudinal maps tend to cover relatively narrow (10°) longitude and local time ranges, and the subspacecraft longitudes vary rapidly per orbit and versus time. For example, the longitudinal coverage for the TES temperatures obtained on the early orbit 28 (Figure 1; October 27, $L_S=205.8^\circ$) is 30° – 50° W, and the latitudinal coverage extends from 40° S to high northern latitudes. However, TES observations during the mapping phase (past $L_S=100^\circ$) incorporate full longitudinal coverage and two local times (0200 and 1400 LT). Comparisons of the Mars season (L_S), longitudes, local times, and sub-Earth latitudes for both sets of observations are presented in Table 1.

Table 1. Observational Parameters for TES Infrared and Kitt Peak Millimeter Comparisons of Mars Temperature Profiles (for Figures 2–8)

$L_S, ^\circ$	Date	TES Orbit	KP LAT _{SE}	TES LAT	KP LONG _{SE}	TES LONG	KP LT _{SE}	TES LT
206	10/27/97	28	...	40° S– 80° N	...	30° – 50°	..	19.1
209	10/31/97	...	1° N	...	295° – 330°	...	10.2	..
213	11/07/97	36	...	50° S– 85° N	...	195° – 245°	...	16.5
214	11/09/97	...	2° S	...	175° – 230°	..	10.2	...
227	11/30/97	52	...	60° S– 85° N	...	110° – 200°	..	15.6
227	11/30/97	..	9° S	...	340° – 30°	...	10.3	...
228	12/01/97	53	...	55° S– 85° N	...	200° – 315°	..	15.6
300	03/27/98	...	24° S	...	220° – 270°	...	11.5	..
304	04/04/98	215	...	45° S– 85° N	...	240° – 255°	..	10.3
308	04/08/98	...	22° S	...	100° – 170°	...	11.6	..
29	09/10/98	550	...	5° N– 85° N	...	190° – 200° 10° – 20°	..	17.5, 5.5
34	09/24/98	...	22° N	...	220° – 250°	...	13.5	...
108	03/10/99	1691–1702	...	60° S– 70° N	...	0° – 360°	..	2, 14
111	03/16/99	...	15° N	...	250° – 280°	...	13.8	...
141	05/19/99	2543–2554	...	70° S– 85° N	...	0° – 360°	..	2, 14
144	05/25/99	...	23° N	...	270° – 320°	...	10.4	...

KP, Kitt Peak. Read 10/27/97 as October 27, 1997. Longitude convention is West.

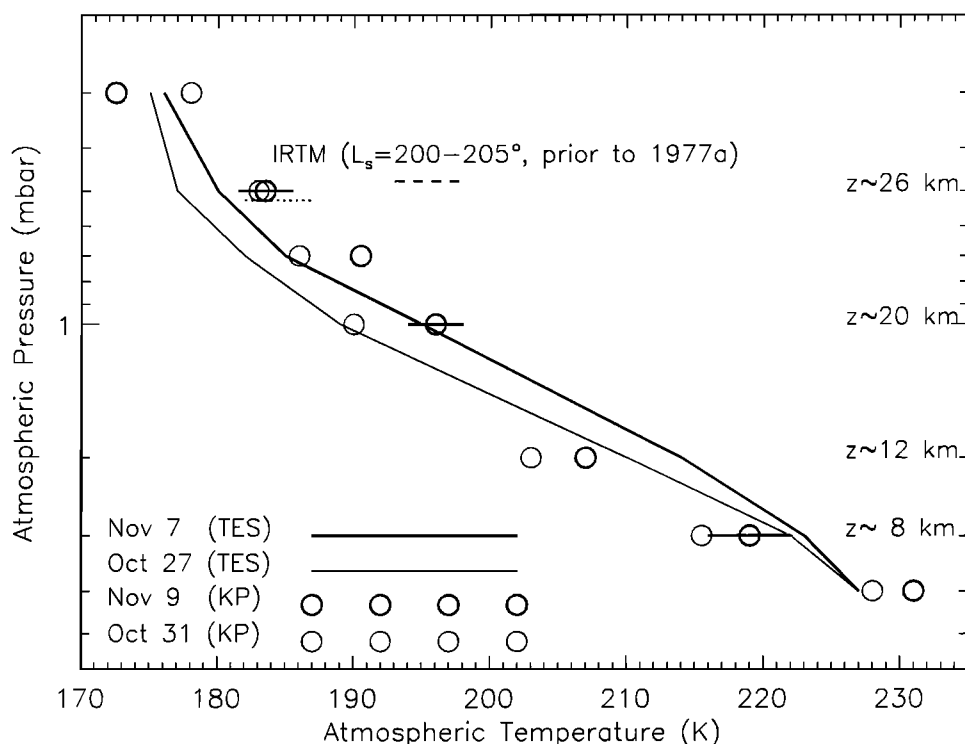


Figure 2. TES (lines) and millimeter (circles) temperature profiles obtained in October–November of 1997 ($L_S=205^\circ\text{--}214^\circ$), prior to the Noachis Terra regional dust storm. The TES profiles are latitudinal averages, obtained from extended TES latitudinal coverage (such as Figure 1) and weighted corresponding to the whole-disk averaging of the ground-based millimeter observations (primarily low- to midlatitudes). For comparison, the 0.5 mbar temperatures from the Viking IRTM experiment over L_S range $200^\circ\text{--}205^\circ$ (pre-1977a storm) in 1976–1978 are indicated by dashed (original) and dotted (modified according to *Wilson and Richardson [2000]*) lines. The dates, longitudes, local times, and sub-earth latitudes for these averages are indicated in Table 1. Several altitude levels corresponding to the atmospheric pressure coordinate are indicated on the right.

Figure 2 presents the $L_S=205^\circ\text{--}214^\circ$ comparison of TES and millimeter temperature profiles, corresponding to the early period of MGS aerobraking. The TES profiles are latitudinal averages calculated to approximate the whole-disk averaging present in the millimeter observations. The natural vertical coordinate for the TES and millimeter retrievals is atmospheric pressure, but we indicate approximate altitude levels on the right-hand vertical side of the figure. The TES temperatures for orbits 28 (thin line) and 36 (thick line), correspond to L_S of 205.8° and 213.0° , respectively. These compare to L_S of 208.8° and 214.2° for the October 31 (thin circles) and November 9 (thick circles) millimeter profiles. Hence the closest comparisons between two data sets in terms of time are orbit 28 versus October 31 (separated by 4 days), and orbit 36 versus November 9 (separated by 1.5 days). For comparison, we have included the range of IRTM $15\text{ }\mu\text{m}$ temperatures ($30^\circ\text{S--}30^\circ\text{N}$, 0700–1800 LT, referenced to the 0.5 mbar atmospheric pressure [*Kieffer et al., 1976*]) for $L_S=200^\circ\text{--}205^\circ$ in 1977, prior to the heavy dust loading marked by the 1977a storm. The dashed range presents the original

IRTM temperatures, and the dotted line region indicates the cooler IRTM temperatures resulting from the *Wilson and Richardson [2000]* correction for a modeled contamination from surface emission.

Figure 3 presents two TES profiles and one millimeter profile taken just after the onset of the Noachis Terra regional dust storm in November of 1997 ($L_S=226^\circ\text{--}227^\circ$). These profiles indicate maximum global atmospheric temperatures observed in the TES and millimeter measurements over the 1997–1998 period. The distinctions in lower atmospheric temperatures for TES orbits 52 and 53 are probably related to longitudinal variations, but there is a 1 day offset in time between these orbits. The IRTM temperatures at $L_S=220^\circ\text{--}234^\circ$ in 1977 remain 10–15 K warmer than at the peak of the 1997 Noachis Terra regional dust storm. Figure 4 presents two Kitt Peak and one TES profile for the $L_S=300^\circ\text{--}308^\circ$ period in the spring of 1998, which is near the end of the first phase of MGS aerobraking (latitudinal coverage degraded considerably in the second aerobraking period of August–October 1998). The TES and millimeter profiles for this $L_S=300^\circ\text{--}308^\circ$ period present simi-

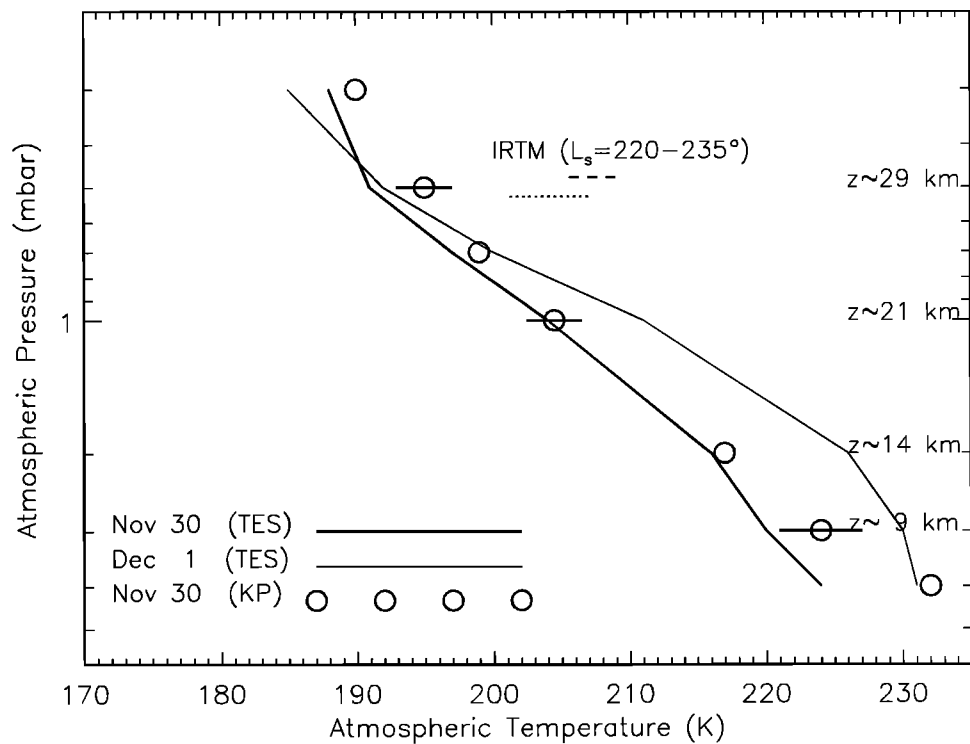


Figure 3. TES (lines) and millimeter (circles) temperature profiles obtained in November-December of 1997 ($L_S = 226^\circ - 227^\circ$), during the Noachis Terra regional dust storm. Figure description same as for Figure 2.

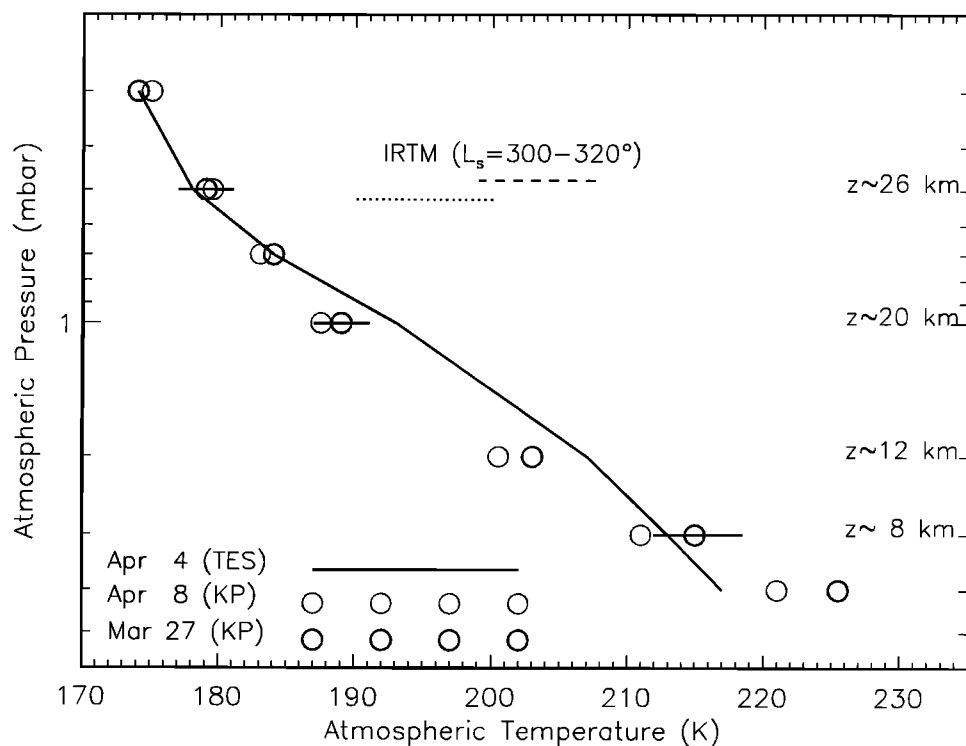


Figure 4. TES (lines) and millimeter (circles) temperature profiles obtained in March-April of 1998 ($L_S = 300^\circ - 308^\circ$), toward the end of the first phase of MGS aerobraking. Figure description same as for Figure 2.

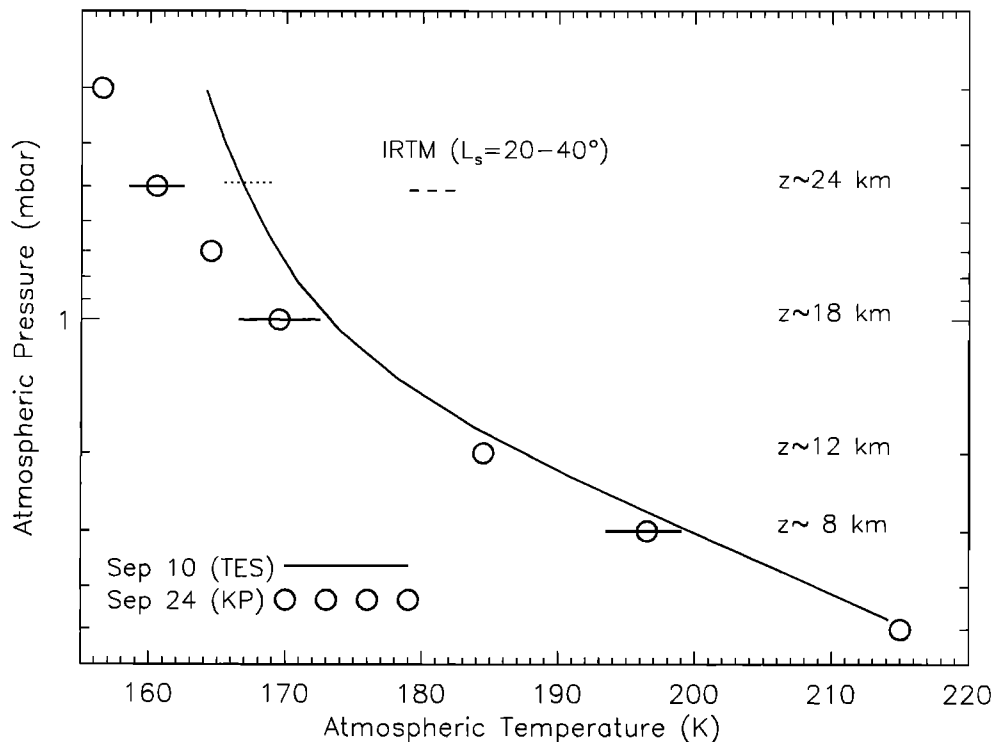


Figure 5. TES (lines) and millimeter (circles) temperature profiles obtained in September of 1998 ($L_S=28^\circ\text{--}34^\circ$) during the early northern spring when global atmospheric temperatures are falling and TES coverage is more limited. Figure description same as for Figure 2.

lar temperatures to the $L_S=205^\circ\text{--}214^\circ$ season 5 months earlier, although the lowermost 10 km is slightly cooler. The IRTM correction (dotted versus dashed lines) is significant (~ 10 K), but the $L_S=300^\circ\text{--}308^\circ$ period in 1977 is significantly warmer (10–25 K) than the $L_S=300^\circ\text{--}308^\circ$ period in 1998 for either case, as a consequence of the late and very intense 1977b storm.

3.2. Aphelion Temperature Profiles (0–30 km altitudes)

Figure 5 compares an $L_S=34^\circ$ Kitt Peak profile to TES temperature measurements obtained on orbit 550 ($L_S=28.5^\circ$), after completion of MGS aerobraking and before mapping operations commenced. The latitudinal coverage of these northern early spring TES observations are more limited (Table 1) than during aerobraking or mapping observations. In addition, the disk averaging of the Kitt Peak millimeter technique leads to maximum differences from low latitude Mars atmospheric temperatures in early northern spring. The sub-earth latitude lies well northward of the subsolar latitude at this time, such that the disk average incorporates a significant northern latitudinal gradient (10–15 K) in Mars atmospheric temperatures. Millimeter disk-averaged temperatures are 3–4 K colder than Mars low-latitude temperatures at this time, whereas for the other profile comparisons, disk averaged millime-

ter temperatures are generally within 1–2 K of Mars low-latitude temperatures. Disk-averaging of the available TES temperatures at $L_S=34^\circ$ leads to 3–5 K agreement with the presented $L_S=34^\circ$ millimeter profile. The Viking model for this period remains 10–15 K warmer (dashed horizontal line, IRTM), while the *Wilson and Richardson* [2000] correction to these IRTM temperatures (dotted horizontal line) brings all three temperature data sets within 5 K of one another.

MGS operations were greatly reduced between the end of aerobraking and the beginning of the mapping mission (March 1999), such that TES observations were not obtained over the $L_S=40^\circ\text{--}100^\circ$ period of Mars aphelion passage (at $L_S=71^\circ$). However, MGS radio occultation profiles were returned over $L_S=74^\circ\text{--}77^\circ$ at Mars high northern latitudes ($64^\circ\text{--}67^\circ$ N) at the end of 1998 (unpublished data provided by D. P. Hinson and the MGS Radio Science Team). There also exists for this season in 1978 a set of three Viking radio occultation profiles measured in the vicinity of the Viking 1 lander site [*Lindal et al.*, 1979]. As shown in Figure 6, average temperature profiles from these MGS (solid line) and Viking (dash-dotted line) radio occultations are remarkably similar, despite their differences in latitude (65° N versus 27° N) and local time (0400 versus 1600 LT). In fact, global circulation model (GCM) atmospheric temperature fields predict

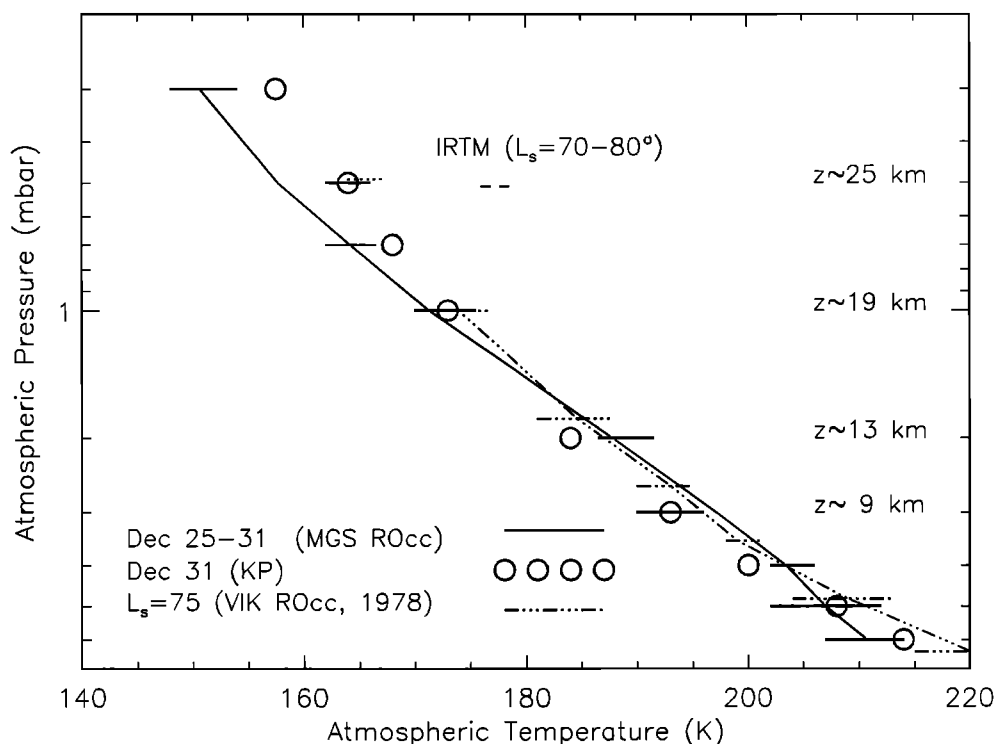


Figure 6. A millimeter (circles) temperature profile from December of 1998 ($L_S=77^\circ$, $LAT_{se}=22^\circ$ N, $LT_{se}=1430$) is compared to the average of three low-latitude Viking radio occultation profiles (dash-dotted line: $L_S=74^\circ$, $LAT=27^\circ$ N, $LT=1600$, 1978), and to the average of 10 high-latitude MGS radio occultation profiles (solid line: $L_S=76^\circ$, $LAT=67^\circ$ N, $LT=0400$, 1998).

very weak (1–3 K) latitudinal gradients between the equator and 70° N at aphelion, and TES temperature fields obtained at $L_S=108^\circ$ (see below) show similarly weak latitudinal gradients over the northern early summer hemisphere. GCM tides also show weak diurnal variations between these two measurements. In this spirit we present an $L_S=77^\circ$ millimeter profile obtained on December 31, 1998 ($LAT_{se}=22^\circ$ N, $LT_{se}=1430$) for comparison to the 1998 MGS and 1978 Viking radio occultation profiles for this season. While this comparison is not as direct as the coincident, contemporaneous TES-millimeter comparisons, the 1–5 K agreement among the aphelion temperature profiles of Figure 6 is significant. The MGS radio occultation measurements are contemporaneous with the millimeter profile measurement. The Viking radio occultation profiles demonstrate that aphelion atmospheric temperatures during the Viking period were as cold as the millimeter aphelion measurements over the Viking 1 lander site, at least for the duration of these Viking radio occultation observations (2 days).

TES mapping operations, which began in early March of 1999, provide complete zonal averaging and local time coverage of 0200 and 1400 LT. The availability of these mapping data is recent relative to the publication of this paper, but several periods have been provided for comparison to the millimeter 1999 observa-

tions. Figure 7 presents a millimeter-TES profile comparison for the $L_S=108^\circ$ – 112° period in mid-March of 1999. This seasonal range is suitable for comparison to the average temperature profile (dash-dotted line) from the Viking 1 (22° N, 1600 LT, $L_S=96^\circ$) and 2 (48° N, 0900 LT, $L_S=117^\circ$) lander descent observations. For altitudes above 5 km, TES-millimeter temperatures agree to within 2–6 K, whereas the average of the Viking lander profiles lies 10–13 K above the TES profile. The corrected IRTM temperatures (dotted horizontal line at 0.5 mbar) also show closer agreement with the TES and millimeter observations, relative to the uncorrected IRTM temperatures (dashed horizontal line).

Figure 8 presents a late northern summer comparison ($L_S=141^\circ$ – 144°) of TES, millimeter, and Pathfinder temperature profiles. The millimeter temperatures are biased ~ 4 K colder than the TES temperatures over the 0–30 km altitude region, which is similar to comparison results for the northern spring and summer periods of Figures 5 and 7. Also similar to the Viking descent profile comparison of figure 7, Pathfinder temperatures are 10–13 K warmer than the TES temperatures, although only for altitudes above ~ 17 km. Pathfinder temperatures actually fall below the millimeter temperatures at the 8 km lower boundary of the Pathfinder retrieval. Schofield *et al.* [1997] and Magalhães *et al.* [1999] argue that the Pathfinder and Viking descent measurements

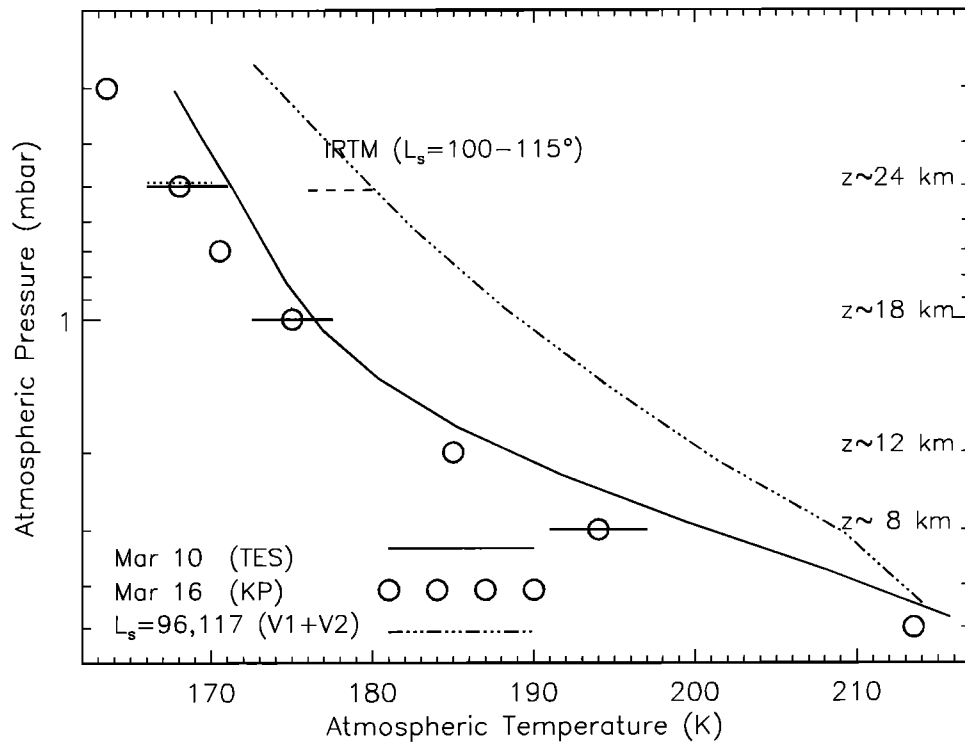


Figure 7. TES (lines) and millimeter (circles) temperature profiles obtained in March of 1999 ($L_S=108^\circ\text{--}112^\circ$), at the beginning of the MGS mapping mission. The dash-dotted profile presents the averaged Viking 1 (22° N , 1600 LT) and 2 (48° N , 0400 LT) lander descent measurements. Figure description same as for Figure 2.

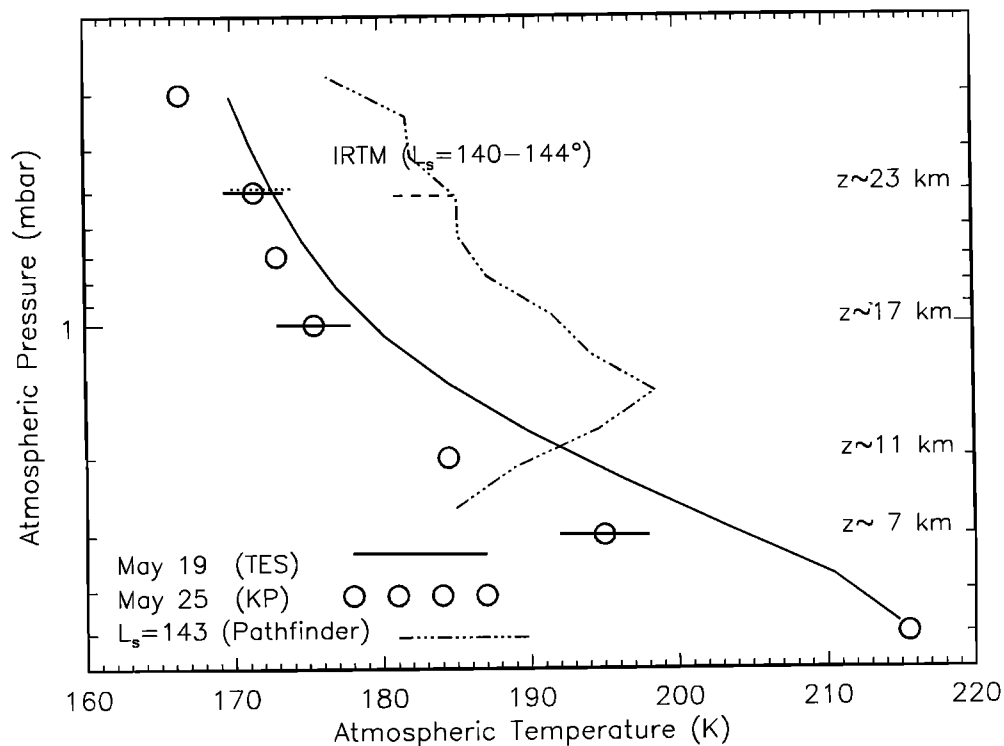


Figure 8. TES (lines) and millimeter (circles) temperature profiles obtained in May of 1999 ($L_S=141^\circ\text{--}144^\circ$), during MGS mapping observations of northern summer. The dash-dotted profile presents the Pathfinder (19° N , 0400 LT) lander descent measurement. Figure description same as for Figure 2.

of Mars atmospheric temperatures are representative of the unchanging dusty, warm background state of the Mars atmosphere. Consequently, they assert that differences between these 1976 and 1997 northern summer measurements must reflect unrecognized diurnal variations in the lower (<15 km) and upper (>50 km, see also [Clancy and Sandor, 1998] atmosphere of Mars, as distinguished by the 0400 LT Viking 1 versus 0400 LT Pathfinder descents.

Colaprete *et al.* [1999] determined that radiative cooling by a nighttime water ice cloud ($\tau \sim 1$) located near the 10 km altitude level could create the 7–15 km level temperature inversion in the Pathfinder descent profile. However, they note that no evidence of a thick nighttime cloud is present in the Pathfinder aerosol opacity measurements. We point out that the required diurnal forcing for such cloud formation is unsupported and that the 1999 TES profile measurements do not indicate 5–15 km temperature inversions in 0200 LT or 1400 LT measurements. The warm middle atmospheric region observed by Pathfinder may, in fact, reflect locally perturbed conditions associated with a Valles Marineris dust storm observed just days before the Pathfinder landing [Wolff *et al.*, 1999].

Overall, the temperature profile comparisons of Figures 2–8 indicate average differences between the TES and millimeter retrievals that are ≤ 6 K over the 0–30 km altitude region. Specifically, the millimeter–TES differences averaged over the presented three perihelion periods are +4 K for the 5–6 km level, -2 to -5 K for the 9–21 km region, and +1 to +3 K for the 22–30 km region. The millimeter–TES differences averaged over the three presented aphelion periods are -3 to -5 K for the 5–6 km level, -6 to -3 K for the 9–21 km region, and -2 to -4 K for the 22–30 km region. These millimeter–TES differences are substantially smaller than the 15–20 K offset between the millimeter and Viking temperatures. Nevertheless, there does appear to be a 2–5 K cold bias in millimeter relative to TES temperature measurements, particularly for the northern spring/summer period ($L_S=20^\circ$ – 160°).

3.3. Dust Storm Effects on TES and Millimeter 0.3 mbar Temperatures

In order to provide more complete coverage of the extended MGS aerobraking period, we present an October 1997 to July 1998 ($L_S=190^\circ$ – 360°) time sequence at the 0.3 mbar pressure level (~ 30 km altitude). For this purpose, we employ comparisons of 30° N and 30° S latitude zonal averages of retrieved TES temperatures to millimeter whole-disk retrievals. TES 0.3 mbar temperatures within $\pm 2.5^\circ$ latitude of 30° S and 30° N were binned in 30° longitudinal intervals and averaged to provide a consistent temperature trend data set in support of MGS aerobraking operations. Although TES averages at 30° N and 30° S are not precisely equivalent to the spatial averaging of the full-disk millimeter

measurements, this 0.3 mbar level comparison provides a reasonably accurate comparison of the TES and millimeter data sets. This is a consequence of modest latitudinal variations in Mars atmospheric temperatures, except over winter high latitudes which are not significantly weighted in the earth-based measurements. The 0.3 mbar level is selected for this comparison because temperatures at this pressure level are a standard product of the TES aerobraking operations, and they exhibit strong sensitivity to dust storm activity. The $L_S=190^\circ$ – 360° range spans the southern hemisphere spring and summer seasons, which exhibit several abrupt increases of dust loading and temperatures in the global Mars atmosphere associated with regional-scale dust storms, including the Noachis Terra regional dust storm [Smith *et al.*, this issue].

Figure 9 presents the trend of TES (dashed vertical lines denote the range of 30° S and 30° N values) and millimeter (circles) 0.3 mbar level temperatures for the October 1997 to July 1998 period, as a function of L_S . The millimeter and TES temperatures differ by typically less than 2–3 K at this ~ 30 km altitude level over this period of roughly one half of a Mars year. Their temporal variations are also very similar. These close correspondences suggest that the seasonal and short-term variations determined from the long-term (1988–1997) millimeter record are representative of coherent changes in the global atmospheric temperature field rather than of complex changes in the latitudinal distributions of Mars atmospheric temperatures. Vertical arrows mark five distinct atmospheric heating events apparent in the millimeter observations during this period, four of which also appear in the TES temperature and dust opacity measurements (at $L_S=190^\circ$, 225° , 270° , and 310°). The $L_S=225^\circ$ event is the strongest by far and is associated with the November 1997 Noachis Terra regional storm at southern low- to midlatitudes [Smith *et al.*, this issue]. The weaker temperature increases at $L_S=190^\circ$, 270° , and 310° have also been identified with regional dust storm activity at southern midlatitudes [Smith *et al.*, this issue]. The $L_S=340^\circ$ temperature increase occurred during a break in TES measurements, associated with the hiatus between the first and second periods of MGS science phasing.

An interesting aspect of these atmospheric heating events is the remarkably short timescale (1–3 days) for global-scale evolution at this 30 km altitude level. The comparable temperature increases in the disk-averaged millimeter and the spatially resolved TES records, and the comparable changes in the 30° S and 30° N TES records both indicate global temperature increases for a vertically extended portion of the Mars atmosphere. Peak temperature increases of the Mars atmosphere during a 1994 global heating event (at $L_S=254^\circ$) occur at altitude levels of 40–50 km [Clancy *et al.*, 1994]; the current millimeter measurements indicate the same behavior for the 1997–1998 dust storm events. Global temperature increases at altitudes below 0–15 km are

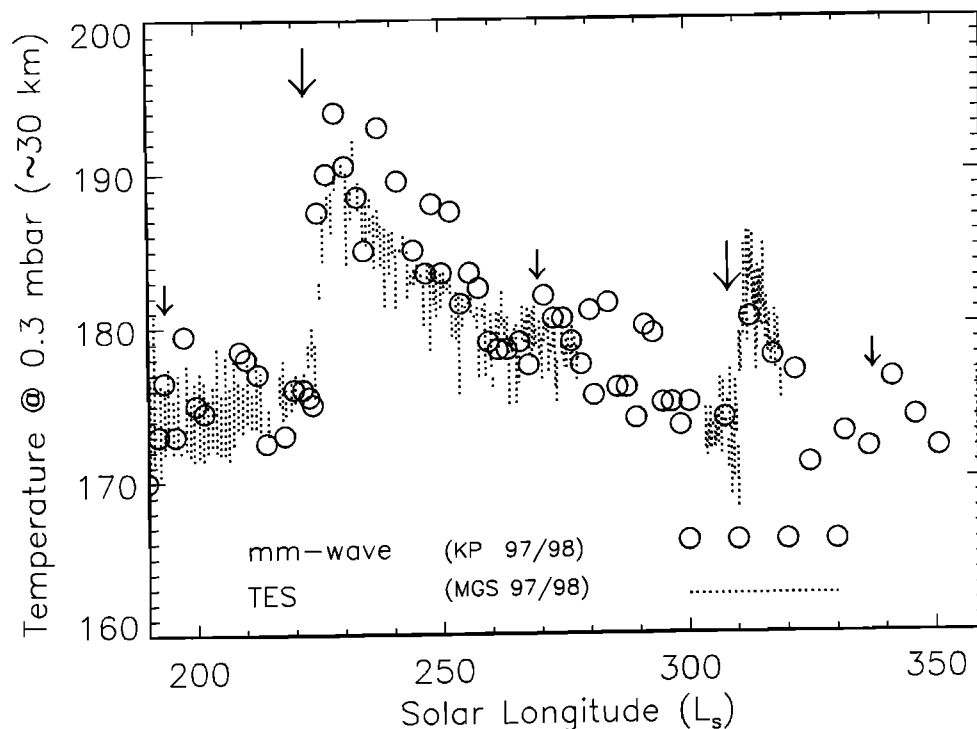


Figure 9. An extended comparison of TES (dotted lines) and millimeter (circles) measurements of Mars atmospheric temperatures for the 0.3 mbar pressure atmospheric pressure level. The full perihelion dust storm season during the 1997–1998 of MGS aerobraking is highlighted ($L_s = 190^\circ$ to 360°). The vertical lines plotted for the TES measurements at each point indicate the temperature range between $30^\circ \pm 5^\circ$ S and $30^\circ \pm 5^\circ$ N zonal averages. The vertical arrows indicate abrupt increases in atmospheric temperatures and dust loading associated with distinct dust storm activity on Mars, the most intense being the Noachis Terra regional dust storm at $L_s = 224^\circ$ [Smith *et al.*, this issue]. Breaks in the TES record correspond to orbital maneuvers and aerobraking periods in which MGS observations were halted.

significantly smaller, as comparison of Figures 2 and 3 shows. Similarly, although TES dust column opacities increase at northern latitudes during these events, the changes are much smaller than at southern latitudes where the sources are located [Smith *et al.*, this issue]. GCM simulations indicate that strong solar absorption by the deep vertical column of dust at southern latitudes and dynamical heating at northern latitudes associated with the intensification of the Hadley circulation lead to almost latitude-independent temperature increases over the low- to midlatitude range on Mars.

3.4. Seasonal and Interannual Variability of 0.5 mbar Level Atmospheric Temperatures

Plate 1 presents a more comprehensive comparison of Mars atmospheric temperature measurements at the 0.5 mbar pressure level (~ 25 km altitude), including the previous 2 Mars years (1992–1996) of millimeter observations and the 1970s period of Mariner 9 and Viking observations. This presentation of 0.5 mbar Mars atmospheric temperatures compares 1997–1999 TES (colored dotted lines), 1992–1999 millimeter (colored circles), 1976–1979 Viking IRTM (dotted and dashed lines

for corrected and uncorrected values, respectively, and thick and thin lines for 1976–1977 versus 1978–1979), 1976 Viking 1 and 2 descents (I_1 and I_2 symbols), Mariner 9 IRIS (cross symbols), and 1997 Pathfinder descent (P symbol) measurements. The 1992–1999 temperature measurements are presented in color (circles for millimeter, dotted lines for TES) to distinguish interannual behavior in the 1992–1999 millimeter temperature record. For the purpose of this comparison, we use the solar longitude range 0° – 360° to define a Mars year and adopt April 11, 1955 ($L_s = 0^\circ$) as the beginning of year 1. In this arbitrary convention, the Mariner 9, Viking, Phobos, and Pathfinder missions occurred in years 9–10, 12–15, 19–20, and 23, respectively. By comparison, the 1992–1999 millimeter observations extend over years 21–24, and the 1997–1999 TES observations extend over years 23 and 24.

To first order, the 1992–1999 millimeter temperature record indicates a high degree of repeatability over the past 3.5 Mars years. Earlier millimeter observations show that this repeatability has extended over the past 5–6 Mars years (since 1988 [Clancy *et al.*, 1996]). The uncorrected IRTM temperatures (solid lines), which are

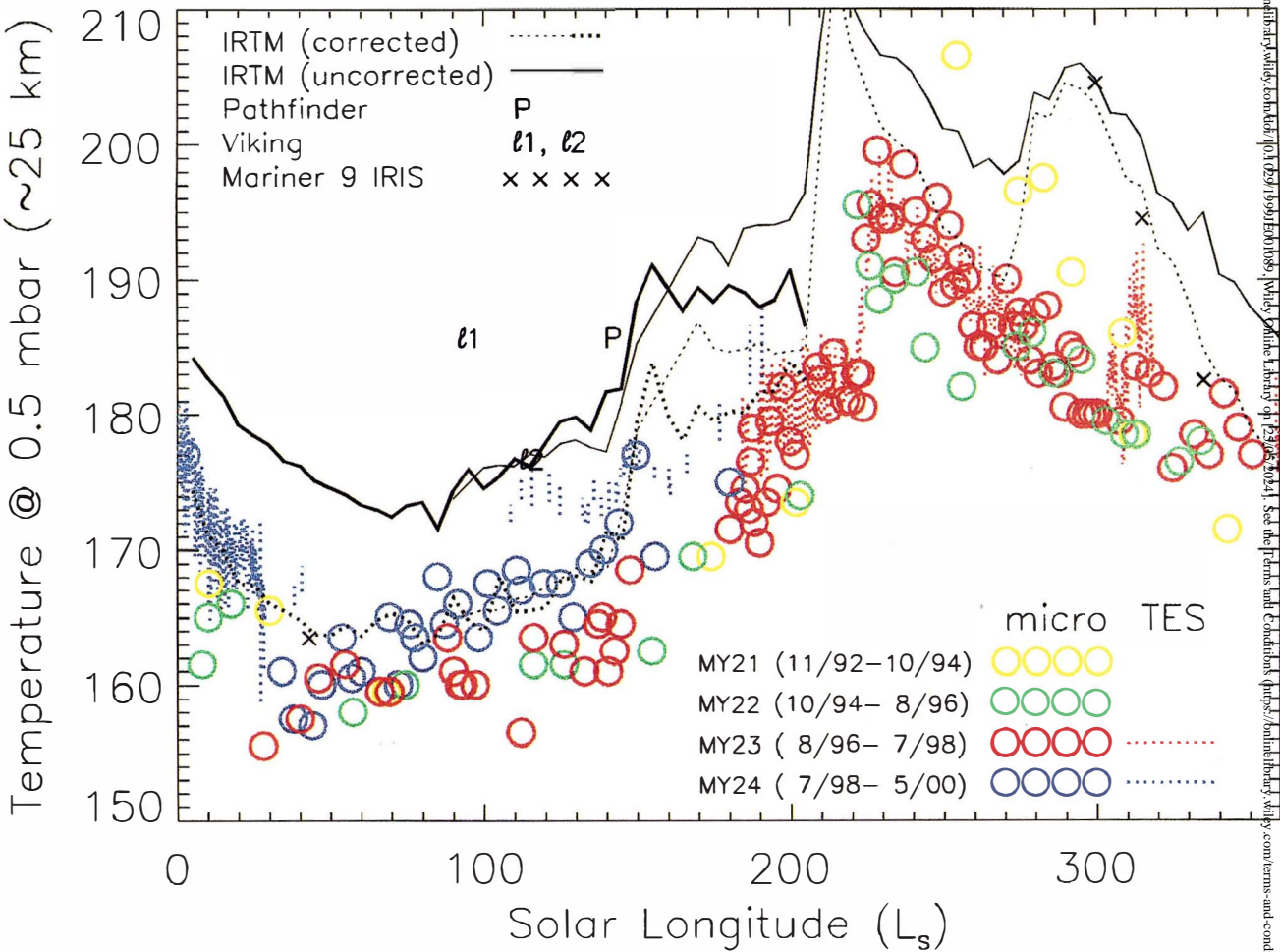


Plate 1. A comparison of Mars measurements for low- to midlatitude atmospheric temperatures at the 0.5 mbar pressure level, as a function of Mars solar longitude L_s . The 1992–1999 millimeter and 1997–1999 TES measurements are color coded to distinguish interannual variability, and we apply an arbitrary numbering of Mars years (year 1 beginning April 11, 1955) to specify the interannual relationships among the Viking (MY12–13), Pathfinder (MY23), MGS TES (MY23–24), Mariner 9 IRIS (MY9–10), and millimeter measurements (MY21–24). The localized entry measurements by Viking [Seiff and Kirk, 1977] and Pathfinder [Schofield et al., 1998] are represented by letter symbols (P, l_1 , l_2). The dayside average IRTM 15 μ m temperatures for three years of the Viking IRTM observations are represented by the dashed line (uncorrected, [Kieffer et al., 1977], year 12 thin line, year 13 thick line). These dayside IRTM temperatures may be biased 10–15 K warm, owing to strong contamination from surface emission. The dotted lines reflect the decrease in the 15 μ m IRTM temperatures, resulting from the Wilson and Richardson [2000] reanalysis. Mariner 9 IRIS measurements are presented by crosses [Conrath, 1975].

indicative of the long-standing Viking model of Mars atmospheric behavior, fall 15 K above the temperatures retrieved by the millimeter measurements in essentially all seasons. By comparison, the corrected IRTM temperatures (dotted lines) are reasonably consistent (within 5 K) with the seasonal and interannual dependence of Mars atmospheric temperatures displayed by the millimeter measurements. Within the millimeter data set, interannual variations in global average atmospheric temperatures (by 5–15 K) are most prominent during the perihelion dust storm season ($L_S=200^\circ$ – 340°) and during the northern summer/fall period ($L_S=100^\circ$ – 200°). These are the same seasons in which millimeter and corrected IRTM temperatures exhibit their largest differences.

The general character of the perihelion dust storm activity is very similar in the consecutive years 22 and 23. An increase in global atmospheric temperatures occurred around $L_S=220^\circ$ in 1995 (year 22), which is very similar to the 1997 (year 23) $L_S=225^\circ$ Noachis Terra event in terms of atmospheric temperature changes. A second, weaker event also occurred at $L_S=270^\circ$ in 1995 (year 22), suggesting that multiple dust storms in a perihelion season may be typical behavior. However, dust storm activity appears to have persisted later in the season in year 23 versus year 22, creating a 5–10 K warmer global atmosphere over $L_S=310^\circ$ – 340° in year 23. Perihelion temperature increases were also observed in the two previous Mars years 20 (not shown in Plate 1) and 21. The L_S at which these events initiated are not determined by the limited frequency of the measurements (particularly in year 20), but the year 21 event appears to have occurred shortly before $L_S=250^\circ$, on the basis of peak temperatures observed at $L_S=254^\circ$ in 1994. This would be substantially later in season than the $L_S=225^\circ$ storms of years 22 and 23, but earlier in season than the initiation of the 1977b dust storm in year 12. Peak atmospheric temperatures observed during the year 21 dust event were actually 10 K greater than observed in years 22 and 23 and comparable to the atmospheric temperature increases that accompanied the Mariner 9 (year 9) and Viking (year 12) great dust storms. (Figure 6 includes five 1994 dust storm observations which were obtained by Emmanuel Lellouch with the 30 m IRAM telescope at Pico Veleta, Spain.) The extended record of atmospheric pressure from the Viking landers suggests weaker perihelion dust storms, comparable to those of the 1990s, occurred in years 13 and 14, whereas a significantly stronger perihelion storm occurred in year 15 [Tillman, 1985; Leovy et al., 1985].

Perihelion atmospheric temperatures may exhibit two distinct cases, corresponding to great dust storms and regional dust storms. Both cases show global atmospheric temperature increases, but those corresponding to regional dust storms are roughly half as large as those corresponding to global dust storms. As a rough estimate of their relative frequency, we note that for the

nine perihelion dust storms measured by spacecraft or millimeter observations, four of these could be classified as great or planet encircling storms (40–50% frequency, similar to the suggestions of Zurek and Martin, [1993]). On the other hand, the brevity, discontinuous coverage, and poor sampling of the observational record do not rule out a continuous range of perihelion dust storm activity over time. In either case, the millimeter measurements of atmospheric temperature increases during regional dust storms in the past 4 Mars years suggest that perihelion dust storms of regional or greater extent occur in every Mars year (in accord with the suggestion of Zurek, [1982]).

Outside of the perihelion dust storm season, differences among the corrected IRTM, millimeter, and TES measurements, and variability within the millimeter temperatures are most prominent during the northern summer/fall seasons ($L_S=100^\circ$ – 200°). For example, TES temperatures exhibit peak differences (5 K) with contemporaneous millimeter measurements over $L_S=120^\circ$ – 140° in 1999 (although ~ 1 K of this difference is associated with low- to high-latitude temperature gradients weighted in the disk-averaged millimeter observations). This period also corresponds to the 10–20 K disagreements between the millimeter-TES profiles and the Viking-Pathfinder descent measurements of atmospheric temperature (as well as the unusual Pathfinder temperature inversion near the 2 mbar, 10 km altitude level). Part of these differences probably reflects increased spatial and temporal variability of the Mars atmosphere in this season. The multiyear millimeter observations show a distinct increase in short-term and interannual variability beyond $L_S \sim 90^\circ$. For example, the lower 10–20 km of the Mars atmosphere was 5–10 K warmer in year 22 than in year 23 over $L_S=115^\circ$ – 200° [Clancy, 1996], and year 23 was 5–10 K warmer than years 21 and 22 at $L_S=200^\circ$. In fact, 1999 (year 24) millimeter measurements indicate a distinct rise in global atmospheric temperatures over $L_S=100^\circ$ – 150° , that place them 5 K warmer than in years 22 and 23, but in close agreement with the corrected IRTM temperatures for this northern summer season. TES temperature measurements at $L_S=180^\circ$ – 190° in 1997 versus 1999 also indicate 5 K warmer temperatures in Mars year 24 versus 23. In addition, variations among the millimeter, TES, and Viking IRTM (corrected) temperatures show a distinct maximum of 10–15 K over $L_S=150^\circ$ – 180° in this northern summer/fall season.

The cold aphelion period ($L_S=10^\circ$ – 90°) presents the greatest degree of repeatability in Mars atmospheric temperatures, in terms of variability within the long-term millimeter data set and in comparison between the corrected IRTM and millimeter observations. Millimeter observations of aphelion atmospheric temperatures exist for years 14, 15, and 19–24. When corrected for the 3–4 K effects of high northern latitude weighting (see discussion of Figure 5), these millimeter temperatures exhibit excellent agreement with TES, MGS and

Viking radio occultation, and corrected Viking IRTM 15 μm measurements. On this basis, all 11 observed Mars aphelions over the period year 9 to year 24, including the Mariner 9 period, have exhibited comparably cold atmospheric temperatures (to within 5 K) at this altitude level.

4. Related Changes in Dust Loading

To a large degree, the amount of dust suspended in the thin CO_2 atmosphere determines the average profile of Mars atmospheric temperatures. The direct effects of dust aerosols on the thermal profile of the Mars atmosphere include atmospheric heating due to absorption of solar flux and atmospheric cooling and heating associated with broadband thermal infrared emission and absorption [e.g., Pollack et al., 1979; Zurek, 1978]. Regional dust storms force abrupt 10–30 K increases in global atmospheric temperatures to altitudes well above 50 km [Clancy et al., 1994]. Mariner 9 Infrared Interferometric Spectrometer (IRIS) observations [Hanel et al., 1972] of elevated Mars atmospheric temperatures during the 1971 global dust storm form the basis for much of our current understanding of atmospheric dust-temperature relationships on Mars [Gierasch and Goody, 1972; Conrath, 1975] (review by Kahn et al., [1992]). Analysis of the Viking lander descent temperature profiles and visible dust column opacities explored a broader range of opacity and diurnal conditions, and provided observational constraints on the solar absorption properties of the dust [Pollack et al., 1979]. Viking IRTM 15 μm data were instrumental in defining the visible/IR opacity ratio of the dust, which relates the relative efficiencies of solar absorption-heating and thermal-emission cooling by the dust [Zurek, 1982; Martin, 1986; Clancy et al., 1995].

There remain considerable uncertainties in the temperature forcing of the Mars atmosphere as a result of dust loading. Reanalysis of the Viking measurements and new Pathfinder measurements indicate that the dust absorbs solar flux less efficiently (compare solar band average single scattering albedo = 0.86 [Pollack et al., 1979] versus 0.92 [Clancy and Lee, 1991] versus 0.88 [Ockert-Bell et al., 1997] versus 0.90 [Tomasko et al., 1999]) and that mean dust particle sizes are ~50% smaller than indicated in the Toon et al. [1977] Mariner 9 based dust model [Chassefière et al., 1995; Clancy et al., 1995; Pollack et al., 1995; Tomasko et al., 1999]. In addition, very little is known about the temporal and spatial variations of the dust particle sizes and absorbing properties. Analysis of column-integrated dust scattering observations from the 1997 Pathfinder lander indicates that local dust particle sizes and solar absorption properties are remarkably similar to those determined from reanalysis of the 1977 Viking lander observations [Tomasko et al., 1999]. However, these surface-based measurements relate to similar locales (northern low-latitude basins) and to dust prop-

erties in the lower atmosphere. Dust sizes, and so their emission/absorption properties, are almost certain to vary with latitude and altitude, owing to size-dependent dust-settling rates [e.g., Murphy et al., 1990].

Perhaps most surprising is how little we understand about the average behavior of Mars atmospheric dust loading, including its seasonal and interannual variability. The generally held model of dust loading for the global Mars atmosphere is drawn largely from the Viking lander measurements of column dust opacities, which implied a minimum background dust opacity of ~0.5 [Pollack et al., 1979; Colburn et al., 1989]. Such dusty conditions were viewed as consistent with the warm atmospheric temperatures determined from the Viking descent measurements and the uncorrected IRTM 15 μm data [e.g., Pollack et al., 1979; Haberle et al., 1997; Forget et al., 1999]. The 1997 Pathfinder measurements of dust opacity and atmospheric temperatures have been interpreted as verification of this dusty, warm model and its long-term applicability [Schofield et al., 1998; Haberle et al., 1999; Smith and Lemmon, 1999]. The colder atmospheric temperatures returned from the long-term record of millimeter observations [Clancy et al., 1996] and their agreement with the presented 1997–1998 TES and millimeter measurements represent a significant contradiction to this Viking-based climatology. If the 1988–1998 Mars atmosphere is 15 K cooler than at the time of the Viking period (1976–1979), it implies that the average dust loading of the global Mars atmosphere is significantly smaller now than at the time of the Viking period [Clancy et al., 1990, 1996]. Dust-dependent temperature profile calculations from Mars global circulation models [Wilson and Hamilton, 1996; Haberle et al., 1997] suggest that that global dust loading levels over the entire Mars year must decrease by at least a factor of 2 between these periods to produce such colder atmospheric temperatures. TES nadir dust opacity retrievals in the 9 μm silicate absorption band provide a valuable test for determining whether such large changes in atmospheric dust loading have occurred between the late 1970s and the 1990s.

Figure 10 presents a comparison of visible dust column opacities at 0°–30° N latitudes as derived from Mariner 9 IRIS (solid triangles) 9 μm dust opacities (1972, scaled by a factor of 2 [Fenton et al., 1997]); Viking lander 1 (plus signs in year 12, crosses in year 13) solar extinction measurements (1976–1978 [Colburn et al., 1989]); Viking IRTM (solid squares in year 12, solid diamonds in year 13); 9 μm dust opacities (1976–78, scaled by a factor of 2 [Martin, 1986]; the colder atmospheric temperatures determined by the Wilson and Richardson reanalysis of IRTM 15 μm radiances will affect the 9 μm dust opacities retrieved from IRTM observations only slightly, reducing retrieved dust opacities by 10–20%); 1989 Phobos (asterisk) solar occultation [Chassefière et al., 1992] and spectroscopic [Drossart et al., 1991; Moroz et al., 1991] observations; 1995–1997

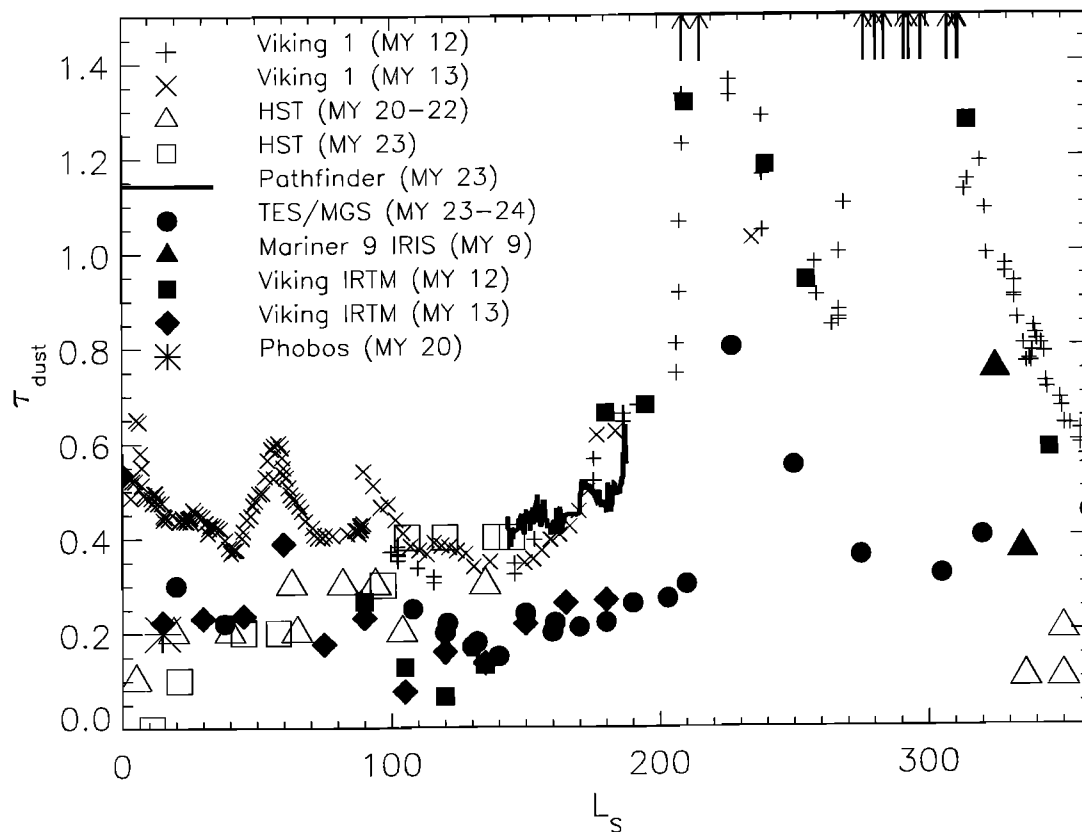


Figure 10. A comparison of visible dust column opacities at Mars northern low latitudes, as determined from 1971-1972 Mariner 9 IRIS (solid triangles) (scaled from $9\ \mu\text{m}$ opacity [Fenton *et al.*, 1997]), 1976-1978 Viking 1 lander (plus symbols in year 12, cross symbols in year 13) [Colburn *et al.*, 1989], 1976-1978 Viking IRTM (solid squares in year 12, solid diamonds in year 13) (scaled from $9\ \mu\text{m}$ opacity [Martin, 1986]), 1989 Phobos (asterisk) [Chassefière *et al.*, 1992; Moroz *et al.*, 1991], 1997 Pathfinder (solid line) [Smith and Lemmon, 1999], 1997-1998 MGS TES (solid circles) [Smith *et al.*, this issue], and 1995-1997 HST (open triangles in years 20-22, open squares in year 23) [Wolff *et al.*, 1999; Clancy *et al.*, 1999] measurements. The Viking lander opacities include only PM observations and have been smoothed with a five-point running mean. Arrows indicate opacities greater than 2 for Viking lander measurements during the 1977a and 1977b dust storms. The 1997-1998 TES and 1972 IRIS values are determined from $9\ \mu\text{m}$ opacity measurements, which have been scaled by a factor of 2 to obtain equivalent visible dust opacities.

Hubble Space Telescope (HST) (open triangles in years 20-22, open squares in year 23) imaging [James *et al.*, 1994; Wolff *et al.*, 1999] and spectroscopy [Clancy *et al.*, 1999]; and Pathfinder solar extinction imaging (solid line [Smith *et al.*, 1997]). Included in Figure 10 are the average TES $9\ \mu\text{m}$ dust opacities for the 0° - 30° N latitude range in 1997-1998 (solid circles) [Smith *et al.*, this issue], which have been scaled by a factor of 2 to present comparable visible dust opacities [Zurek, 1982; Clancy *et al.*, 1995]. Afternoon dust opacities from the Viking 1 lander record (smoothed with a running five-point average) are presented, and the Viking and Pathfinder opacities are scaled to a surface pressure of 6.1 mbar (in accord with the TES opacities).

Several points follow from the comparisons of Figure 10. The Mars southern spring/summer atmosphere in 1996-1998 (years 22-23) does show significantly lower dust loading than during the 1976-1977 Viking period

(year 12). At L_S of 190° - 320° the 1997-1998 TES measurements imply visible dust opacities at northern low latitudes which are 2-8 times lower than during the Viking period. TES dust measurements prior to the Noachis Terra storm show a factor of 2-3 less dust loading, compared to Viking 1 lander and IRTM measurements prior to the 1977a storm (0.3 versus 0.6 - 0.8 at $L_S=180^\circ$ - 205°). Notice, however, that IRTM dust opacities at $L_S=180^\circ$ - 185° are lower in year 13 than in year 12). Perihelion dust storm activity ($L_S=205^\circ$ - 280°) was much weaker in 1997-1998 relative to the 1977 period. The Noachis Terra dust storm of 1997 led to relatively modest dust loading in the northern hemisphere, as compared to the large dust opacities observed by both Viking landers and IRTM during the 1977a and 1977b dust storms (visible dust opacities of 0.6 - 0.8 versus 2 - 4). Although there are 30-50% increases in TES dust opacities between $L_S=300^\circ$ and 360° (which correspond to

distinct $L_S=310^\circ$ and 340° atmospheric heating events; see Figure 5), there was no second dust storm in 1997–1998 comparable to the 1977b storm. Consequently, the $L_S=280^\circ$ – 320° seasonal range was also much less dusty (3–8 times) in year 23 than during the equivalent season in year 12. This seasonal range was also less dusty in 1998 than observed after the 1971 great dust storm (year 9; compare TES and IRIS), although by $L_S=330^\circ$ – 340° the 1972 dust loading had decayed to comparable levels observed in 1998.

The $L_S=350^\circ$ – 180° period of northern spring/summer exhibits a more complex variation among the TES, Viking lander and IRTM, HST, and Phobos dust opacity measurements. At $L_S=360^\circ$ TES measurements are 2–3 times larger than the HST opacities, but are in reasonable agreement with the dust columns measured by Viking 1 and IRTM in 1977. However, the $L_S=300^\circ$ – 360° period in 1998 presents an increasing dust column owing to the late season dust storm events at $L_S=310^\circ$ and 340° (Figure 5). By comparison, the Viking 1977 and Mariner 9 1972 dust opacities over this L_S range decreased by a factor of 2–4, associated with the decay of the 1977b and 1971 storms. The TES opacities at $L_S=20^\circ$ – 40° are comparable to the Phobos (year 20), HST (Years 20–23), and Viking IRTM (years 12–13) measurements for this season ($\tau_{vis} \sim 0.1$ – 0.3), and are roughly a factor of 2 less than the Viking lander 1 opacities. The northern summer season at $L_S=100^\circ$ – 180° shows good agreement among the Viking lander, HST, and Pathfinder observations, whereas the Viking IRTM (1976, 1978) and MGS TES (1997, 1999) measurements are typically lower by a factor of 2.

The differences between the 1978 Viking lander and IRTM opacities over $L_S=10^\circ$ – 180° (year 13) and the 1997 TES and Pathfinder measurements at $L_S=190^\circ$ (year 23) are particularly surprising, as these are contemporaneous measurement sets. Zurek [1982] raised the possibility that Viking lander dust opacities obtained prior to the 1977 storms may not be fully representative of low- to midlatitude dust loading at this time. We suggest that the Viking and Pathfinder lander opacities over $L_S=10^\circ$ – 190° include the effects of enhanced boundary layer dust loading from dust devil activity in these low basins [e.g., Metzger et al., 1999], as well as contributions from afternoon cloud opacities (particularly for the $L_S=60^\circ$ – 140° aphelion cloud period). Incomplete separation of cloud versus dust scattering is the major uncertainty in determining HST dust opacity, as ice particle scattering is 3–4 times more effective than dust scattering for increasing the visible/ultraviolet brightnesses analyzed in these studies [Wolff et al., 1999; Clancy et al., 1999]. The recent identification of the aphelion cloud belt in Viking IRTM observations [Tamppari et al., 1999] implies that water ice clouds may affect the aphelion dust opacities retrieved from Viking lander [Colburn et al., 1989] and orbiter [Thorpe, 1981] analyses. Unaccounted effects from cloud opacities and lower boundary enhancements of

dust loading both tend to bias the Viking lander opacities high relative to the vertically-extended, dust-only opacities retrieved from 9 μm TES and IRTM nadir retrievals. Such a change to the Viking-based characterization of dust loading in this season is at least partly corroborated by the lower atmospheric temperatures determined for this season in 1976 and 1978 (years 12 and 13) by the Wilson and Richardson [2000] reanalysis of the Viking IRTM 15 μm measurements.

The dust opacity measurements of Figure 10 indicate decreased atmospheric dust columns between the Viking and recent periods, particularly for the $L_S=190^\circ$ – 340° seasonal range. The decreased dust loading during the perihelion dust storm season in 1997–1998 also corresponds to significantly colder atmospheric temperatures (by 10–15 K) in 1997–1998 versus 1977. On the other hand, 10–15 K differences between the millimeter and Viking 15 μm temperatures (corrected) over $L_S=150^\circ$ – 180° correspond to a seasonal range in which HST, Viking, and Pathfinder dust column measurements exhibit relatively good agreement, and Viking IRTM opacities are actually a factor of 2 lower. The abrupt 10–15 K increases in Viking 15 μm IRTM and millimeter temperatures over $L_S=145^\circ$ – 150° in years 12 and 13 were not accompanied by comparably sharp increases in the atmospheric dust column, as evidenced by either the Viking lander or Viking IRTM opacity records.

It is also notable that the corrected 15 μm IRTM measurements of 20–30 km atmospheric temperatures are now in conflict with the two Viking descent temperature profiles at $L_S=96^\circ$ and 117° . A similar conflict exists between the cold millimeter profiles and the warm Pathfinder descent temperature profile at $L_S=143^\circ$ in 1997 [Schofield et al., 1998; Clancy and Sandor, 1998, Figure 8]. The millimeter temperature measurements do show distinctive interannual and short-term (over 1–2 weeks) variability during this period. Although there is no clear correlation of dust opacity variations with these temperature differences, a significant dust storm did erupt in Valles Marineris several days before and nearby the Pathfinder landing site on Mars [Wolff et al., 1999]. This storm was observed to decay shortly after the Pathfinder landing, and so may have contributed to regionally and temporally restricted dust loading at the time of the Pathfinder entry.

At this time, a simple relationship between Mars global-average atmospheric temperatures and dust column opacities is not evident. The Viking-based model of a constant background dust level, which is well mixed vertically and horizontally (over low- to midlatitudes) implies a fairly direct relationship between warmer atmospheric temperatures and increased dust column opacities. This behavior appears to be present during the perihelion dust storm season ($L_S=205^\circ$ – 360°), where colder temperatures and lower dust column opacities are unambiguously presented in 1997–1998. However, such a direct relationship is not evident during the

$L_S=0^\circ$ – 200° seasonal range, where descent temperature profiles disagree with global remote sensing measurements; interannual dust opacity variations may or may not exist, depending on whether Viking lander or IRTM $9\ \mu\text{m}$ measurements best characterize global dust loading during 1976–1978.

It has been argued that the influence of nonlinear interactions between water ice and dust aerosols may serve to enhance short-term, interannual, and spatial (e.g., the descent profiles represent transitory local conditions) variations of atmospheric dust loading and enforce the confinement of solar heating by dust aerosols to altitudes below 10–15 km in the northern spring/summer seasons [Clancy *et al.*, 1996]. Recent modeling of this mechanism suggests the potential importance of ice condensation on dust aerosols, in terms of both gravitational settling rates and the aerosol single scattering albedo [Rodin *et al.*, 1999]. The cold Mars atmosphere around aphelion implies low altitudes (≤ 10 km) for water ice cloud formation during the northern spring/summer seasons. The abrupt rise in Mars atmospheric temperatures in late northern summer (over $L_S=140^\circ$ – 150°) may reflect a discrete increase in dust heating of the atmosphere, as cloud formation and its suppression of dust solar absorption break down in late northern summer. Limb profiling of atmospheric temperatures, dust, and clouds by TES will address these questions shortly.

5. Conclusions

Extensive temperature profiling measurements of the Mars atmosphere were obtained by spacecraft infrared (MGS/TES) and ground-based millimeter (Kitt Peak NRAO) experiments during the 1997–1999 aerobraking and early mapping phases of the MGS mission. Appropriate latitude averages of the spatially resolved MGS temperatures are compared to the disk-averaged millimeter temperatures for the 0–30 km altitude region of the Mars atmosphere. These profile comparisons demonstrate 2–5 K agreement between the TES and millimeter data sets for selected L_S of 205° – 214° , 226° – 227° (the Noachis Terra regional dust storm), 300° – 308° , 28° – 34° , 108° – 112° (Viking descent profile comparison), and 141° – 144° (Pathfinder descent comparison). In addition, 1999 MGS and 1978 Viking radio occultation measurements exhibit good agreement with a 1999 millimeter temperature profile for $L_S=74^\circ$ – 77° . Time sequences of TES and millimeter temperatures at pressure levels of 0.3 mbar (~ 30 km altitude) and 0.5 mbar (~ 25 km altitude) are presented over the extended September 1997 ($L_S=190^\circ$) to September 1999 ($L_S=180^\circ$) period. Both data sets show a series of very abrupt global atmospheric temperature increases of 5–15 K, the largest of which is related to the late November 1997 Noachis Terra regional dust storm [Christensen *et al.*, 1998; Smith *et al.*, this issue]. Comparison of the 1997–1999 millimeter observations to previous years of millimeter observations indicates very similar

seasonal and dust storm behaviors for the Mars atmosphere over the past 4–5 Mars years, including abrupt 10–15 K global temperature increases in each Mars perihelion season.

Over the entire 1997–1999 period of observations, global Mars atmospheric temperatures determined from the TES and millimeter measurements are 10–20 K colder than have been inferred from Viking [e.g., Haberle *et al.*, 1997] and Pathfinder [e.g., Schofield *et al.*, 1998] atmospheric measurements. These differences are substantially reduced by the Wilson and Richardson [2000] reanalysis of the Viking $15\ \mu\text{m}$ radiances, which leads to decreases of 5–15 K in 0.5 mbar atmospheric temperatures derived for the Viking period. On the basis of this correction, the Mars atmosphere during 1997–1999 is ~ 5 – 10 K colder than during the 1976–1978 Viking period for the seasonal range $L_S=150^\circ$ – 180° , 10–15 K colder over $L_S=205^\circ$ – 330° , but within 5 K of the Viking period temperatures for the remainder of the Mars year.

Colder current conditions over the $L_S=205^\circ$ – 330° period correlate with relatively low perihelion dust loading in 1997–98 as compared to 1977. Dust opacities retrieved from the 1997–1998 TES $9\ \mu\text{m}$ absorption measurements are 2–8 times smaller than those determined from Viking lander and IRTM observations over this perihelion dust storm season. Away from the perihelion southern summer season, interannual variations in global atmospheric temperatures are more modest and are not clearly associated with distinct changes in column dust opacities. Global average 0.5 mbar temperatures from millimeter and TES measurements are 5–10 K warmer during early northern summer ($L_S=100^\circ$ – 150°) in 1998–1999 (year 24) versus 1993–1997 (years 21–23), and 5–10 K colder during late northern summer ($L_S=150^\circ$ – 180°) versus 1976–1978 (years 12 and 13). Changes in the vertical distribution rather than the vertical column of dust loading may be responsible for these interannual variations in northern summer atmospheric temperatures. The Mars aphelion atmosphere (northern spring, $L_S=0^\circ$ – 100°) presents minimum conditions of interannual and short-term variability. Minimum dust opacities ($\tau_{vis} \sim 0.1$ – 0.3), peak cloud opacities ($\tau_{vis} \sim 0.1$ – 0.5), and cold atmospheric temperatures would be typical of all observed Mars aphelion seasons if Viking IRTM 15 and $9\ \mu\text{m}$ measurements rather than the Viking lander measurements are representative of 1976–1978 global conditions for Mars atmospheric temperatures and dust loading in this season.

These results conflict with the conclusions from Pathfinder atmospheric analyses [Smith and Lemmon, 1999; Haberle *et al.*, 1999; Magalhães *et al.*, 1999] that the Mars atmosphere has remained in the dusty, warm state characterized by Viking lander measurements since the time of these Viking observations 20 years ago. They lend support to conclusions that water ice clouds are likely to form at lower altitudes than previously thought (below 10 km around aphelion), and may contribute significant influences on the photochemistry, dust radiative

forcing, and interannual variability in the global Mars climate system [Clancy *et al.*, 1996].

Acknowledgments. This work presents a set of millimeter-wave observations which were obtained and analyzed under JPL contract 960349 as part of a broad program of science advisory support for the Mars Global Surveyor aerobraking operations. We acknowledge the privilege and opportunity of our participation in the MGS Atmospheric Advisory Group and the personal support extended by Dan Lyons and Richard Zurek. The TES measurements employed in this comparison result from the diligent efforts of the entire TES team and the joint JPL/Lockheed Martin spacecraft operations. Observational support for the Kitt Peak millimeter measurements was graciously and generously provided by the National Radio Astronomy Observatory (NRAO, operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation). We are especially indebted to the Kitt Peak 12 m NRAO telescope operators.

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(Received May 18, 1999; revised September 29, 1999; accepted October 5, 1999.)