Mesospheric Winds and Temperatures from JCMT Sub-millimeter CO line Observations during the 2003 and 2005 Mars Oppositions.

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Introduction: The Aug/Sept 2003 and Oct/Nov 2005 oppositions of Mars occurred near perihelion, presenting maximum angular resolution as viewed from the Earth (25 and 20 arcsec, respectively) as well as peak zonal and meridional winds within the Mars atmosphere. During both oppositions, we obtained measurements of sub-millimeter Mars rotational lines for ^{12}CO (345.796 GHz) and ^{13}CO (330.588 GHz) at five coarsely resolved positions on the Mars disk; corresponding to center, east, west, north and south limb offsets from the 20S, 50E-140W sub-earth positions observed on Mars (figure 1). These high signal/noise absorption spectra allow accurate determinations for coarsely resolved (~20 km vertical, ~3000 km horizontal) zonal and meridional winds at 35-80 km altitudes, as well as atmospheric temperature profiles over 0-80 km altitudes.

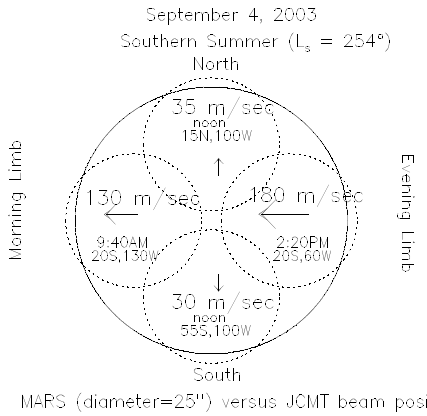


Figure 1. *Schematic of four antenna beam locations (N, S, E, W, center position not shown) on the disk of Mars. ^{13}CO and ^{12}CO line integrations are obtained for each date. Wind speeds and directions (arrows) are indicated for the September 4, 2003 observation.*

CO Line Observations: The James Clerk Maxwell Telescope (JCMT) diffraction beam-width (FWHM~13" at J=2-3 CO transition frequencies) filled roughly half the Mars disk during the 2003 and 2005 Mars oppositions, as indicated in figure 1. The deep ^{12}CO absorption line (shown for the Sep03 disk center position in figure 2) provides well behaved (linear in T, no scattering) temperature weighting functions up to 80 km altitudes (pressure < 1 μbar, Clancy and Sandor, 1998), as well as sharp absorption cores which facilitate accurate line shift measurement for Doppler wind determinations. J=2-3 ^{13}CO line absorptions provide CO mixing ratio determinations at altitudes below 40-45 km, above which photochemical model profiles are adopted. They also provide for extension of Doppler wind determinations below the lower altitude limit of ^{12}CO measurements (40-45 km) to ≤ 35 km.

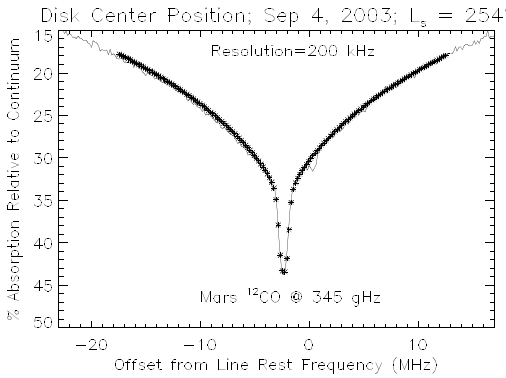


Figure 2. *Line center portion of a Mars 345 GHz ^{12}CO absorption spectrum, which is Doppler shifted from zero rest frequency (notice a weak terrestrial mesospheric absorption at rest frequency) The observed absorption (solid line) is fit by a 2D radiative transfer simulation (asterisk symbols), which determines the 0-85 km temperature profile associated with the noon LT, 20S sub-earth latitude of the disk center spectral pointing.*

2003 Temperature Profiles: The Mars 2003 perihelion temperature profiles retrieved from the five pointing positions on Mars present large-scale atmospheric averages for local times (LT) centered on ~9:30am, noon, and 2:30 pm at the sub-solar latitude of ~20S; as well as averages for latitudes

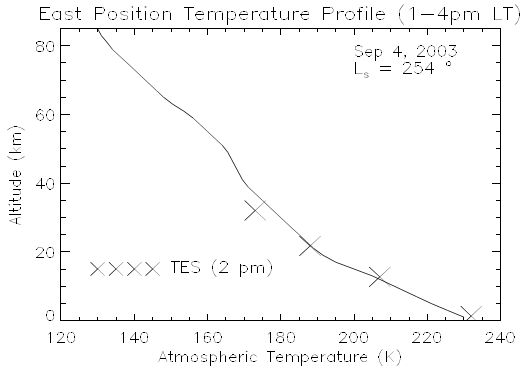
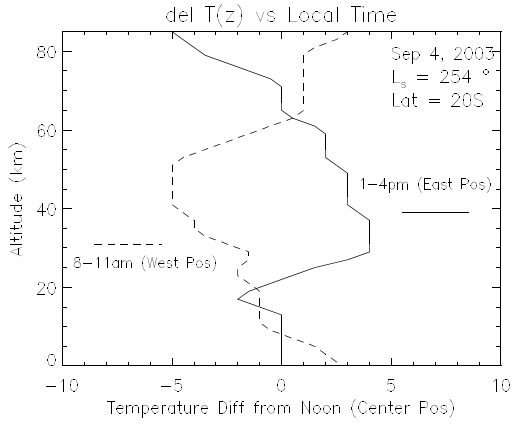


Figure 3, *Atmospheric temperature profile retrieved from the Sep03 East beam position (solid line) com-*

pared to nearly coincident (location, -1day, and LT) TES nadir temperatures over 0-30 km region.
of 55S, 20S, and 15N centered on an LT of noon. Figures 3-4 indicate the accuracy of these temperatures with respect to TES (figure 3), and the inclusion of thermal tides in the profile retrievals as a function of local time at 20S (figure 4). While the spatial and LT averaging presented in these temperature profiles are substantial, figure 4 still represents the first profile measurement of thermal tides in the Mars atmosphere over an extended altitude range.



FifFigure 4. *The noon LT temperature profile retrieved for the Sep03 disk center ^{12}CO observation has been subtracted from the East (pm) and West (am) beam position profiles to reveal the altitude profile of solar thermal tides at 20S latitude over 40-150W longitudes in Mars southern summer (L_s = 254°).*

2003 Doppler Winds: Accurate Doppler wind determinations are provided by differencing of disk center ^{12}CO and ^{13}CO spectra from the four limb position spectra. Spectral line differences with the East and West limb positions gives morning and afternoon zonal winds about the sub-earth latitude of ~20S, which also corresponds to the sub-solar latitude in these mid and late southern summer seasons observations. Spectral line differences with the North and South limb positions provide meridional winds at the noon local time and 30-150W longitudes viewed. The sharp spectral gradients within the CO line absorption cores provide maximum sensitivity to wind Doppler shifts, which are contributed by 50-80 km altitudes for the ^{12}CO line and by 30-40km altitudes for the ^{13}CO line.

^{12}CO line difference spectra for the East and West beam positions during August and September 2003 JCMT observations are presented in figure 5. The 24 hr eastward rotation of Mars contributes effective 240 m/s Doppler limb velocities which, in the absence of atmospheric winds, would lead to ~ 2.5% peak amplitudes in limb difference spectra. The much reduced East and West line difference peaks observed indicate strong easterly zonal circulations at the season (L_s=251-254º) and latitude (20S) of these measurements. Retrieved zonal Doppler winds are presented in figures 6 (Aug03) and 7 (Sep03).

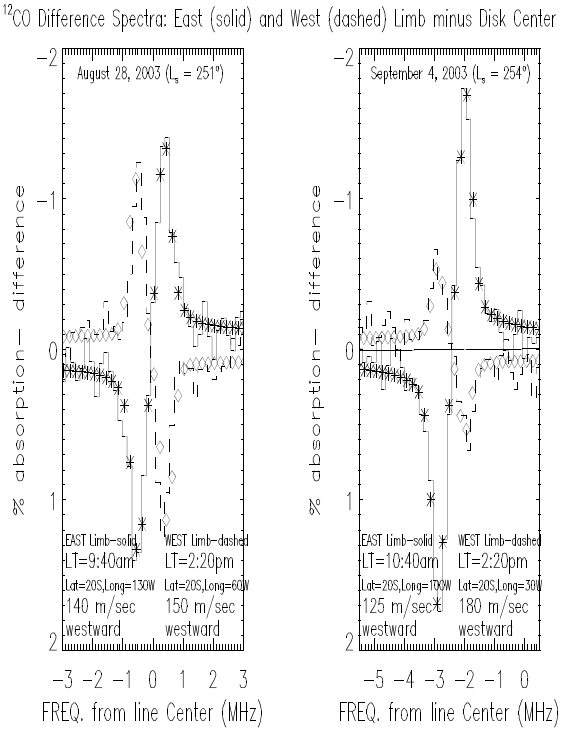


Figure 5. *West (am) and East (pm) limb spectra differences from the disk center spectra for Aug (left) and Sep03 (right) JCMT 345 GHz ^{12}CO spectral line observations. The folded difference spectrum has been subtracted to isolate the asymmetric Doppler line shift component of the difference spectrum.*

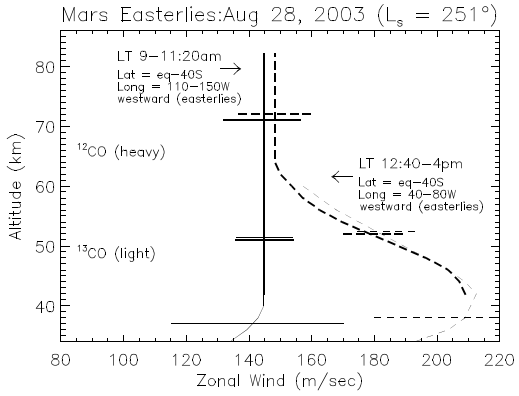


Figure 6. *Zonal easterly wind profiles derived from Aug 28, 2003 JCMT ^{12}CO (heavy lines) and ^{13}CO (light lines) spectral line Doppler shifts observed at East (am - solid lines) and West (pm – dashed lines) limb positions on Mars.*

Strong (120-200 m/s) easterly winds are indicated for 35-80 km altitudes at the sub-earth (and sub-solar) latitudes of 20S during the Aug (figure 6) and

Sep 2003 (figure 7) observations. In both cases, the longitudes of observation correspond to the Tharsis/Solis Planum plateaus (West, am) and the Valles Marineris and associated chasma regions to the east (East, pm). East limb (pm) zonal easterlies are typically 50 m/s greater than West limb (am). Preliminary comparisons to the European Mars Climate Database (EMCD, based on MGCM calculations- Forget et al., 1999) indicate that a substantial portion of the observed differences in East-West limb position winds may be associated with longitudinal rather than LT forcing. The average observed easterlies are generally 20-50% greater than the EMCD predictions for this season. The vertical profile shapes are similar in that peak winds occur below 60 km.

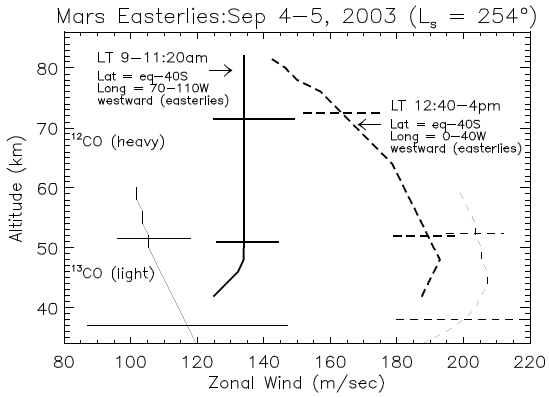


Figure 7. *Description same as figure 7, for the Sep 4-5, 2003 period of JCMT observations.*

Meridional winds at noon LT are derived from ^{12}CO and ^{13}CO line spectra differences corresponding to North and South minus disk center beam positions, obtained for the Sept 4-5, 2003 JCMT observations.

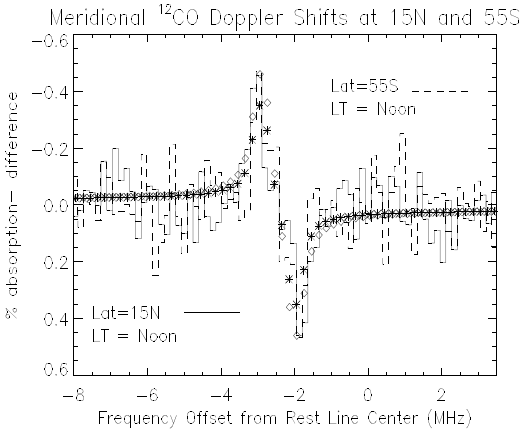


Figure 8. *North (5S-35N latitudinal range, solid line) and South (35S-75S latitudinal range, dashed line) beam position line differences from the disk center ^{12}CO spectrum observed on Sep 4-5, 2003. Doppler shifts are poleward (negative) in both cases.*

Figure 8 presents the ^{12}CO line differences. For both the North and South beam positions, meridional winds of 30-40 m/s are directed poleward (figure 9). The magnitude and direction of these poleward meridional circulations are in general agreement with the ECMD predictions for these latitude ranges, LT (noon), and season (southern summer).

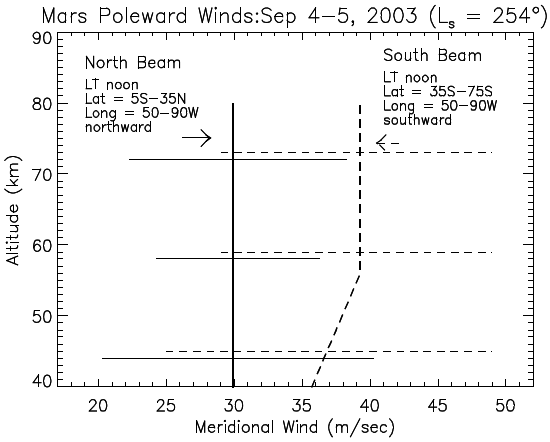


Figure 9. *Poleward meridional circulations are observed in both the north (5S-35N, solid line) and south (35S-75S) beam positions centered at noon LT during Sep 4-5, 2003 (L_s=254º).*

2005 Temperatures: Analyses of the recent 2005 Mars opposition measurements from JCMT remain incomplete, but it is clear that a significant heating affected the Mars atmosphere to very high altitudes at the time of these observations (L_s = 315-318º). Figure 10 compares the ^{12}CO disk center spectra observed on Nov 4, 2005 (heavy line) versus that observed Aug 28, 2003 (light line). The much shallower depth of the Nov 2005 line absorption reflects a much warmer atmosphere, relative to the 2003 spectrum, up to the highest altitudes sounded by these 345 GHz ^{12}CO spectra (> 80 km).

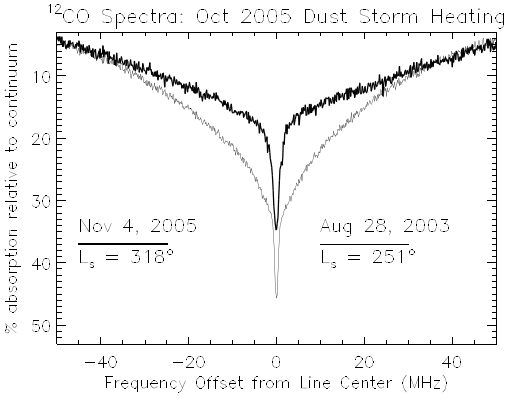


Figure 10. *A comparison of the central portions of 345 GHz ^{12}CO spectra observed for the disk center of Mars on Aug 28, 2003 (light line) and Nov 4, 2005 (heavy line).*

Figure 11 compares the 0-85 km temperature profiles corresponding to the two spectral line obser-

vations presented in figure 10. Above the 10 km altitude level, atmospheric temperatures (at noon LT) increase by 20-25K in the Nov 2005 versus the Aug 2003 profiles. These increases persist to the top (80-85 km) altitude of temperature retrieval.

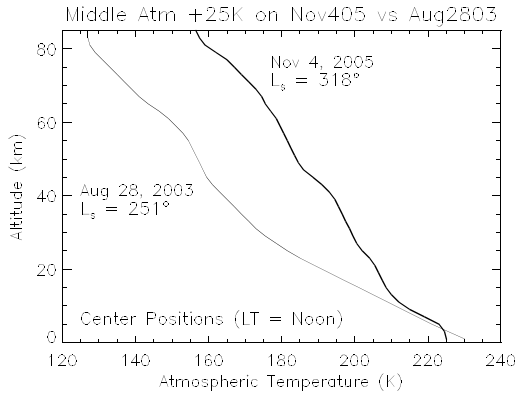


Figure 11. *Mars disk center temperature profiles retrieved from the Nov 5, 2005 (Heavy line) and Aug 2003 (light line) spectral line observations presented in figure 10. Substantial (>20K) heating of the middle atmosphere in 2005 is associated with L_s = 310-330º seasonal dust storm activity.*

The late southern summer season of the 2005 observations (L_s = 318º) would nominally lead to reduced, rather than increased, atmospheric temperatures relative to the peak southern summer season (L_s = 254º) associated with the 2003 observation. However, the L_s = 310-330º period corresponds to a discrete dust storm season on Mars during which global dust loading and atmospheric temperatures have been observed to increase in each Mars year observed by the Mars Global Surveyor TES experiment (Smith, 2004). In the case of these 2005 JCMT observations, a significant Mars regional dust storm was observed by Mars-based platforms (MGS, Mars Express, and MER) and Earth-based telescopes (HST, ground) in the prior week. The image of figure 12 (Mars north is oriented at the bottom of this image, courtesy of Clay Sherrod Arkansas Observatories) shows a bright regional dust storm, imaged on Oct 28, 2005 over the Arabia Terra region.

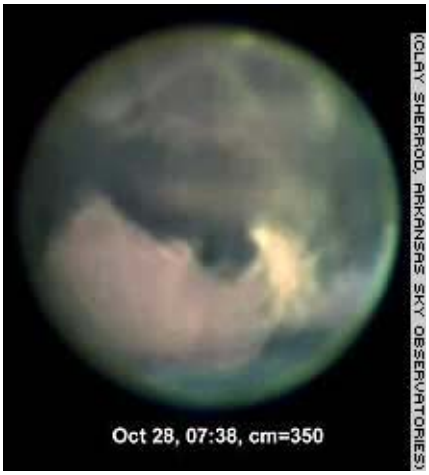


Figure 12. *Color image of a regional dust storm on Mars, from the Clay Sherrod Arkansas Observatories (downloaded from the CNN webpage).*

Summary of Results: Key measurements regarding the southern summer period of these Mars atmospheric observations include **1)** intense (120-200 m/sec), vertically deep (>100 m/sec to below 40 km altitudes) zonal easterlies; **2)** meridional midday winds of 30-40 m/sec poleward at northern subtropical (5S-35N) and high southern (35-75S) latitudes; **3)** measurement of thermal tide signatures in 0-85 km temperatures about 20S latitude; and **4)** measurement of >20K warming of the global Mars atmosphere over 10-80 km altitudes associated with a late southern summer (L_s = 310º) dust storm in 2005.

Observations regarding the general circulation of the Mars atmosphere in the L_s = 251-254º southern summer season of 2003 are in reasonable agreement with the GCM predictions provided by the ECMD, with the exception that significantly stronger easterly winds (20-50%) are returned by the observations. Previous millimeter observations of Mars Doppler winds have also suggested stronger easterly circulations than predicted by models (Lellouch et al., 1993; Forget et al., 1999). Model comparisons to the JCMT Oct/Nov 2005 observations (L_s = 318º), including effects of the observed warming event (figures 10-11) in thermal tide and zonal/meridional wind measurements, remain to be derived.

References:

Lellouch, E., J. J. Goldstein, S. Bougher, B. Theodore, and J. Rosenqvist, Mars' middle atmosphere circulation near equinox from microwave observations, *Bull. Amer. Astron. Soc.*, **25**, 1060, 1993.

Forget, F., F. Hourdin, R. Fournier, C. Hourdin, and O. Talagrand, Improved general circulation models of the Martian atmosphere from the surface to above 80 km, *J. Geophys. Res.*, **104**, 24155-24175, 1999.

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