MARS EQUATORIAL MESOSPHERIC CLOUDS

R.T. Clancy, M.J. Wolff, B.A. Whitney, *Space Science Institute, Boulder CO, USA (Clancy@space-science.org)*, **B.A. Cantor**, *Malin Space Science Systems, La Jolla, CA, USA.*

Summary: We report the occurrence of a new type of cloud in the Mars atmosphere, apparent as high altitude (60 to 80 km - mesospheric), vertically discrete aerosol scattering layers. Mars Global Surveyor (MGS) limb observations from the Thermal Emission Spectrometer (TES) over 2-3 pm local times (LT) indicate distinctive temporal and spatial distributions that suggest strong dynamical influences in the formation of these Mars equatorial mesospheric (MEM) clouds. They exhibit high occurrence frequencies at the beginning and end of the aphelion northern summer season on Mars (centered at L_s = 30° and 150°), where they are confined to equatorial (15S-15N) latitudes and two relatively narrow longitude ranges (330-20W and 50-120W).

Limb images from the MGS Mars Orbital Camera (MOC) over 1-3 pm LT indicate significant horizontal variations in these mesospheric clouds on scales of 25-50 km, which couple with the limb viewing geometry to introduce ambiguity in the altitude of individual cloud identifications. Based on the observed distribution of projected limb heights, MEM clouds exhibit peak optical depths that are quite significant (τ_{vis} ~ 0.01) for the low-pressure region of formation (~ 1 μbar), within a fairly narrow altitude range of 70-80 km. Undetectable 5-40 μm signal within TES IR limb spectra precludes direct compositional information (i.e., water versus CO_2 ice). However, the observed upper limit for infrared scattering in the context of the observed visible scattering (TES solar band and MOC blue filter) indicates small aerosol particle sizes (R_{eff} ≤ 0.5 μm) for water or CO_2 ice compositions.

If MEM clouds are water ice, vigorous dynamical transport of water vapor to the 70-80 km altitude of cloud formation is required to produce the substantial cloud optical depths observed. If the mesospheric clouds are CO_2 ice, very cold (≤ 105 K) atmospheric temperatures are required for the season and location of their occurrence. Spatially resolved temperature measurements of the Mars mesosphere are very limited, but the Pathfinder entry profile (Lat=19N, Long=34W, L_s =142°, LT= 4 am) exhibited cold, CO_2 saturation temperatures around 80 km for a location and season consistent with MEM cloud occurrence. Furthermore, disk-average 70-80 km Mar atmospheric temperatures from ground-based sub-millimeter observations indicate minimum values (daytime, 40S-40N, ≤ 120 K) for the solar longitude ranges of MEM clouds, as do European Climate Database (EMCD- see Forget et al, 1999) model temperature fields at 82 km.

Introduction: One of the more interesting aspects of the atmospheric temperature profiles retrieved during the Pathfinder descent entry was the detection of cold 80 km altitude temperatures below the saturation conditions for CO_2 ice formation (Schofield et al., 1997).

Clancy and Sandor (1998) suggested the relatively frequent occurrence of CO_2 ice clouds in the 70-80 km altitude region, on the basis of observed (Pathfinder and sub-millimeter ground-based) cold temperatures, Pathfinder images of blue (small size) ice clouds in the predawn sky (Smith et al., 1997), and Mariner 6 and 7 near-IR (4.3 micron) identification of CO_2 ice in equatorial limb tangent views around L_s=200° in 1969 (Herr and Pimental, 1970 – but which may be due to non- LTE CO_2 emission).

Before MGS observations, it remained unclear whether CO_2 or water ice aerosols are ever present at > 60 km altitudes. Dust aerosols had been identified at such high altitudes in Mariner 9 (Anderson and Leovy, 1978), Viking (Jaquin et al., 1986) and MGS (Clancy et al., 2003) limb radiances, associated with the 1971, 1977, and 2001 global dust storms, respectively. The highest detached ice cloud identified from Viking limb data occurred at a projected tangent altitude of 55 km, at 16S, 72W and L_s = 176° (Jaquin et al., 1986; recently modeled by Montmessin et al., 2002).

Global Distribution from TES Limb Scans: TES limb scans in solarband (0.3-3.0 μm), thermal broadband (5-100 μm), and mid-IR spectra (6-50 μm, 5 or 10 cm^{-1} resolution) constitute the first and still only mapping data set for the middle atmosphere of Mars (Christensen et al., 1992; Smith, 2003).

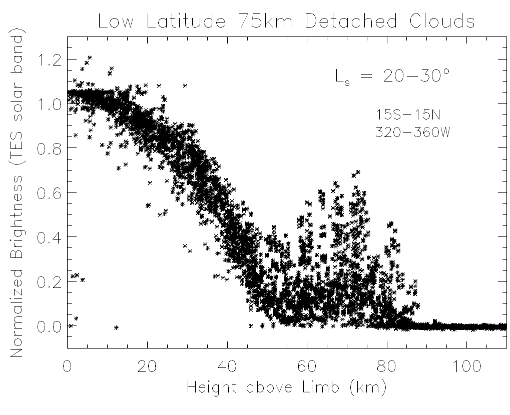

Figure 1. *TES solarband (λ_{mean}~0.7μm) limb profiles. An accumulated set of TES limb scans over the indicated time/spatial bin reveals the Mars equatorial mesospheric ("MEM") clouds at 60-80 km.*

Although the spatial grid of these limb scan data is fairly coarse (10-15 km vertical, 10º latitudinal, and ~30º longitudinal resolutions), their daily coverage over multiple Mars years yields excellent mapping capabilities for definitions of seasonal and global distributions. Consequently, the first definitive measurements of Mars middle atmospheric (mesospheric) detached clouds were provided by MGS TES solarband limb scans (Clancy, 2003; Clancy et al., 2004).

Figures 1-3 present the global distribution of Mars bright mesospheric clouds as a function of altitude, latitude, longitude and season (solar longitude, L_s). As demonstrated in figure 1, these clouds occur as detached layers of remarkably bright (optically significant) ice clouds, which project in limb views over 50-85 km altitudes. As figure 2 demonstrates, they are distinctly low latitude (equatorial, 15S-15N) clouds, and further confined to 1 or 2 longitudinal ranges (330-20W and 50-120W). Based on their low latitude, middle atmosphere location, we have termed these detached cloud layers Mars Equatorial Mesospheric (MEM) clouds. MEM cloud longitude

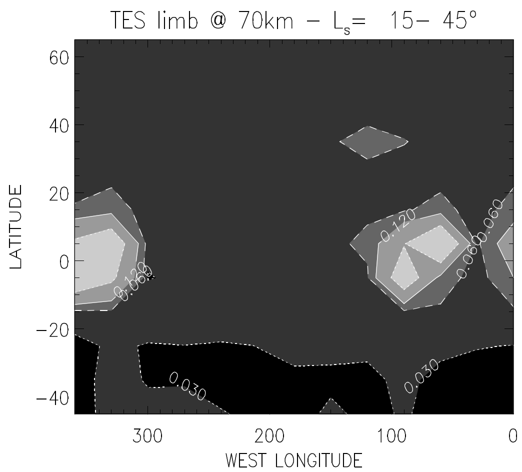

Figure 2. *The mapping MGS TES limb observations allow a unique definition of the spatial and seasonal distributions of Mars mesospheric clouds, which are equatorially as well as longitudinally restricted.*

and latitude distributions correlate well with minimum temperature regions in the ECMD global model temperature fields, at the altitudes (~ 80 km) and seasons (see figure 3) of MEM cloud occurrence. The MEM cloud seasonal occurrence frequency is as distinctive as their spatial distribution, with two L_s ranges (Figure 3: 10-50º, 110-170º) that roughly bound the aphelion cloud belt season for Mars. This seasonal behavior also correlates well with minimum ~80 km temperatures in the ECMD model temperature fields.

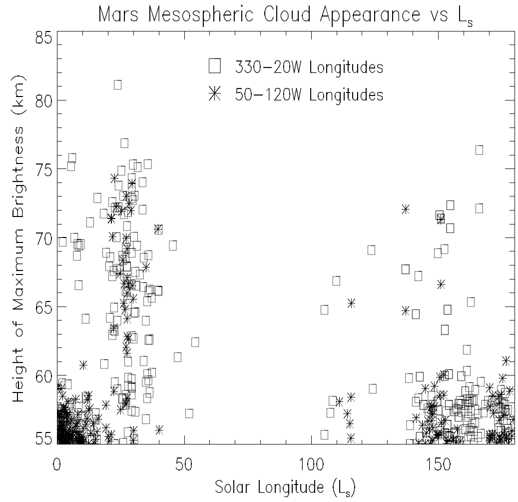

Figure 3. *A very distinctive seasonal character is apparent for Mars equatorial mesospheric (MEM) clouds. They occur at the beginning and end (but not during) the Mars aphelion season (L_s = 71º).*

MOC Limb Images: The appearance of MEM clouds in the MGS TES limb data motivated their detection with MGS MOC (Mars Orbiter Camera) wide angle (WA) imaging. Based upon the spatial and seasonal frequency derived from the TES observations, we requested MOC limb imaging in the Spring of 2004. MOC images of MEM clouds strikingly reveal their 2D structure, which had been inferred from the TES limb scans. While they have been bserved in both blue and red MOC WA limb images, the majority of these MOC images of MEM clouds are from the blue filter WA camera..

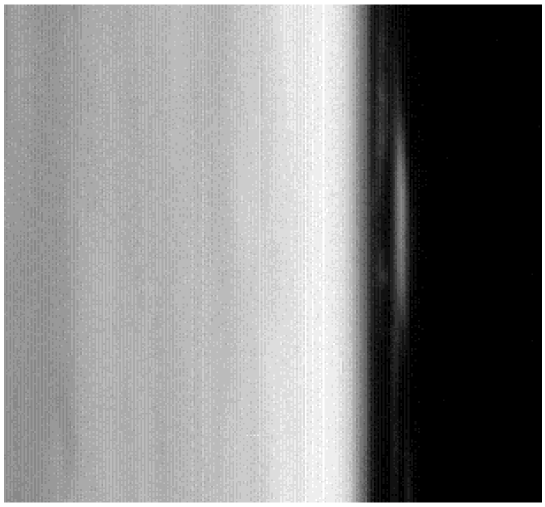

Figure 4. *MOC WA blue limb image of MEM cloud, observed May 5, 2004 - Ls = 29° latitude of 3.8S - 4.2S, longitude of 72W (projected). The central bright cloud extends about 25 km horizontally.*

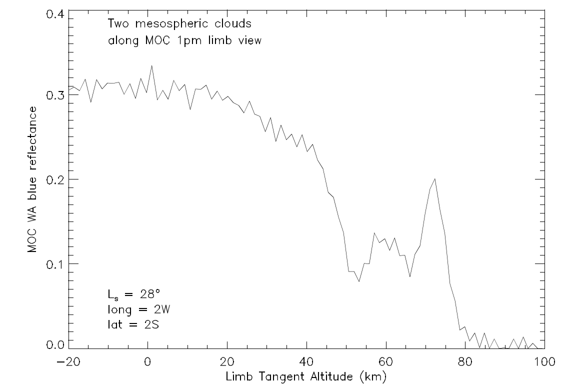

Figure 5. *Cross-section from a MOC blue WA image of the Mars atmospheric limb. Dust and ice aerosols in the lower 40 km of the atmosphere lead to nearly constant limb brightnesses out to 40 km. Above 40 km altitudes, two detached aerosol layers appear projected against the limb at 60 and 75 km limb altitudes. The brightest, 75 km layer presents a MEM cloud at this limb tangent altitude. The lower detached layer is believed to also be an MEM cloud at a similar altitude, but viewed along the limb path in the fore or background of the 75 km limb tangent altitude.*

TES Limb Spectra Observations: TES limb observations include thermal IR spectra (range of 5-50 μm, resolution of 5-10 cm^{-1}) coincident with the solarband radiances. Discrimination of ice (12 and 45 μm) and dust (9 and 18 μm) aerosols is provided by these TES IR spectra (figure 6), when aerosol particle sizes are sufficiently large (R_{mean} > 0.5 μm) to produce measurable thermal IR emission and scattering. Retrieved IR-to-solarband opacity ratios provide dust and ice cloud particle size determinations. For radiative transfer (RT) analysis of the TES limb

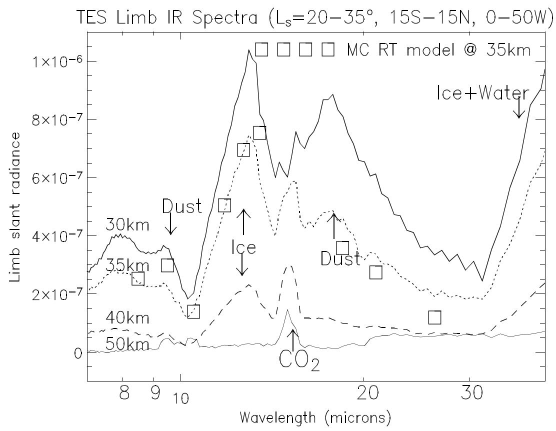

Figure 6. *TES limb spectral averages, over the indicated Ls, lat, and long bins, are presented for tangent altitudes of 30, 35, 40, and 50 km. CO_2 gas and water ice/dust aerosol emission-scattering features are indicated by arrows. Model RT calculations (square symbols) are compared to the TES limb spectrum at 35 km tangent altitude (dotted line).*

observations, we employ a spherical monte carlo RT model, which incorporates multiple scattering, thermal emission, vertical (or 3D) aerosol distributions/properties, and TES atmosphere and surface temperatures (Whitney et al., 1999).

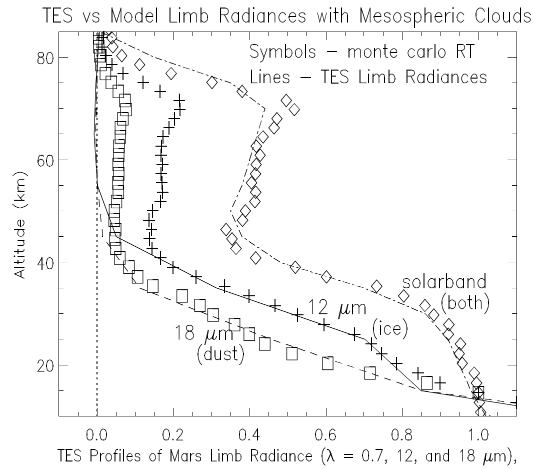

Figure 7. *Limb profile averages of TES solarband (ice+dust, dash-dotted line), 12 μm (ice, solid line), and 18 μm (dust, dashed line) radiances for ~100 individual limb profiles in which the solarband radiances indicate an MEM cloud present. Symbols indicate RT model fits to averaged profile data, for inferred model opacity and particle size profiles ofr dust and ice aerosols (see figure 8).*

Although MEM clouds are readily identified in individual TES solarband limb scans, they are not apparent in the coincident TES IR spectra. To improve the sensitivity of the TES IR spectral measurements, we have averaged ~100 limb scans for which MEM clouds are clearly identified in solarband radiances. Figure 7 presents these limb average measurements (lines) against RT model simulations (symbols) for best-fit optical depth profiles of water ice and dust aerosol profiles. Self-consistent fits at solarband and thermal IR wavelengths are provided by 1.5 μm (R_{mean}) particle sizes, for altitudes below 40 km. However, such large particle sizes (whether water or CO_2 ice) produce significant thermal IR radiances, from scattering of surface IR emission, that are not present in the measurements (figure 7, compare model symbols to measurement lines above 40 km altitudes).

Figure 8 indicates the vertical profiles of dust (dashed line) and ice (solid lines) opacities (km^{-1}) fit to the TES average profile measurements of figure 7. The ice aerosol is spectrally identified as water ice below 40 km altitudes, where both ice and dust particle sizes are fit with R_{mean}= 1.5 μm. The distinctive capping of the lower (0-20 km) dust opacities by water ice hazes at 20-40 km is characteristic of lower atmospheric, low-to-mid latitude aerosol distributions for this pre-aphelion (L_s = 0-50º) season on Mars. The MEM ice cloud layer centered above 70 km, which is more seasonally and spatially restricted (figures 2 and 3), may be either water or CO_2 ice composition. MEM cloud particle sizes are constrained to be less than 0.5 μm (R_{mean}).

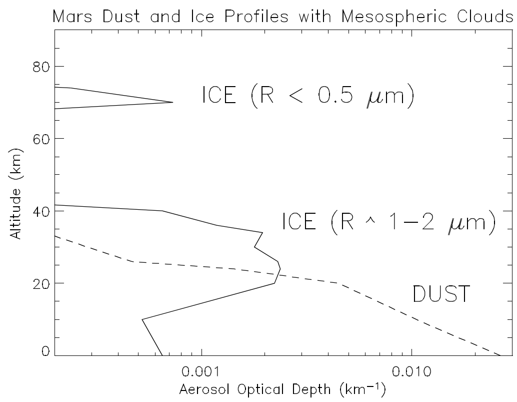

Figure 8. *Nominal dust and ice particle sizes (R_{mean} = 1.5 μm) and opacities fit the lower altitude (20-40 km) TES limb radiances. The mesospheric clouds scatter strongly in the visible, but not in the thermal IR. RT models indicate these clouds must be small water ice or CO_2 ice particles (R_{mean} < 0.5 μm).*

Conclusions:

- ► Detached limb clouds at high (70-75 km) altitudes are prominent in MGS TES solar-band limb scans and MGS MOC wide-angle (WA) limb images (1-3 pm local times).
- ► Their occurrence frequency approaches unity at the beginning and end of the aphelion northern summer season on Mars (centered at L_s =30° and 150°), where they are confined to equatorial (15S-15N) latitudes and two longitude ranges (330-20W and 50-120W). These distributions correlate well with minimum (110-120 K) atmospheric temperatures in the ECMD model climatology at ~80 km.
- ► Both the TES and MOC limb measurements indicate significant horizontal variations in these Mars equatorial mesospheric (MEM) clouds on scales ≤ 50 km, which leads to ambiguity in their precise altitude distribution. They may populate a fairly narrow altitude range of 70-80 km, based on the distribution of projected limb heights.
- ► Peak optical (visible) depths are quite significant (≤0.01) for the low pressure region of formation (~1 microbar). It remains unclear as to their composition (water or CO_2). In either case, co-added MGS thermal IR spectra require cloud particle radii < 0.5 μm (i.e., “blue ice clouds,” such as observed from Pathfinder predawn sky images though attributed to lower altitudes, Smith et al., 1997).

References:

Anderson, E.M., and C.B. Leovy, Mariner 9 television limb observations of dust and ice hazes on Mars, *J. Atmos. Sci.*, **35**, 723-734, 1978.

Christensen, P.R., et al, Thermal Emission Spectrometer Experiment: Mars Observer Mission, *J. Geophys. Res.* , **97**, 7719-7734, 1992.

Clancy, R.T., and B.J. Sandor, CO_2 ice clouds in the upper atmosphere of Mars, *Geophys. Res. Lett*., **25**, 489-492, 1998.

Clancy, R.T., M.J. Wolff, B.A. Whitney, and B. A. Cantor, Vertical distribution of dust optical depth during the 2001 planet encircling storm from a spherical radiative transfer analysis of MOC limb images, *Proceedings of the Sixth International Conference on Mars*, Pasadena, CA, July 2003.

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.

Herr, K.C., and G.C. Pimental, Evidence for solid carbon dioxide in the upper atmosphere of Mars, *Science*, **167**, 47-49, 1970.

Jaquin F., P. Gierasch, and R. Kahn, The vertical structure of limb hazes in the martian atmosphere, *Icarus, 68,* 442–461, 1986.

Montmessin, F., P. Rannou, and M. Cabane, New insights into Mars dust distribution and water-ice cloud microphysics, *J. Geophys. Res.*, **107**, 10.1029/2001JE001520, 2002.

Schofield, J.T. et al., The Mars Pathfinder Atmospheric Structure Investigation/Meteorology Experiment (ASI/MET), *Science*, **278**, 1752-1758, 1997.

Smith, P.H. et al., Results from the Mars Pathfinder Camera, *Science*, **278**, 1758-1765, 1997.

Smith, M.D., TES Limb-Geometry Observations of Aerosols", *Proceedings of the Sixth International Conference on Mars*, Pasadena, CA, July 2003.

Whitney B. A., M. J. Wolff, and R. T. Clancy, Monte carlo radiative transfer models for Mars, *Proceedings of the Fifth International Conference on Mars*, Pasadena, CA, July 10-14, 1999.