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Climatology of the Mars Upper Atmosphere from Accelerometer Experiment Measurements

G.M. Keating (1), S.W. Bougher (2), J.M. Forbes (3), M.E. Theriot (1), and R.H. Tolson (4)

(1) George Washington University, Newport News, VA, United States (gerald.m.keating@nasa.gov, +1 757 874-5648), (2) University of Michigan, Ann Arbor, MI, United States, (3) University of Colorado, Boulder, CO, United States, (4) National Institute of Aerospace, Hampton, VA, United States

Accelerometer experiment measurements have been made on 3 spacecraft orbiting Mars to determine the global character of the Mars thermosphere and exosphere. Atmospheric densities can be determined from Newton's Second Law and from the definition of aerodynamic coefficients:

$\rho_D = (2\mathrm{m}\ \mathrm{a}_D) / (\mathrm{A}\ \mathrm{v}^2\ \mathrm{C}_D)$, [1]

where ρ_D=atmospheric density, m=spacecraft mass, a_D=acceleration due to atmospheric drag, A= aerodynamic reference area, v= spacecraft velocity relative to atmosphere, and C_D = aerodynamic force coefficient along effective velocity vector. Aerodynamic properties were calculated with Direct Simulation Monte Carlo (DSMC) and free molecular flow codes. Momentum accommodation coefficients were assumed to be unity. Then both free molecular flow and continuum regimes were taken into account. The measured acceleration (a_m) is composed of a number of terms given by:

$\mathrm{a}_m = \mathrm{a}_b + \mathrm{a}_D + \mathrm{a}_g + \mathrm{a}_{ACS} + \omega \times (\omega \times \mathrm{r}) + (\mathrm{d}\omega/\mathrm{dt}) \times \mathrm{r}$, [2]

where the terms are acceleration due to the instrument bias, aerodynamic forces, gravity gradient, attitude control system thruster activity, and angular motion of the accelerometer about the center of mass (2 terms). The instrument bias was determined from comparison of the accelerometer measurement above the atmosphere to that within the atmosphere. Angular motion contributions to the acceleration were removed using the rate gyro data that were received at 1 second averaged values. The inertial measurement unit (IMU) is composed of accelerometers and the rate gyro. The motion about all three spacecraft axes are coupled through the onboard momentum supplied by reaction wheels. The orientation of the spacecraft is obtained from the orbital ephemerides and quaternions, also averaged to 1 second samples. The most difficult acceleration to remove is caused by thruster firing. When averaging is done over multiple orbits this uncertainty is reduced. The data used in these analyses are at least 39 second means to remove noise and high order fluctuations so that climatology can be established. In many cases multiple orbits are averaged to study the climatology.

The accelerometer measurements are obtained on both inbound and outbound trajectories. The atmospheric drag near periapsis over multiple orbits tends to circularize the orbit and decrease the altitude of apoapsis. The near polar orbits precess resulting in a periapsis near the pole precessing towards the equator. This results in measurements over a wide range of latitudes. Since accelerometer measurements are obtained on both the inbound and outbound trajectories the vertical structure of the atmosphere can also be measured. From vertical structure, estimates can be made of scale height and temperature of the atmosphere. The mean molecular weight which decreases with increasing altitude can be estimated from Bougher's Mars Thermosphere Global Circulation Model (MTGCM). The orbits of these three spacecraft are nearly sun-synchronous with near equatorial measurements near 0300 and 1500 local solar time. These are near the times of minimum and maximum thermospheric temperature respectively.

The three orbiting spacecraft where accelerometer measurements have been obtained have a combined total of over 3000 vertical structures from Mars Global Surveyor, Mars Odyssey, and Mars Reconnaissance Orbiter. Several vertical structure measurements have been obtained by entry spacecraft.

Studies from the three spacecraft show variations with latitude, season, dust storms, tidal waves, day to night, aphelion to perihelion, and solar activity. The measurements also show a stability of climatology when compared with MEX stellar occultation measurements the year before the Mars Reconnaissance Orbiter measurements. Correlations between inbound and outbound trajectories, which can cross the same latitude nearly a month apart, also show stability of climatology.

Planetary-scale tidal waves are observed from the thermospheric accelerometer measurements from all three spacecraft. Apparently the waves propagate up from the lower atmosphere and tend to move eastward as the sun moves to the west. From the near sun-synchronous orbits of the three spacecraft, wave 2 and wave 3 structures with amplitudes from max to min near a factor of 2 are clearly evident. Comparison of MGS wave 2 dayside and MRO wave 2 nightside give evidence of a phase change of 90º longitude between day and night. The wave 2 extends to 70º latitude contrary to a Kelvin wave effect. Wave 3 appears to be further east near the equator than at higher latitudes. This is in accord with Forbes (2002). However, the weakest portion of the wave appears to be near the equator contrary to a Kelvin wave. Additional studies need to be performed concerning the origin of these tidal waves.

Studies have been performed concerning the nature of temperature variations at low and high latitudes. Within 40º of the equator, temperature variations are fairly uniform with temperature rising with altitude as is expected for a thermosphere. Averaging the results within 40º of the equator, the temperature rises asymptotically approaching some constant value above 160km that is apparently the value of the exospheric temperature. The results are compared with Bougher's MTGCM. On the nightside, the vertical structure appears to be in accord with the MTGCM with exospheric temperatures near 135 Kelvin. However, on the dayside, temperatures are cooler than the MTGCM. Dayside exospheric temperatures observed to be near 200 Kelvin may indicate less atmospheric escape than the MTGCM temperatures would predict. Exospheric temperatures detected by Forbes et al., (2008), when MGS was near 390km and periapsis was near 50º South give similar results.

We have discovered winter polar warming in the lower thermosphere from the accelerometer measurements. Near the North winter pole at 100km we discovered temperatures sharply increasing with latitude from 75º North to 87º North by 85 Kelvin contrary to an atmosphere in radiative equilibrium. Apparently meridional flow from the summer to winter hemisphere results in strong adiabatic heating near the winter pole causing the warming. This effect is stronger near the winter North Pole than near the winter South Pole apparently due to the planet being near perihelion at North Pole winter but near aphelion at South Pole winter. The stronger solar input apparently results in stronger meridional flow from summer to winter and stronger adiabatic heating. These results are in general accord with the MTGCM. We also find higher densities in winter at low and mid latitudes than in summer. The dynamical processes of meridional flow from summer to winter that generates adiabatic heating in the winter hemisphere may also change the density. Similar results are obtained with the MTGCM.