SOLAR FLUX VARIABILITY AND MARS' THERMOSPHERE DENSITIES DERIVED FROM ORBITAL TRACKING DATA

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Introduction:

In this paper, daily neutral density values at 390 km in the thermosphere of Mars are obtained through analysis of Mars Global Surveyor (MGS) orbital tracking data, and are used to elucidate the response of Mars' thermosphere to long- and short-term variations of solar flux during 1 January – 31 December, 2003. Comparisons are made with identical analyses of contemporaneous daily densities at 420 km obtained from accelerometer measurements on the earth-orbiting CHAMP (CHAllenging Minisatellite Payload) satellite. The Mars data are also examined for the possible effects of coronal mass ejections enveloping the planet, especially during the October 29 – November 1, 2003 "superstorms" when Earth and Mars were nearly in opposition.

A recent study by Withers and Mendillo (2005) demonstrates the response of peak (ca. 140 km) electron densities in the martian ionosphere to day-to-day changes in solar flux due to solar rotation. However, little is know about the dependence of Mars' thermosphere neutral densities or temperatures on solar flux. Estimates of exospheric temperatures have been obtained from plasma scale heights measured by radio occultations, airglow scale heights, and entry probe and orbiter measurements, as well as estimates from thermosphere general circulation models (see summary by Keating and Bougher, 1992). These data suggest an exospheric temperature response to long-term changes in solar flux significantly larger than for Venus. Densities derived from precise orbit determination of the MGS satellite by Bruinsma and Lemoine (2002), covering the period February 1999 – September 2000, also revealed evidence for month-to-month changes in density connected with solar activity. The MGS drag data presented here for 2003 are the first observations that illustrate the response of Mars' neutral thermosphere to the quasi-27-day periodicity of EUV fluxes emanating from the Sun.

The response of Mars' thermosphere to changes in solar flux is relevant to the study of the upper atmospheres of both Earth and Venus. As noted by Keating and Bougher (1992), exospheric temperatures on Venus are much smaller than those on Earth, and moreover, the response of Venus' thermosphere to solar cycle and 27-day solar flux variations is much weaker than for Earth. Although uncertainties remain concerning heating efficiency and the possible role of eddy diffusion, they conclude that CO_2 cooling is the main mechanism that regulates Venus' thermosphere response to variability in solar EUV radiation. Since the cooling rate is sensitive to the excitation of CO_2 by collisions with atomic oxygen, the $[O]/[CO_2]$ ratio and the rate of the O-CO_2 reaction are critical parameters in determining the efficiency of this cooling mechanism. On Earth, solar radiative heating in the thermosphere is largely balanced by conduction, although a doubling of CO_2 (i.e., in connection with anthropogenic effects) can lead to significant cooling of the thermosphere (e.g., Roble and Dickinson, 1989). (Note: Studies of long-term changes in satellite drag suggest that such effects are already occurring, e.g., Emmert et al., 2004; Keating et al., 2000). Although $[O]/[CO_2]$ ratios are about a factor of 10 less than on Venus, on Mars CO_2 cooling still serves to maintain low exospheric temperatures in comparison to Earth. Thus, Mars is an "intermediate" case between Earth and Venus, where both conduction and cooling are potentially important. The ability to simultaneously simulate the upper atmosphere responses of Earth, Mars and Venus (cf. Bougher and Roble, 1991; Bougher et al., 1999) with inter-consistent and self-consistent $[O]/[CO_2]$ ratios, eddy diffusivities, heating efficiencies and O-CO_2 reaction rates, will lead to a much improved understanding of all these planetary atmospheres, and in particular will better enable us to model anthropogenic effects on Earth's upper atmosphere. The present data set will provide an important constraint on first-principles modeling activities that attempt to model the dependence of Mars upper atmosphere neutral densities on solar EUV flux.

Density Determinations:

During 2003, MGS was in a near-circular, mapping orbit with a periapsis altitude near 370 km and an apoapsis altitude near 430 km. Densities were derived from precise orbit determination of the MGS satellite using the same techniques used by Bruinsma and Lemoine (2002) in their analysis of MGS data covering the period February 1999 – September 2000. Briefly, The MGS tracking data were processed using the GEODYN orbit determination software at the Goddard Space Flight Center. The tracking data were processed in daily arcs. The adjusted parameters in each arc include the spacecraft state, a drag coefficient/scale factor (FD) per day, a solar radiation pressure reflectivity coefficient (FS) per arc, ambiguity biases for the range data, and frequency biases for the one-way Doppler data when these data are present. The modeling used the IAU2000 reference system and a static gravity model derived from three years of MGS data, MGM1041D. The daily mean drag factors were converted to daily mean densities and normalized to a constant altitude of 390 km using the DTM-Mars model (Bruinsma and Lemoine, 2002).

Density values were obtained from the CHAMP accelerometer measurements in the manner described by Bruinsma and Biancale (2003) and Bruinsma et al. (2004), and are normalized to a constant altitude of 420 km using the DTM2000 empirical model (Bruinsma and Thullier, 2003).

Solar Flux Proxy:

As for Earth, the solar fluxes responsible for heating of Mars' upper atmosphere are in the extreme ultraviolet (EUV) range of the solar spectrum. It is common to utilize the 10.7 cm radio flux (designated F10.7) as a proxy for EUV, as both emissions are thought to originate in the Sun's corona, and therefore to be highly correlated in time. In the present analysis, we also utilize the 10.7 cm daily radio flux as a proxy for EUV variability, with the view that we will later investigate use of a better proxy, such as E10.7 (Tobiska et al., 2000) at a later time.

Even using F10.7, some assumptions must be made to extrapolate fluxes measured at Earth to those expected to be (or have been) received at Mars. Corrections must be made for the varying distances of Earth and Mars from the Sun, and for variations in the Earth-Sun-Mars angle as the planets orbit around the Sun (See Figure 1). With respect to the latter, at Mars the flux from the Sun is shifted in time from that observed at Earth by an amount determined by the Earth-Sun-Mars angle, and the rotation period of the Sun (assumed to be 27 days). Note that the above procedure also assumes that the integrated flux from this hemisphere of the Sun does not change during this time interval. Hereafter, we refer to these F10.7 values extrapolated to Mars as "adjusted F10.7".

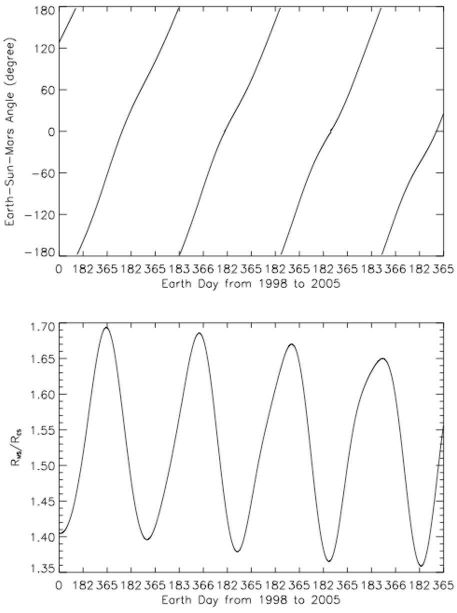

Figure 1. Earth-Sun-Mars angle (top) and ratio of Mars/Earth distances to the Sun (bottom). The Earth-Sun-Mars angle is assumed negative when Earth trails Mars (i.e., prior to opposition), and positive when Mars trails Earth (i.e., after opposition).

Results:

Solar flux variability of Mars' thermosphere. In our analyses we separate short-term and long-term variations in density and F10.7 in the following manner. First, 27-day running means, slipped once per day, are applied to the time series, and then a set of residuals is determined by subtracting the raw data from the running mean. Then, in order to reduce noise in the density data and to isolate the variability associated with solar rotation, and to help suppress geomagnetic variations in the CHAMP densities, a 5-day running mean is applied to the residuals. In the following, we refer to these quantities as the '27-day means', and the 'mean residuals', respectively.

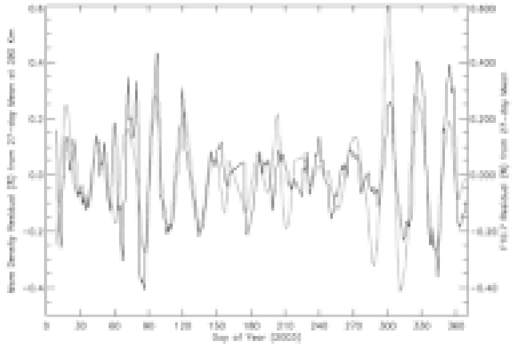

Figure 2. Mean residuals (percent with respect to 27-day running mean) of Mars thermosphere density at 390 km and adjusted F10.7 during 2003.

Figure 2 illustrates the mean residuals, expressed in percent differences from the 27-day means, for the MGS densities and F10.7 index. Note the very high correlation between densities and F10.7, especially when a strong quasi-27-day periodicity is present. In Figure 3, we provide a scatter plot of the data in Figure 2, and a least-squares fit to the data to quantify the change in density with respect to change in adjusted F10.7. We find that the percent change in density corresponds, on average, to 0.63 times the percent change in adjusted F10.7 (correlation coefficient = 0.66). This is the first demonstration of density variations in Mars thermosphere associated with the rotation of the Sun.

Figure 4 illustrates the 27-day running means of Mars thermosphere density at 390 km and adjusted F10.7. The correlation here is very good, except during the period from 1 July – 1 October, 2003. A dust storm occurred in Mars' Northern hemisphere during July, 2003, and the anticipated inflation of the atmosphere due to enhanced solar radiation absorption by dust in the lower atmosphere may account in part for the departure between the two curves in Figure 4 during July, 2003. However, by August 2003, the dust storm had abated, and it is unlikely that any residual effects remained in thermosphere densities after about 1 August 2003.

Solar flux variability of Earth's thermosphere. We now turn to a similar analysis of the daily mean CHAMP data covering 2003. Figure 5 contains the same information as Figure 2, except for CHAMP daily mean densities at 420 km, and F10.7 at Earth. As expected, the correlation between densities in Earth's thermosphere and solar flux changes due to the Sun's rotation is also very good. Note that the solar flux variations seen at Earth are different from those thought to be seen at Mars, due to the corrections applied to F10.7 for Mars (cf. Figure 1).

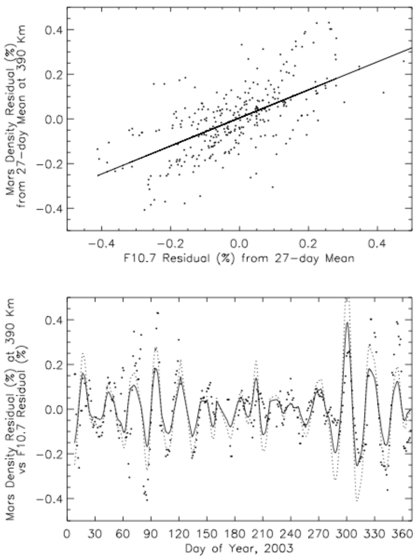

Figure 3. Top: Scatter plot of data in Figure 2. Bottom: Data in Figure 2 (dots for density, dashed for adjusted F10.7), and linear regression fit of density residual with respect to adjusted F10.7 residual (solid line).

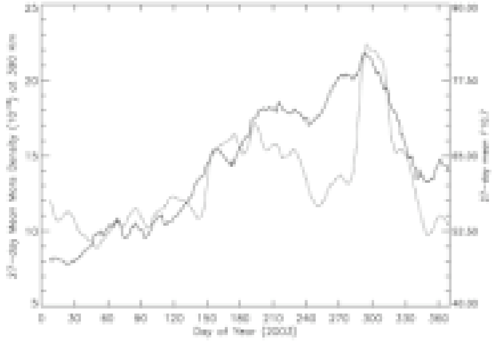

Figure 4. 27-day running means of Mars' thermosphere density at 390 km and adjusted F10.7.

Figure 6 provides a scatter plot of the data in Figure 5, and a least-squares fit to the data to quantify the change in density with respect to change in adjusted F10.7. This is the same depiction that was provided for the Mars data in Figure 3. The percent change in density in Earth's atmosphere at 420 km corresponds, on average, to 0.96 times the percent change in F10.7 (correlation coefficient = 0.84). This can be compared to the value of 0.63 in Mars' thermosphere at 390 km, with respect to changes in adjusted F10.7 there. Thus, the solar flux response appears to be larger in Earth's atmosphere, which is anticipated. However, some correction may need to be applied to account for the different mean density and pressure levels of the MGS and CHAMP satellites, in order to make this comparison more meaningful. Another approach would be to calculate the exospheric temperature variations that the density variations correspond to, in order to perform a more equitable comparison. These issues are currently under study.

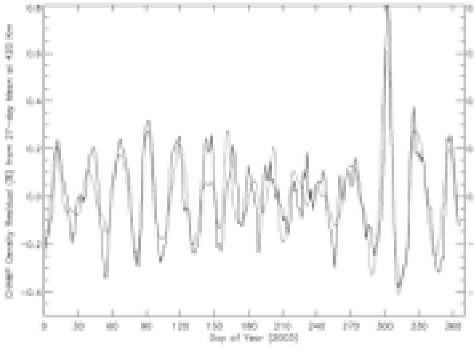

Figure 5. Same as Figure 2, except for CHAMP daily mean densities at 420 km, and F10.7 at Earth.

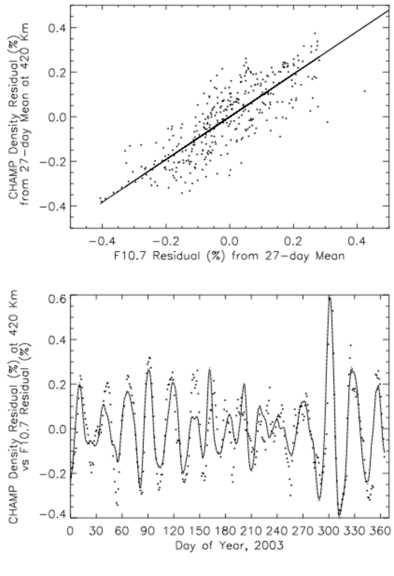

Figure 6. Same as Figure 3, except for CHAMP daily mean densities at 420 km, and F10.7 at Earth. The fitting curve and the F10.7 curve are almost indistinguishable in the bottom panel of this figure.

Figure 7 illustrates the 27-day running means of Earth's thermosphere density at 420 km and F10.7. The overall correlation is quite good, except that the differences between the curves prior to day 240 require explanation. These differences may be due to the precession of the CHAMP orbit through local time and season during this period. In addition, some differences may be reduced when a better proxy for EUV flux (i.e., E10.7) is used instead of the 10.7 cm radio flux.

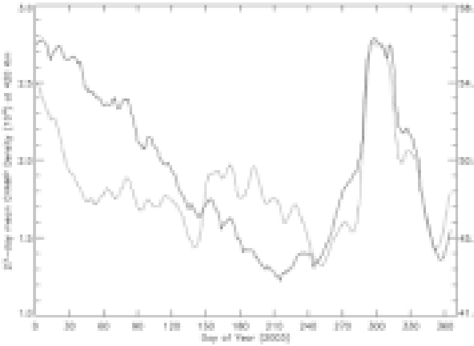

Figure 7. Same as Figure 4, except for CHAMP daily mean densities at 420 km, and F10.7 at Earth.

Effects of CMEs. Both data sets were analyzed for the potential effects of coronal mass ejections and solar wind coupling on the thermosphere densities. Running 11-day means were applied to the data sets to significantly suppress the 27-day rotation effect, and the residuals from this running mean were examined for possible connections with the planetary (terrestial) geomagnetic daily index, Ap. As expected, the residuals on Earth were highly correlated with Ap. No evidence for any connection between CMEs and Mars thermosphere density were found. In particular, we examined the period corresponding to the October 29 – November 1 superstorms observed on Earth, and when Earth and Mars were nearly in opposition (The Earth-Sun-Mars angle was about 22^{o}). No visible effect was observed. This is not surprising, as the strong solar wind-magnetosphere-ionosphere-thermosphere connection on Earth is highly dependent on the presence of a planetary magnetic field, which is absent on present-day Mars. However, this result does not preclude the possibility of local effects occurring in the vicinity of magnetic anomalies on Mars, whose influences on the solar wind may be present at certain locations.

Conclusions and Future Efforts:

The primary result to emerge from the present study is that Mars' thermosphere exhibits a well-defined and strong relationship with solar fluxes modulated by the rotation of the Sun (i.e., '27-day variation'), similar to that on Earth except at about two-thirds the magnitude. This data set should provide a valuable constraint on thermosphere GCMs that attempt to self-consistently and inter-consistently model solar flux influences on the thermospheres of Earth, Mars and Venus, and to disentangle the relative roles of CO_2 cooling, thermal conduction, heating efficiency and eddy diffusion in the determining the thermal and density structures of these planets.

In the future, we intend to extend the MGS drag analysis to include the period 1999-2005 in order to better characterize the long-term response to solar activity, and to better establish the relationship between thermosphere density and dust levels in the lower atmosphere. We also plan to investigate whether other proxies for solar EUV fluxes (e.g., E10.7) better define relationships with the thermosphere densities of Earth and Mars.

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