Solar Rotation Effects on the Thermospheres of Mars and Earth

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The responses of Earth's and Mars' thermospheres to the quasi-periodic (27-day) variation of solar flux due to solar rotation were measured contemporaneously, revealing that this response is twice as large for Earth as for Mars. Per typical 20-unit change in 10.7-centimeter radio flux (used as a proxy for extreme ultraviolet flux) reaching each planet, we found temperature changes of 42.0 ± 8.0 kelvin and 19.2 ± 3.6 kelvin for Earth and Mars, respectively. Existing data for Venus indicate values of 3.6 ± 0.6 kelvin. Our observational result constrains comparative planetary thermosphere simulations and may help resolve existing uncertainties in thermal balance processes, particularly CO_2 cooling.

The Sun's atmosphere rotates with a period of about 25 days near the equator and 35 days near the poles. This differential rotation causes magnetic field lines to twist, resulting in the formation of active regions that release enhanced solar energy in various forms, including the extreme ultraviolet (EUV) radiation responsible for heating the hot outermost region of a planetary upper atmosphere, the thermosphere [circa (ca.) ≥ 100 km for Earth, Mars, and Venus]. The rotation of solar active regions produces periodicities in EUV flux emanating from the Sun and subsequently absorbed by planetary thermospheres. Although variations in Mars' ionosphere electron densities due to day-to-day changes in solar flux (*1*) and even solar flares (*2*) have recently been discovered, relatively little is known about the response of Mars' neutral thermosphere to short-term solar flux variations.

Planetary thermosphere temperatures are determined by the efficiency with which absorbed radiation is converted to heat, the rates of molecular and eddy heat conduction, and the rate of radiative cooling (*3*), particularly by CO_2 at 15 μm (*4*). Excitation of the CO_2 molecule that leads to the 15-μm emission occurs primarily through collisions with atomic oxygen (O). The CO_2 cooling rate therefore increases with the O/CO_2 mixing ratio, which is roughly 0.0001, 0.1, and 1.0 at 150-km altitude in the thermospheres of Earth (*5*), Mars (*4*), and Venus (*4*), respectively. Despite the low mixing ratio for Earth, a doubling of CO_2 is calculated (*6*) to result in a 50 K reduction in exospheric temperature, that part of the thermosphere temperature profile that is constant with height (above about 250-km altitude for Earth and 150-km altitude for Mars and Venus). CO_2 cooling is a complex process, because local thermodynamic equilibrium (LTE) does not generally apply. Major uncertainties in the cooling process remain, including the rate of CO_2 excitation by O, k_E.

Laboratory measurements for k_E are not available under planetary thermosphere conditions, so indirect means have been used to estimate k_E (*4*). Constraining numerical simulations of two or more planetary thermospheres to observational data is a recognized approach for reducing uncertainties in certain common parameters such as k_E (*4*). This methodology requires measuring the responses of the planetary thermospheres to changes in solar forcing. It is our goal to establish the response of Mars' neutral thermosphere to the quasi–27-day periodicity of EUV fluxes emanating from the Sun and to compare it with Earth's thermosphere response during the same time interval. Comparisons are also made with results previously reported for Venus (*4*).

The data consist of daily Mars neutral mass densities at 390 km inferred from precise orbit determination of Mars Global Surveyor (MGS) during 1 January to 31 December 2003. In this method, tracking data are used to measure changes in orbital period, and models for radiation pressure, gravity field, and satellite drag coefficient are used to isolate atmospheric density and its drag effect on the orbit. Application of the technique to MGS is described in detail in a study (*7*) devoted to development of an empirical drag temperature model (DTM) of Mars' thermosphere, DTM-Mars. DTM-Mars is used to normalize density values to a constant altitude of 390 km. Daily average density values at Earth were obtained from challenging minisatellite payload (CHAMP) satellite accelerometer measurements (*8*, *9*) that were averaged along the orbit and normalized to a constant altitude of 420 km by using the DTM2000 empirical model (*10*) for the terrestrial thermosphere. The 2003 time period was chosen because of the large quasi–27-day variations in solar flux, the contemporaneous availability of MGS and CHAMP data, and the fact that Mars was relatively close to opposition (see below).

To maintain uniformity with other similar analyses for planetary thermospheres, particularly those for Venus (*4*), we use the 10.7-cm radio flux (designated F10.7) as a proxy for EUV variability. Because F10.7 is measured at Earth, some assumptions must be made to estimate solar fluxes received at Mars. Corrections must be made for the varying distances of Earth and Mars from the Sun and for the variations in the Earth-Sun-Mars angle as the planets orbit around the Sun. "Opposition" is when the Earth-Sun-Mars angle is 0°, which occurred on 28 August 2003. During 2003, the ratio of Mars' distance from the Sun to that of Earth decreased from 1.64 to 1.50, whereas the Earth-Sun-Mars angle changed from –101.4° (Earth trailing Mars) to +48.5° (Earth leading Mars). The flux from the Sun varies as the inverse of distance squared. We assume that the solar flux at Mars 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). This assumes that the integrated flux from the Earth-facing hemisphere of the Sun does not change during this time interval, although it is known that active regions of the Sun evolve with time. Possible implications of this assumption are noted below. Hereafter, it is understood that F10.7 values quoted in

Table 1. Thermosphere responses of Earth, Mars, and Venus to quasi–27-day variations in solar flux from the Sun. $\Delta\rho$ is the percent change in thermosphere density (390-km altitude for Mars and 420-km altitude for Earth), ΔF is the absolute change in 10.7-cm solar radio flux (F10.7) received at the planet, r is the linear correlation coefficient, and ΔT is the change in exospheric temperature (K).

	$a_1 = \Delta\rho/\Delta F$	r	$\Delta T/\Delta F$	$\Delta T/\Delta F$ ratio to Earth
Earth 2003 (all)	0.63	0.80	1.58	1.00
Days 75–150	0.99	0.91	2.48	1.00
Days 270–365	0.68	0.90	1.70	1.00
Mars 2003 (all)	0.84	0.61	0.47	0.30
Days 75–150	2.05	0.87	1.15	0.46
Days 270–365	1.39	0.88	0.78	0.46
Venus			0.15–0.21	0.062–0.12

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connection with Mars were adjusted to Mars' orbit in the above manner.

In order to isolate the quasi–27-day rotation effect, we processed the time series of daily densities and F10.7 fluxes in the following manner. For the CHAMP data, data points occurring on days when the daily global magnetic index, A_p (*11*), exceeded 50 were first removed (*12*). Then 27-day means, shifted forward one day at a time, were applied to each time series, and a set of residuals was determined by subtracting the raw data from the 27-day running means. Lastly, in order to reduce noise in the density data, to isolate the variability associated with solar rotation, and to diminish possible geomagnetic effects in the CHAMP data, we applied a 5-day running mean to the residuals. Below we refer to the latter as "mean residuals." Upper-limit uncertainty estimates for the mean residuals, which include both experimental and geophysical effects, were determined empirically from the noise level of the data. Root mean square (RMS) noise levels were calculated by using the density residuals that remained after filtering out variations with time scales greater than about 10 days, i.e., those variations primarily associated with solar rotation effects. RMS noise levels less than 1% for both Earth and Mars were generally found except after day 270, when Mars RMS levels were near 2%. Uncertainties of order ±RMS are implied. As shown below, the observed percent density responses are sufficiently large in comparison to support confidence in our results and conclusions. We now provide our numerical results, which are all tabulated in Table 1.

The mean density residuals (expressed in percent with respect to the 27-day mean) at Mars and Earth were compared with their corresponding F10.7 mean residuals (Figs. 1 and 2, respectively). Note the close relationship between variations in density and F10.7, especially when a strong quasi–27-day periodicity is present. Also shown in each figure are two least squares linear fits to the data points of the form $\Delta\rho = a_0 + a_1\Delta F$, where $\Delta\rho$ is the percent change in density with respect to mean density (a_0) over the interval, ΔF is the absolute change in F10.7 flux at the planet, and $a_1 = \Delta\rho/\Delta F$. In one case the fit is performed over the whole year, and in the other the fit is applied over 27-day intervals that are sequentially shifted forward 1 day at a time. When applied over the whole year for Mars, a value of $a_1 = 0.84$ is obtained with a linear correlation coefficient of $r = 0.61$. For Earth we find values of $a_1 = 0.63$ and $r = 0.80$. The lower correlation for Mars compared with Earth may be due, in part, to assumptions made in inferring solar fluxes at Mars from those measured at Earth. However, the running 27-day fits provide marked improvements in reproducing the observations during two time periods of enhanced flux variability (days 75 to 150 and 270 to 365) and represent a better measure of the planetary response to short-term solar flux variability. Correlation coefficients for both Earth and Mars during these periods (denoted intervals I and II in the figures) attain correlation coefficients near 0.90, with values of a_1 equaling 0.99 and 0.68 for Earth and 2.05 and 1.39 for Mars.

Comparing the above coefficients, it would appear that Mars's thermosphere is more responsive to solar flux changes than that of Earth. However, these results do not correspond to the same mean density levels in the two atmospheres. Some normalization of these results is required. Because the thermosphere temperatures in both planetary atmospheres are constant with height above 250 km, we can use an empirical model to relate exospheric temperature changes to density changes in each atmosphere. For this purpose, we used the DTM2000 model for Earth and the DTM-Mars model for Mars and thus obtained the change in exospheric temperature

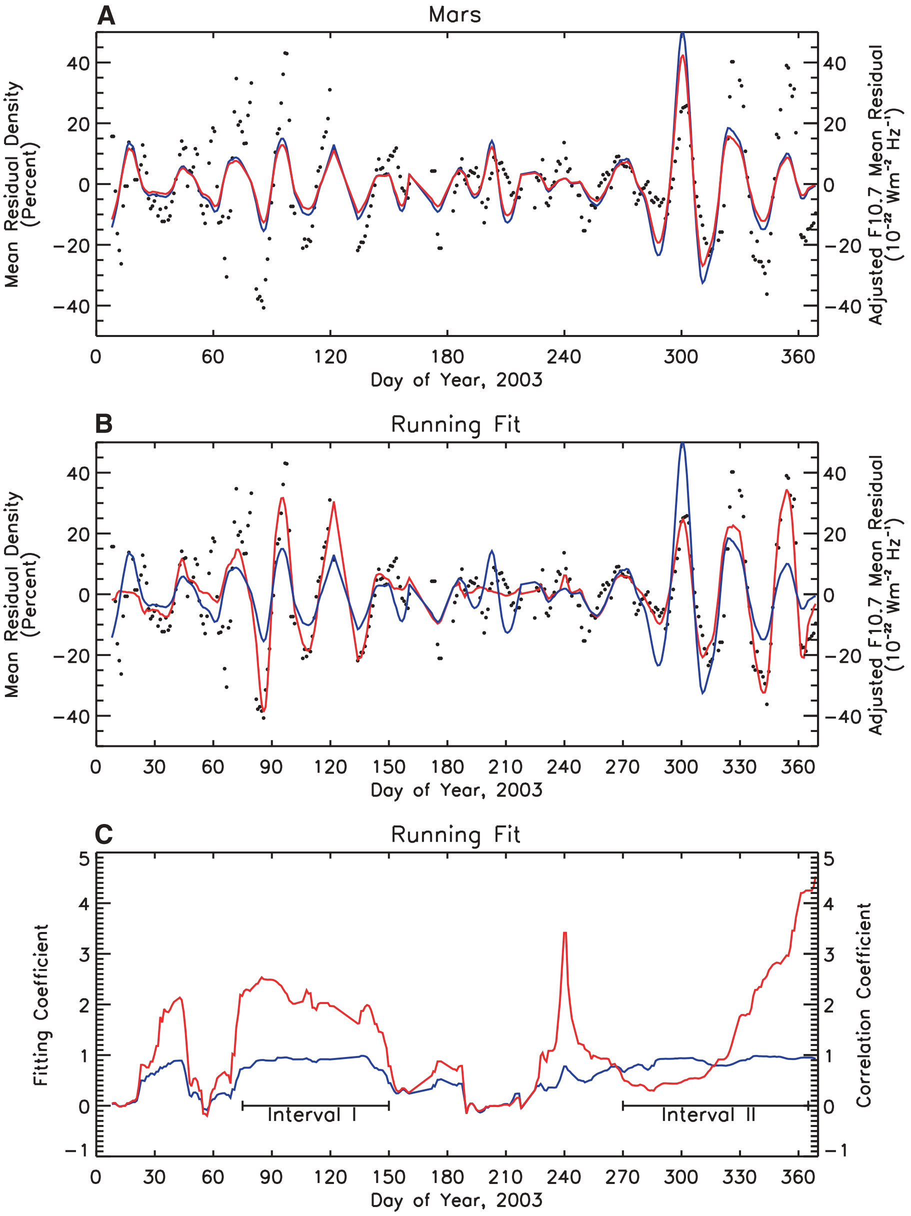

Fig. 1. (**A**) MGS mean residual densities (percent) at 390 km (dots), F10.7 flux adjusted to Mars' orbit (blue line), and least squares fit of residual densities with respect to adjusted F10.7 (red line) for Earth calendar year 2003. (**B**) Same as (A), except with 27-day fit slipped forward once per day. (**C**) Fitting coefficient a_1 (red line) and correlation coefficient r (blue line) versus time for moving 27-day fit. Intervals I and II denote days 75 to 150 and 270 to 365, respectively, when density and F10.7 are most highly correlated (r close to 1.0).

per unit flux received at each planet, $\Delta T/\Delta F$ (Table 1). Also included in Table 1 is the range of values of $\Delta T/\Delta F$ from 0.15 to 0.21 inferred for Venus from analyses of Pioneer Venus neutral mass spectrometer and drag analyses (*4*, *13–15*) and the results for Mars and Venus normalized to those of Earth. Focusing on the two intervals of enhanced solar flux variability, we find that Mars' thermosphere is about 50% as responsive to changes in solar flux, due to rotation of the Sun compared with Earth, but on the order of four to seven times more responsive than Venus. Note that these results are independent of the distance of the planet from the Sun, because we have used absolute changes in solar flux received at the planet in our analysis. Rather, the range of responses is determined by the different mixing O/CO_2 mixing ratios and the absolute concentrations and distributions of CO_2 in these planetary thermospheres (*4*).

When interpreting the 27-day effect in Earth's thermosphere, one must be cautious about similar periodicities being introduced in connection with high-speed solar wind streams interacting with the magnetosphere and their subsequent heating effects in the thermosphere. High-speed streams originate in solar coronal holes that also rotate with the Sun. To investigate this possibility, we verified that the mean residual time series for daily mean K_p (*16*) was uncorrelated (r = 0.17) with the CHAMP density residuals. Further, linear regression analyses of CHAMP densities were performed that included both F10.7 and K_p terms, resulting in an F10.7 coefficient that differed insignificantly from those a_1 values tabulated in Table 1. We conclude that our results for CHAMP represent the solar flux response unaffected by any geomagnetic influence.

Our results should constrain numerical models that strive to simultaneously emulate solar flux influences on the thermospheres of Earth, Mars, and Venus in order to disentangle the relative effects of heating efficiency, CO_2 cooling, and thermal conduction on the thermal and density structures of these planets. Because cooling of Earth's thermosphere due to increases in CO_2 levels over the past 4 decades appears to be occurring (*17–19*), improved characterization of the CO_2 cooling process will help to understand and predict the fate of our own upper atmosphere to anthropogenic effects (*6*).

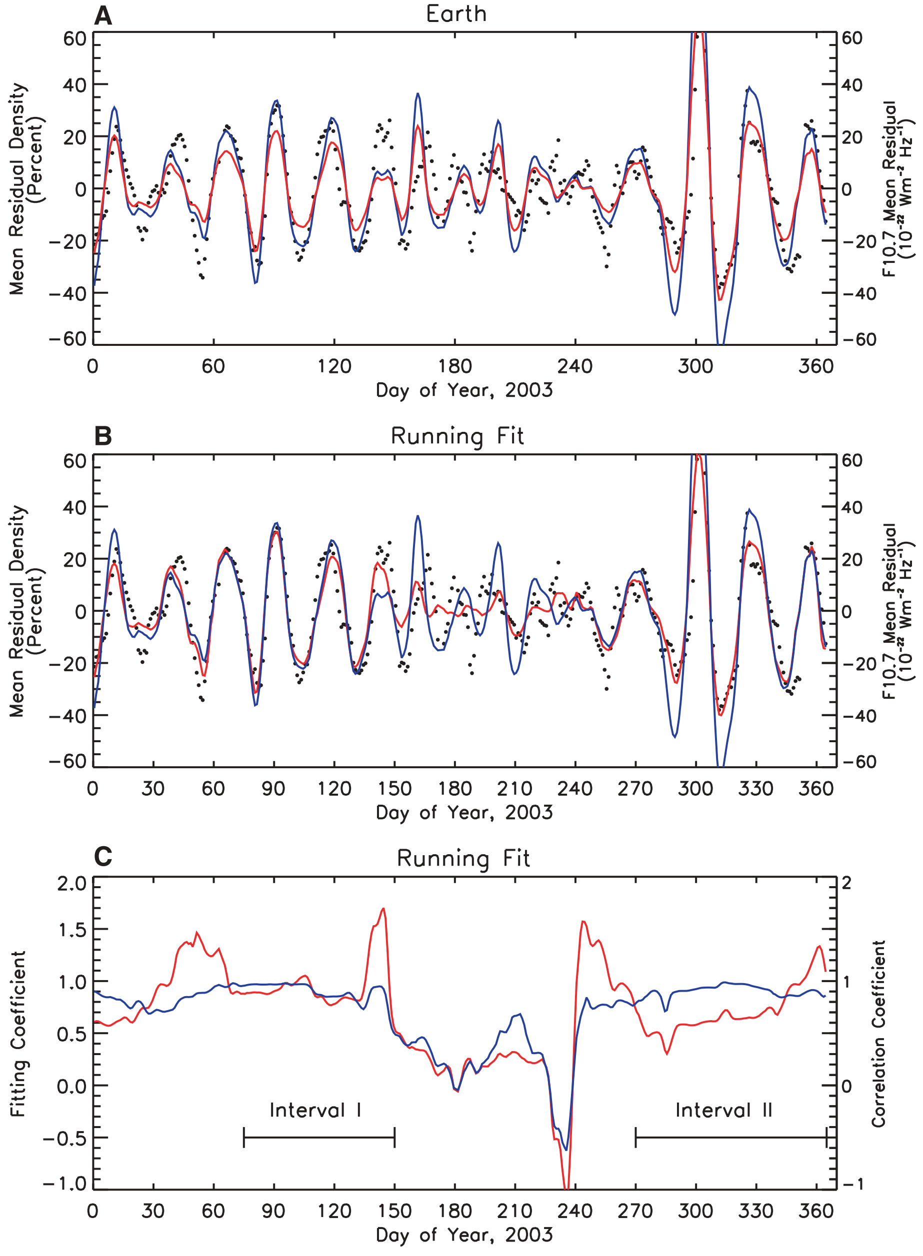

Fig. 2. (**A** to **C**) Same as Fig. 1, except for CHAMP densities at 420 km in Earth's atmosphere.

References and Notes

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