GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L01201, doi:10.1029/2007GL031904, 2008

Solar flux variability of Mars' exosphere densities and temperatures

Jeffrey M. Forbes,[1] Frank G. Lemoine,[2] Sean L. Bruinsma,[3] Michael D. Smith,[2]
and Xiaoli Zhang[1]

Received 5 September 2007; revised 31 October 2007; accepted 20 November 2007; published 10 January 2008.

[1] Using densities derived from precise orbit determination of the Mars Global Surveyor (MGS) spacecraft from 1999 to mid-2005, the response of Mars' exosphere to long-term solar change is established and compared to that of Earth and Venus. At Mars, exosphere temperatures (weighted towards high-latitude Southern Hemisphere daytime conditions) change only 36–50% as much as those at Earth as solar activity increases from solar minimum to solar maximum, whereas the response at Venus is one-fifth that at Mars. General circulation models suggest that this difference may be strongly influenced by adiabatic cooling associated with the thermosphere general circulation. However, other processes such as differences in CO_2 cooling rates may also be playing a role. **Citation:** Forbes, J. M., F. G. Lemoine, S. L. Bruinsma, M. D. Smith, and X. Zhang (2008), Solar flux variability of Mars' exosphere densities and temperatures, *Geophys. Res. Lett.*, *35*, L01201, doi:10.1029/2007GL031904.

1. Introduction

[2] From a comparative planetary perspective, the responses of the upper atmospheres of the terrestrial planets (i.e., Earth, Mars and Venus) to solar variability pose interesting challenges and opportunities. The relative importance of such processes as heating efficiency, radiative cooling, thermal conduction and dynamics must be considered [e.g., *Bougher et al.*, 2000]. These planetary atmospheres are sufficiently different, yet sufficiently alike, that their comparative study allows deeper understanding and insight to be achieved for each planet.

[3] Studies have established that the thermospheres of Venus and Mars are about 10% and 30–50% as responsive as Earth, respectively, in terms of exosphere temperature changes due to solar EUV variability associated with the ~27-day rotation of the Sun [*Forbes et al.*, 2006, 2007; *Keating and Bougher*, 1987, 1992]. These differences are thought to be primarily due to the increased importance of CO_2 cooling in damping the responses at these planets, as compared to Earth and to each other.

[4] In terms of long-term solar variability, Earth has benefited from many measurements from satellite-borne and ground-based instrumentation, as well as orbital analyses of satellites, over several solar cycles. These results are embodied in empirical models such as MSISE-90 [*Hedin*, 1991], DTM94 [*Berger et al.*, 1998] and NRLMSIS-00 [*Picone et al.*, 2002]. For Mars some sense of long-term change due to solar variability has been inferred from sparse and disparate data sets such as in-situ mass spectrometers, airglow, and plasma scale heights [e.g., see *Keating and Bougher*, 1987, 1992; *Bauer and Hantsch*, 1989; *Bauer*, 1999]. Some of these data, in particular the plasma scale heights, may underestimate the exosphere temperature response since the inferred temperatures may correspond to that part of the temperature profile lower in the thermosphere (ca. 130 km) than representative of the exosphere temperature (i.e, above 180–220 km during daytime at solar maximum [*Bougher et al.*, 1999]). The widely-quoted exosphere temperature response of Mars by *Stewart* [1987] is also strongly dependent on plasma scale height data. For Venus, information on solar cycle variability of exosphere temperature is available from Magellan and Pioneer Venus Orbiter measurements (see review by *Kasprzak et al.* [1997]).

[5] The objective of the present study is to establish the response of Mars' exosphere densities and temperatures to long-term solar change, and to compare Mars' exosphere response with that of Earth and Venus. Compared to previous studies, ours is distinguished by the length, quality and quantity of data employed, and the wide range of solar conditions over which the data are collected. Our work is also relevant to the calculation of Martian volatile escape rates, which are sensitive to variations in the density and temperature of Mars' exosphere.

2. Data

[6] The Mars density data consist of daily values inferred from precise orbit determination (POD) of the Mars Global Surveyor (MGS) spacecraft from 1 February 1999 – 7 July 2005. Each density value is determined from analysis of Deep Space Network (DSN) observations over processing arcs with lengths of 4–5 days, and normalized to a constant altitude of 390 km using the DTM-Mars empirical model [*Bruinsma and Lemoine*, 2002], which is based in part on almost 2 years of MGS drag data of the type presented here. The MGS satellite is in a 93.7°-inclination 1400-0200 LT sun-synchronous 370 × 437 km frozen orbit with periapsis confined to $-40°$ to $-60°$ latitude. The density values presented here therefore represent averages over all longitudes, and are strongly biased towards daytime Southern Hemisphere conditions. The POD technique is similar to that utilized by *Bruinsma and Lemoine* [2002] and in recent studies devoted to solar flux changes in density due to rotation of the Sun [*Forbes et al.*, 2006, 2007]. Briefly, we employed the MGM1041c gravity model [*Lemoine*, 2003], and took into account such processes as third-body gravity perturbations due to the Sun, planets, and satellites of Mars;

---

[1] Department of Aerospace Engineering Sciences, University of Colorado, Boulder, Colorado, USA.

[2] NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

[3] Department of Terrestrial and Planetary Geodesy, Centre Nationale D'Etudes Spatiales, Toulouse, France.

0094-8276/08/2007GL031904$05.00

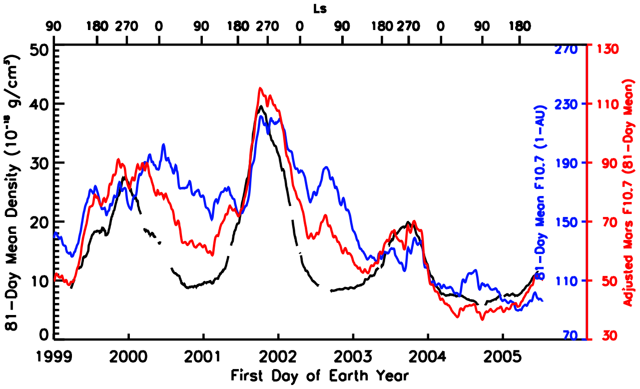

Figure 1. 81-day running mean Mars densities at 390 km (black), 10.7 cm solar flux at 1 AU (blue) and at Mars (red) vs Earth year (bottom x-axis) and L_s (top x-axis). Errors in the 81-day mean densities are estimated at 2% (RMS).

solar and planetary radiation pressure on the spacecraft; a detailed macromodel of the spacecraft; thruster firings; and changes in mass due to fuel consumption. We also used the observations to empirically infer corrections to the macromodel reflectivity parameters, the Mars k_2 Love number, and annual and semiannual variations in the gravity field due to condensation and sublimation processes in Mars atmosphere. Earth atmosphere, solid tide and ocean tidal loading corrections were also applied to the DSN tracking data. Uncertainties for the daily values are estimated at 17% (RMS), and are mainly due to tracking errors and solar radiation pressure modeling. Uncertainties in the 81-day mean values (see below) are therefore estimated at $17/\sqrt{81} \approx 2\%$ (RMS). A constant bias of up to 10% is also possible due to uncertainties in the assumed drag coefficient; however, this does not affect analyses and conclusions below, which are focused on rate of change of density and derived exosphere temperature with respect to solar flux.

3. Results

[7] Since we are primarily interested in solar flux changes over much longer than a solar rotation (~27 days), we concentrate on 81-day running mean values of all parameters, which will be understood in the following unless otherwise specified. Figure 1 illustrates daily values of density normalized to a constant altitude of 390 km versus time from 1 February 1999 through 7 July 2005. Also shown are F10.7 values at 1 AU and adjusted to Mars, which are used as proxies for solar EUV fluxes. Note that the F10.7 values at 1 AU cover a wide range, from about 90 solar flux units (sfu) to 230 sfu. The values at Mars are derived from the 1 AU fluxes taking into account variations in Mars' distance from the Sun, and differences in angular distance between the positions of Mars and Earth with respect to the Sun, assuming that the EUV-emitting active regions of the Sun do not evolve during this interval. This latter assumption can be important for day-to-day solar flux variations especially near conjunction, but has relatively small effects on the 81-day mean values.

[8] The density variations in Figure 1 are characterized very well (correlation coefficient R = 0.96) by a simple linear regression formula containing a linear term in F10.7 (at Mars) and a relatively small seasonal term in Ls, the longitude of the Sun with respect to the vernal equinox of Mars. In units of 10^{-18} cm^{-3},

$$\rho_{390} = 3.72 + 0.28\overline{F}_{10.7} - 4.5\cos(L_s - 72^\circ) \tag{1}$$

In order to compare the response of Mars' and Earth's thermospheres to changes in solar flux, it is necessary to convert to exosphere temperature (T_∞) using a model, in this case DTM-Mars. The change in the observed T_∞ with time, and the least-squares fit of the form:

$$T_\infty = 130.7 + 1.53\overline{F}_{10.7} - 13.5\cos(L_s - 85^\circ) \tag{2}$$

are illustrated in Figure 2. The correlation coefficient is 0.99. Also shown by the lower curve in Figure 2 is the 81-day and zonal-mean dust optical depth averaged between ±30° latitude measured in Mars' atmosphere [*Smith*, 2004], an index of dust content and related heating and expansion of Mars' atmosphere. During 2001 a planet-encircling dust storm occurred. Unfortunately, the rise in dust content occurs contemporaneously with a large increase in solar flux, and the two effects on exosphere temperature cannot be distinguished. We attempted several approaches to isolate any possible effect due to dust-related heating and atmospheric expansion, but no definitive results could be obtained. For instance, when looking at daily values of T_∞, F10.7 and dust optical depth, the added variability in F10.7 and T_∞ due to rotation of the Sun [*Forbes et al.*, 2006] again precluded definitive conclusions. Adding the dust index in the least-squares fit had little effect. We also excluded the dust storm period in deriving equation (2), and attempted to correlate the difference between the fit curve and the observed temperatures, and the dust index. Equation (2) did not change much, leading us to conclude that the dust storm did not perceptibly influence exosphere temperature or density.

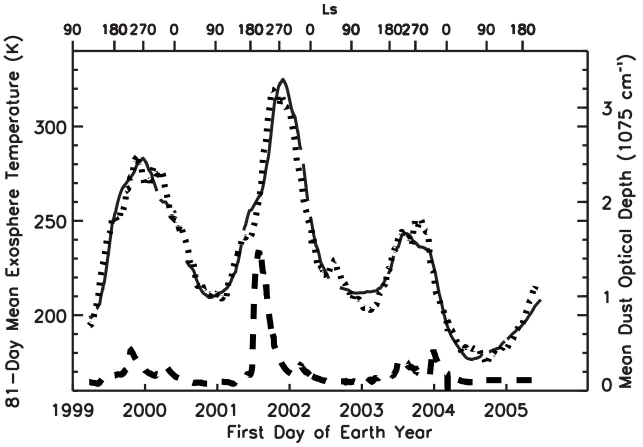

Figure 2. 81-day mean Mars exosphere temperature (solid), least-squares fit (dotted), and zonal mean optical depth averaged between ±30° latitude (dashed) vs. Earth year (bottom x-axis) and L_s (top x-axis). Errors in the 81-day mean exosphere temperatures are estimated at 2–3% (RMS).

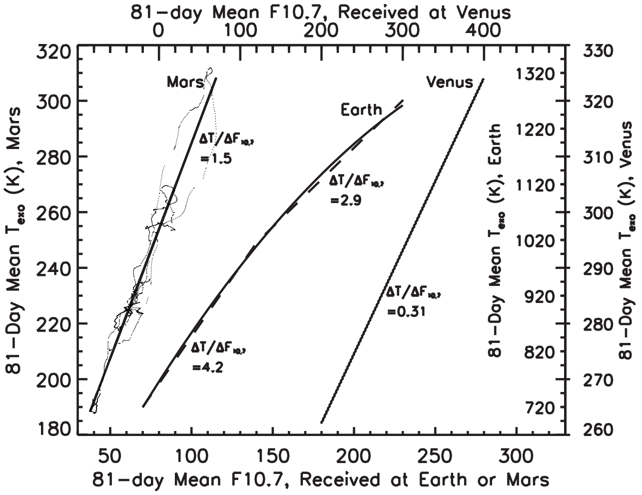

Figure 3. 81-day mean exosphere temperature at Mars, Earth and Venus versus 81-day mean 10.7 cm solar flux *received at the planet*. The Mars least-squares fit slope is $\Delta T/\Delta \overline{F}_{10.7} = 1.5$, whereas the MSISE-90 and NRLMSIS-00 models for Earth indicate a value of 4.2 at low to moderate levels of solar activity, and a value of 2.9 at higher levels of solar activity. For Venus a value of 0.31 is indicated [*Kasprzak et al.*, 1997].

[9] Figure 3 provides a comparison between the responses of the thermospheres of Earth, Mars and Venus to long-term solar variability. The line labeled "Mars" represents the solar flux term in equation (2), and the data points around it are the same as the data points in Figure 2, with the small seasonal (L_s) effect removed. The slope of the Mars line is $\Delta T/\Delta \overline{F}_{10.7} = 1.5$, which means that exosphere temperature changes by 1.5 K per solar flux unit (sfu) change received at the planet. For Venus, the value is 0.31 [*Kasprzak et al.*, 1997], about one-fifth that of Mars. The corresponding curve for Earth is also indicated, and is obtained from MSISE-90 [*Hedin*, 1991], which is a statistical representation based upon measurements from many satellites and also incoherent scatter radar data. Earth's response is not linear, and its slope varies from 2.9 at solar maximum to 4.2 at solar minimum, i.e., a factor of 2 to 3 greater than the response at Mars. The curve for NRLMSIS-00 is almost identical with that for MSISE-90.

4. Discussion and Conclusions

[10] The above value of $\Delta T/\Delta \overline{F}_{10.7} = 1.5$ for Mars is considerably less than the values of 2.7 and 4.1 derived from the multi-source (plasma scale height, airglow, mass spectrometer) data summarized by *Keating and Bougher* [1987] and *Stewart* [1987], respectively. It is also considerably greater than the value of about 0.6 inferred by *Bauer and Hantsch* [1989] and *Bauer* [1999] based strongly on plasma scale height and MGS accelerometer data, both of which correspond to about 130 km altitude. As noted previously, this latter result is not likely reflective of the exospheric temperature response at higher altitudes, and cannot be directly compared with the present results.

[11] According to MSISE-90, the response of Earth's exosphere temperature to solar flux variability is virtually independent of latitude and local time. However, general circulation model results for Mars [e.g., *Bougher et al.*, 2000, 2006] indicate that the response can differ between day and night, and also with respect to latitude. MGS is in a 370 × 437 km and 1400/0200 local time orbit with periapsis between −40° to −60° latitude throughout the time period considered here. Since most drag occurs within 1–2 scale heights of periapsis, the results presented here should be considered only applicable to 1400 LT in the Southern Hemisphere of Mars.

[12] It is important to note that the raw data for this investigation consists of density values that represent averages over 4–5 Mars days and over all longitudes. Therefore, it is not possible to comment on the possible extension into the exosphere of the large longitude variations in density known to exist in the lower thermosphere (ca. 100–140 km) due to vertically-propagating non-migrating tides [*Forbes and Hagan*, 2000; *Forbes et al.*, 2002; *Withers et al.*, 2003; *Angelats i Coll et al.*, 2004].

[13] A small exosphere temperature response to dust storm heating in the lower atmosphere is consistent with model results. For a 20-sol planet-encircling dust storm near Mars perihelion (Ls = 270), *Bougher et al.* [1997] find factors of 5–10 increases in density near 110 km. However, near the exobase (ca. 220 km) a 10–20 K *cooling* is found in the dayside Southern Hemisphere, a ~50 K warming at northern polar latitudes, and a ~20–50 K warming on the nightside at all latitudes. These temperature changes are strongly influenced by adiabatic heating and cooling due to modification of the general circulation in response to direct heating effects in the lower atmosphere, as well as the vertically-propagating semidiurnal tide. Considering the orbit of MGS with periapsis in Southern Hemisphere daytime, it is not surprising that dust storm effects are difficult to distinguish in Figure 2.

[14] Adiabatic heating and cooling may also be relevant to the interpretation of the exosphere temperature responses for both Earth and Mars in Figure 3. Several processes determine Mars' exosphere temperature and its variability [*Bougher et al.*, 1999, 2000]: (1) EUV flux, and its changes with solar cycle, solar rotation and distance from the Sun; (2) molecular thermal conduction; (3) CO_2 cooling; and (4) adiabatic heating and cooling associated with global dynamics. According to *Bougher et al.* [1999, 2000], the primary balance is between cooling by molecular heat conduction and EUV heating, with CO_2 cooling playing a tertiary role. For Venus and Earth, CO_2 cooling is more and less important, respectively, than for Mars. However, for Mars adiabatic cooling due to rising motions within the global circulation plays a progressively more important role in the heat budget as solar activity increases. At least at low to middle latitudes, for higher levels of solar EUV flux strong vertical winds (and adiabatic cooling) suppress the temperature response on the dayside of Mars. At Earth, ion drag serves to suppress any solar cycle variation of the EUV-driven circulation and along with it the adiabatic cooling effect, permitting a more robust exosphere temperature response to long-term changes in solar EUV flux [*Hagan and Oliver*, 1985]. It is not clear from the model results whether this mechanism still applies for the MGS densities and temperatures which are weighted towards middle and high latitudes. Definitive interpretation requires

closer analysis of model outputs taking into account the orbital configuration of MGS.

[15] The primary conclusion of this paper is that the response of Mars' Southern Hemisphere daytime thermosphere to long-term solar flux variability is 36–50% that of Earth and about five times that of Venus. This is in agreement with previous determinations with respect to shorter-term variations (~27 days) connected with rotation of the Sun [*Forbes et al.*, 2006, 2007]. It remains to be seen whether the latter result is attributable to the higher (yet uncertain) O/CO_2 concentration ratios in Mars' thermosphere which influence the relative efficiency of CO_2 cooling, and whether the former might be more connected with the adiabatic cooling effects discussed previously. In any case, the results presented here ought to constitute an important constraint on the heat budgets of thermosphere general circulation models that attempt to self-consistently and inter-consistently model the thermospheres of Earth and Mars [e.g., *Bougher et al.*, 2000, 2006]. Such validation is key for whole-atmosphere model frameworks which capture the global-scale dynamics of the entire Mars atmospheric system [e.g., *Bougher et al.*, 2006]. Solar cycle variations are best investigated using such models.

[16] **Acknowledgments.** J. Forbes was supported by the Glenn Murphy Professorship at the University of Colorado. F. Lemoine acknowledges the NASA Mars program for support and the MGS Radio Science Team (in particular Dick Simpson of Stanford University) for providing the DSN tracking data and other ancillary spacecraft information.

References

Angelats i Coll, M., F. Forget, M. A. Lopez-Valverde, P. L. Read, and S. R. Lewis (2004), Upper atmosphere of Mars up to 120 km: Mars Global Surveyor accelerometer data analysis with the LMD general circulation model, *J. Geophys. Res.*, *109*, E01011, doi:10.1029/2003JE002163.

Bauer, S. J. (1999), Mars upper atmosphere: Response to solar activity, *Anzeiger Abt. II*, *136*, 19–22.

Bauer, S. J., and M. H. Hantsch (1989), Solar cycle variation of the upper atmosphere temperature of Mars, *Geophys. Res. Lett.*, *16*(5), 373–376.

Berger, C., R. M. Biancale III, and F. Barlier (1998), Improvement of the empirical thermospheric model DTM: DTM-94—Comparative review on various temporal variations and prospects in space geodesy applications, *J. Geod.*, *72*, 161–178.

Bougher, S. W., J. Murphy, and R. M. Haberle (1997), Dust storm impacts on the Mars upper atmosphere, *Adv. Space Res.*, *19*(8), 1255–1260.

Bougher, S. W., S. Engel, R. G. Roble, and B. Foster (1999), Comparative terrestrial planet thermospheres: 2. Solar cycle variation of global structure and winds at equinox, *J. Geophys. Res.*, *104*(E7), 16,591–16,611.

Bougher, S. W., S. Engel, R. G. Roble, and B. Foster (2000), Comparative terrestrial planet thermospheres: 3. Solar cycle variation of global structure and winds at solstices, *J. Geophys. Res.*, *105*(E7), 17,669–17,692.

Bougher, S. W., J. M. Bell, J. R. Murphy, M. A. Lopez-Valverde, and P. G. Withers (2006), Polar warming in the Mars thermosphere: Seasonal variations owing to changing insolation and dust distributions, *Geophys. Res. Lett.*, *33*, L02203, doi:10.1029/2005GL024059.

Bruinsma, S., and F. G. Lemoine (2002), A preliminary semiempirical thermosphere model of Mars: DTM-Mars, *J. Geophys. Res.*, *107*(E10), 5085, doi:10.1029/2001JE001508.

Forbes, J. M., and M. E. Hagan (2000), Diurnal Kelvin wave in the atmosphere of Mars: Towards an understanding of "stationary" density structures observed by the MGS accelerometer, *Geophys. Res. Lett.*, *27*(21), 3563–3566.

Forbes, J. M., A. F. C. Bridger, S. W. Bougher, M. E. Hagan, J. L. Hollingsworth, G. M. Keating, and J. Murphy (2002), Nonmigrating tides in the thermosphere of Mars, *J. Geophys. Res.*, *107*(E11), 5113, doi:10.1029/2001JE001582.

Forbes, J. M., S. Bruinsma, and F. G. Lemoine (2006), Solar rotation effects in the thermospheres of Mars and Earth, *Science*, *312*, 1366–1368.

Forbes, J. M., S. Bruinsma, F. G. Lemoine, B. R. Bowman, and A. Konopliv (2007), Variability of the satellite drag environments of Earth, Mars and Venus due to rotation of the Sun, *J. Spacecr. Rockets*, *44*, 1160–1164.

Hagan, M. E., and W. L. Oliver (1985), Solar cycle variability of exospheric temperature at Millstone Hill between 1970 and 1980, *J. Geophys. Res.*, *90*, 12,265–12,270.

Hedin, A. E. (1991), Extension of the MSIS thermosphere model into the middle and lower atmosphere, *J. Geophys. Res.*, *96*(A2), 1159–1172.

Kasprzak, W. T., G. M. Keating, N. C. Hsu, A. I. F. Stewart, and S. W. Bougher (1997), Solar activity behavior of the thermosphere, in *Venus II*, edited by S. W. Bougher, D. M. Hunten, and R. J. Phillips, pp. 225–257, Univ. of Ariz. Press, Tucson, Ariz.

Keating, G. M., and S. W. Bougher (1987), Neutral upper atmospheres of Venus and Mars, *Adv. Space Res.*, *7*(12), 57–71.

Keating, G. M., and S. W. Bougher (1992), Isolation of major Venus thermospheric cooling mechanism and implications for Earth and Mars, *J. Geophys. Res.*, *97*(A4), 4189–4197.

Lemoine, F. G. (2003), *MGM1041c Gravity Model*, *Mars Global Surveyor Radio Sci. Arch. Vol.*, vol. MGS-M-RSS-5-SDP-V1, Geosci. Node, Planet. Data Syst., Wash. Univ., St. Louis, Mo. March 28.

Picone, J. M., A. E. Hedin, D. P. Drob, and A. C. Aikin (2002), NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, *J. Geophys. Res.*, *107*(A12), 1468, doi:10.1029/2002JA009430.

Smith, M. D. (2004), Interannual variability in TES atmospheric observations of Mars during 1999–2003, *Icarus*, *167*, 148–165.

Stewart, A. I. F. (1987), Revised time dependent model of the Martian atmosphere for use in orbit lifetime and sustenance studies, *LASP-JPL Internal Rep. PO NQ-802429*, Jet Propul. Lab., Pasadena, Calif.

Withers, P., S. W. Bougher, and G. M. Keating (2003), The effects of topographically-controlled thermal tides in the Martian upper atmosphere as seen by the MGS accelerometer, *Icarus*, *164*, 14–32.

S. L. Bruinsma, Department of Terrestrial and Planetary Geodesy, Centre Nationale D'Etudes Spatiales, Toulouse F-31401, France. (sean.bruinsma@cnes.fr)

J. M. Forbes and X. Zhang, Department of Aerospace Engineering Sciences, University of Colorado, Boulder, CO 80309, USA. (forbes@colorado.edu; xiaoli.zhang@colorado.edu)

F. G. Lemoine and M. D. Smith, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. (frank.lemoine@gsfc.nasa.gov; michael.d.smith@nasa.gov)