JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 44, No. 6, November–December 2007

Satellite Drag Variability at Earth, Mars, and Venus due to Solar Rotation

Jeffrey M. Forbes*
University of Colorado, Boulder, Colorado 80309
Sean Bruinsma†
Centre Nationale d'Etudes Spatiales, 31401 Toulouse, France
Frank G. Lemoine‡
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771
Bruce R. Bowman§
U.S. Air Force Space Command, Colorado Springs, Colorado 80914
and
Alex Konopliv¶
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

DOI: 10.2514/1.28013

Thermosphere densities from precise orbit determination of Mars Global Surveyor, Pioneer Venus Orbiter, and Magellan are used with contemporaneous data from six Earth-orbiting satellites to investigate the responses of these planetary satellite drag environments to changes in solar flux due to the sun's rotation. For comparative purposes, these results are cast in the form of equivalent exosphere temperature variations. Per 10-unit change in 10.7-cm radioflux (used as a proxy for extreme ultraviolet flux) reaching each planet, we find temperature changes of 20.6, 7.0, and 2.0 K for Earth, Mars, and Venus, respectively. The different responses are thought to reflect the differing efficiencies of CO_2 cooling and extreme ultraviolet heating in these upper atmospheres, and thus provide an important constraint on planetary atmosphere models that seek to self-consistently and interconsistently simulate the thermospheres of these planets. Our results also provide new data for empirical density models that are used to predict the satellite drag environments of these planets.

Nomenclature

$F10.7$ = 10.7-cm solar flux
$\Delta F10.7$ = change in 10.7-cm solar flux
ΔT = change in exosphere temperature (T)

I. Introduction

ACCURATE planetary thermosphere density models are required for operational prediction of aerobraking and reentry environments, mission planning, and other orbital prediction applications. Advances in this area require datasets that cover adequate ranges of solar and planetary conditions, first-principles models that self-consistently connect all observables and related processes, and the physical understanding necessary to cast empirical models into appropriate forms. Some problems are best addressed within the context of comparative planetary studies, essentially using nature as a laboratory to test the fidelity of models across a broad range of parameters. For instance, numerical modeling studies of the thermospheres of Earth, Mars, and Venus demonstrate the importance of CO_2 cooling as well as extreme ultraviolet (EUV) heating efficiency to the thermal balances of these planetary atmospheric regions [1–4]. The macroscopic efficiency of CO_2 cooling is dependent on the relative concentrations of O and CO_2, and on the poorly known O-CO_2 rate coefficient. As an example, quasi-27-day variations in density derived from atmospheric drag on the Pioneer Venus spacecraft have been used, in combination with a Venus thermosphere general circulation model, to derive a range of values for the O-CO_2 rate coefficient to satisfy all available constraints, and to suggest possible implications for the thermospheres of Earth and Mars [3]. This work demonstrates the utility of a comparative atmosphere approach in reducing some of the uncertainties associated with CO_2 cooling in thermal balance studies of planetary upper atmospheres.

A shortcoming of works such as [3] is that the comparative observational data used do not cover the same intervals of time. A truly definitive comparative planetary analysis in the sense of a "controlled experiment" would involve *simultaneous* measurements of the response to varying solar conditions at two or more planets. A first step in this direction was made in [5], in which the responses of Earth's and Mars's thermospheres to the quasi-periodic (quasi-27-day) variation of solar flux due to solar rotation were measured contemporaneously, revealing that this response is more than twice as large for Earth as for Mars. Per 10-unit change in 10.7-cm radioflux (used as a proxy for EUV flux) reaching each planet, they found temperature changes of 21.0 and 9.60 K for Earth and Mars, respectively. Existing data for Venus [3] (however, during different time periods) indicate values of order 1.8 K.

In the present work, we use exosphere temperatures deduced from orbital drag analyses of the Mars Global Surveyor (MGS), the Pioneer Venus Orbiter (PVO), and Magellan satellites, and six Earth-orbiting satellites during contemporaneous time periods, to perform a comparative analysis of exosphere temperature variations at Earth, Mars, and Venus due to the rotation of the sun. To provide a consistent intercomparison that is independent of altitude, we convert these responses to exospheric temperature using empirical

Presented as Paper 6393 at the AIAA/AAS Astrodynamics Specialist Conference, Keystone, Colorado, 21–24 August 2006; received 10 October 2006; revision received 9 March 2007; accepted for publication 10 May 2007.

*Professor, Department of Aerospace Engineering Sciences, UCB 429. Associate Fellow AIAA.

†Research Scientist, Department of Terrestrial and Planetary Geodesy.

‡Research Scientist, Planetary Geodynamics Laboratory Code 698. Member AIAA.

§Research Scientist, Space Analysis Division/A9A. Senior Member AIAA.

¶Planetary Scientist.

models. These data then provide important inputs to empirical modeling of the quasi-27-day effect, and also constrain first-principles models that attempt to simultaneously and self-consistently model the responses of Earth's, Mars's, and Venus's thermospheres to short-term changes in solar activity. In particular, these constraints should help to further resolve uncertainties connected with CO_2 cooling and other thermal balance issues.

II. Data

The Mars density data consist of daily values at 390 km inferred from precise orbit determination (POD) of MGS during two intervals of particularly pronounced quasi-27-day variability of solar flux: days 75–150 and 270–365 of 2003. The MGS satellite is in a 93.7 deg-inclination 1400–0200 local time (LT) sun-synchronous orbit, and thus the values presented here consist of day–night averages over nearly all latitudes. The POD technique is the same as that used in a previous study devoted to development of an empirical model of Mars's thermosphere, DTM-Mars [6], except that daily arcs and the MGM1041c [7] gravity model are employed. DTM-Mars was also used to normalize density values to a constant altitude of 390 km and to convert the densities to exosphere temperatures.

The Venus data originate from two sources. Exosphere temperatures from drag analyses of PVO were obtained directly from the NASA Planetary Data System. Variability associated with solar rotation is not evident for nighttime data, and so two daytime intervals are considered in the present analysis: days 100–220, 1979, and days 320–375 of 1980–1981. These data and periods are the same as those previously analyzed in [3]. In addition, one daytime interval (days 250–365 of 1992) of daily density data was obtained from an updated POD of the Magellan satellite using the more recent MGNP180U [8] gravity model. Exosphere temperatures for the Magellan data were obtained using the Venus model developed by Hedin et al. [9]. The orbital inclinations of Pioneer Venus and Magellan were 105 and 85.5 deg, respectively.

Earth data for the same periods are derived from orbital drag analyses of several satellites from an extensive multidecade dataset, which forms the basis for development of a real-time methodology for updating drag specifications at North American Aerospace Defense Command (NORAD) [10,11]. These satellites are listed in Table 1. Satellite perigees precess over a wide variety of local times and latitudes for each time interval considered. Exosphere temperatures for the Earth-orbiting satellite data were obtained using the J70 model [12].

III. Methodology

To maintain uniformity with other similar analyses for planetary thermospheres, we use the 10.7 cm radioflux (designated $F10.7$) as a proxy for EUV variability. Indeed, a repeat of our analysis using the $E10.7$ index [13], developed to provide an improved proxy for EUV fluxes, showed lower correlations with the densities presented here. In addition, at Venus we found that the proxy solar EUV flux index obtained directly from PVO electron temperature probe data [14] did not correlate any better with exosphere temperature variability than $F10.7$.

Table 1 Identification and orbital data for Earth-orbiting satellites, including International (INTL) and popular (NAME) designations, orbital inclination (INCL), and nominal perigee. Note the Venus Lander is a Russian spacecraft that never left Earth's orbit. All satellite apogees exceed 2000 km

INTL	NAME	INCL, deg	PERIGEE, km
1972-023E	Venus Lander	52.2	220
1969-064C	Intelsat	30.2	265
1975-072B	Delta-1 R/B	89.2	330
1960-Xi1	Explorer 8	49.9	400
1969-015E	OV1-19 R/B	104.8	500
1969-001A	Vanguard 2	32.9	500

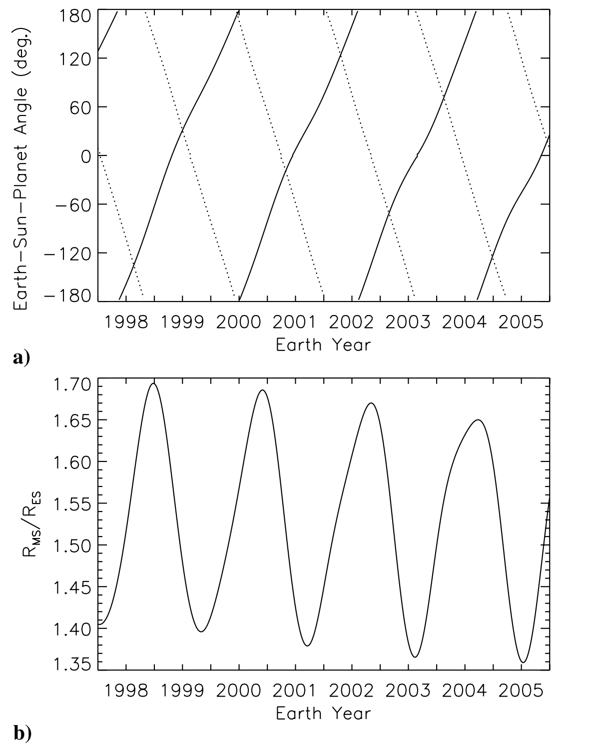


Fig. 1 a) Earth–sun–planet angle for Mars (solid lines) and Venus (dotted lines) and ratio of Mars/Earth distances to the sun b). The Earth–sun–planet angle is assumed negative when Earth trails the planet (i.e., before opposition), and positive when the planet trails Earth (i.e., after opposition).

Because $F10.7$ is measured at Earth, some assumptions must be made to estimate solar fluxes received at Mars and Venus. Consider Mars as an example. 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 Fig. 1). "Opposition" is when the Earth–sun–Mars angle is 0 deg, which occurred on 28 August 2003. During 2003, the ratio of Mars's distance from the sun to that of Earth decreased from 1.64 to 1.50, while the Earth–sun–Mars angle changed from -101.4 deg (Earth trailing Mars) to $+48.5$ deg (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. Note that the rotation periods of the sun as seen by Earth, Mars, and Venus (i.e., the synodic periods) are all slightly different. However, since the sidereal period of solar rotation varies with latitude and also with solar cycle [15], and our method for relating solar flux to atmospheric changes is insensitive to the exact synodic period (see Sec. IV), a synodic solar rotation period of 27 days is assumed for extrapolating solar fluxes to each planet. Note also that we assume the integrated flux from the Earth-facing hemisphere of the sun not to change during this time interval, although it is known that active regions of the sun evolve with time. The implications of this assumption are noted below. A similar procedure was adopted for the phasing of solar flux at Venus using the angles depicted in Fig. 1. Because of its near-circular orbit around the sun, for the magnitude of flux solar flux at Venus we simply adjusted the published values of $F10.7$ at 1 AU (astronomical unit) by a constant factor of $1/(0.53)$ [2]. Hereafter these $F10.7$ values extrapolated to Mars and Venus are referred to as "adjusted $F10.7$."

IV. Results

Figures 2 and 3 depict the results for Mars (top panels) obtained from the MGS orbital analysis, and the exosphere temperatures obtained from the six satellites at Earth (bottom panels). Figures 4–6

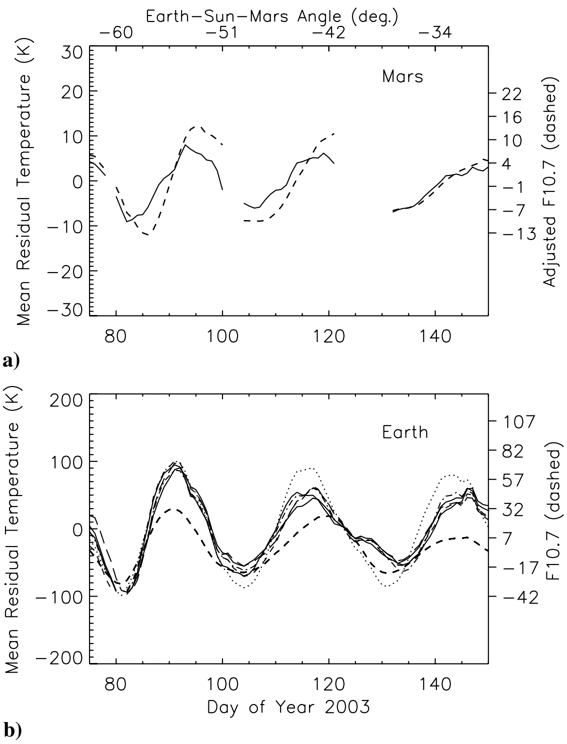


Fig. 2 a) Mean residual exosphere temperatures (solid line) and adjusted *F*10.7 (dashed line) at Mars during days 75–150 of 2003. b) The corresponding data at Earth for the six satellites in Table 1: 1972-023E (long-dashed line), 1969-064C (dash-dot-dotted line), 1975-072B (solid line), 1960-Xi1 (dashed line), 1969-015E (dash-dotted line), and 1969-001A (dotted line).

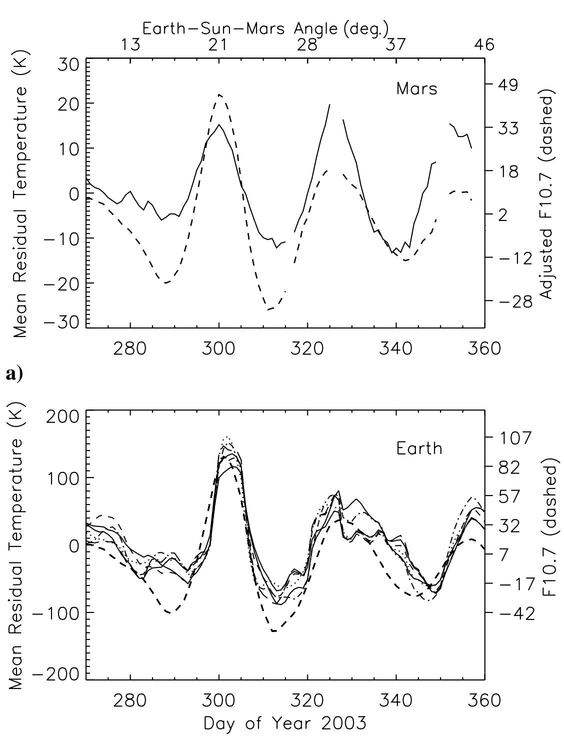


Fig. 3 a) Mean residual exosphere temperatures (solid line) and adjusted *F*10.7 (dashed line) at Mars during days 270–365 of 2003. b) The corresponding data at Earth for the six satellites in Table 1: 1972-023E (long-dashed line), 1969-064C (dash-dot-dotted line), 1975-072B (solid line), 1960-Xi1 (dashed line), 1969-015E (dash-dotted line), and 1969-001A (dotted line).

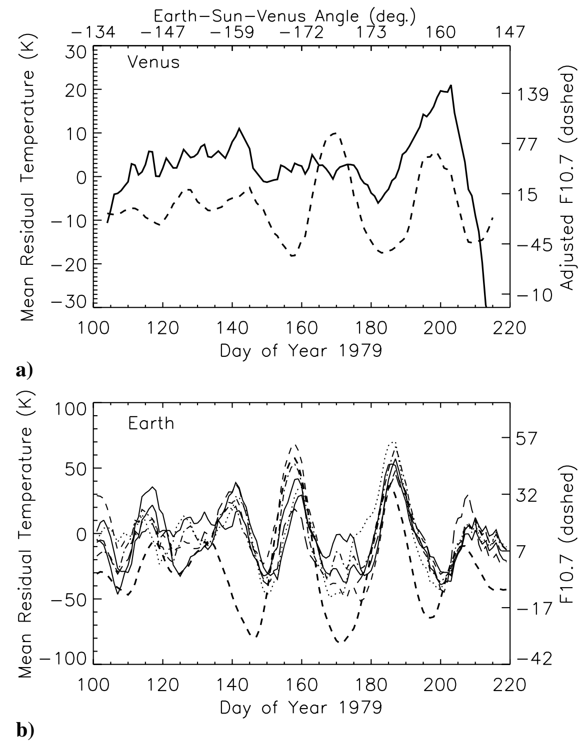


Fig. 4 a) Mean residual exosphere temperatures (solid line) and adjusted *F*10.7 (dashed line) at Venus during days 100–220 of 1979. b) The corresponding data at Earth for the six satellites in Table 1: 1972-023E (long-dashed line), 1969-064C (dash-dot-dotted line), 1975-072B (solid line), 1960-Xi1 (dashed line), 1969-015E (dash-dotted line), and 1969-001A (dotted line).

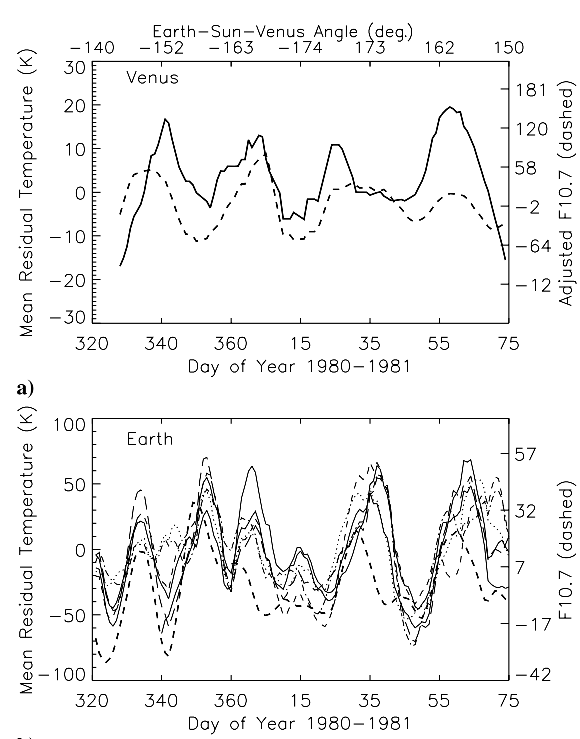


Fig. 5 a) Mean residual exosphere temperatures (solid line) and adjusted *F*10.7 (dashed line) at Venus during days 320–375 of 1980–1981. b) The corresponding data at Earth for the six satellites in Table 1: 1972-023E (long-dashed line), 1969-064C (dash-dot-dotted line), 1975-072B (solid line), 1960-Xi1 (dashed line), 1969-015E (dash-dotted line), and 1969-001A (dotted line).

provide similar depictions for the PVO and Magellan data for Venus, and the corresponding contemporaneous Earth exosphere temperatures. It is immediately obvious that the correlations with $F10.7$ variations near the 27-day period increase significantly from Venus to Mars and to Earth. In addition, the temperature amplitudes associated with the quasi-27-day variation also increase significantly in this order. In fact, at Venus the connection between temperature change and $F10.7$ is barely discernible and even questionable. This is due to the strong damping effect of CO_2 cooling. Also, assuming that these connections are real, the phasing varies from cycle to cycle so that it is difficult to find a single linear coefficient that simply relates the solar and temperature variations. The origin of much of this temporal misalignment at Venus and Mars is probably due to the inadequacies of extrapolating the solar flux measured at Earth to each of these planets. However, note that the correlation between solar flux variability and temperature variability at Venus is much improved when the Earth–sun–Venus angle is smaller (Fig. 6 vs Figs. 4 and 5).

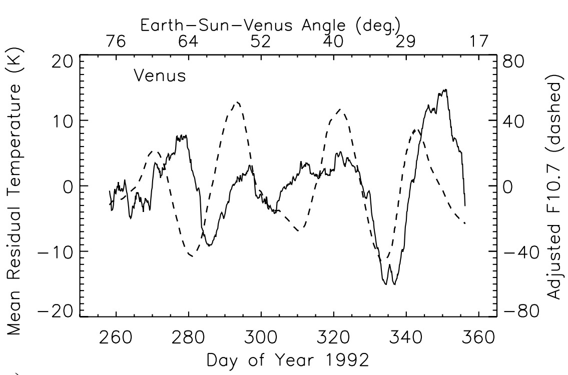
To circumvent this problem in the interest of obtaining some quantitative results, we have considered each positive and negative excursion of temperature (ΔT) and $F10.7$ ($\Delta F10.7$) as a pair, and calculated the corresponding value of $\Delta T/\Delta F10.7$. For this purpose the averages of all six Earth-orbiting satellites were used to obtain a single data point. The average values of $\Delta T/\Delta F10.7$ were computed for each time interval corresponding to those in Figs. 2–6, and all available data for each planet were also averaged as a single dataset. In the latter case, standard deviations were also computed. All of these results are summarized in Table 2. Also included are the values of $\Delta T/\Delta F10.7$ at Mars and Venus relative to Earth. We see that the cumulative data for each planet (labeled "all periods") are quite representative of the individual periods considered and indicate the following: per 10-unit change in 10.7-cm radioflux (used as a proxy for EUV flux) reaching each planet, we find temperature changes of 20.6, 7.0, and 2.0 K for Earth, Mars, and Venus, respectively. Considered another way (last column in Table 1), Mars is about one-third as responsive to solar flux variations associated with the rotation of the sun as Earth, whereas Venus is only about one-tenth as responsive. Note that we have indicated the values for Venus in Table 2 to represent upper-limit values, as we discuss below.

Table 2 Thermosphere response of Earth, Mars, and Venus to changes in solar flux due to the sun's rotation. ΔF = change in 10.7 cm solar radioflux ($F10.7$) received at the planet; ΔT = change in exospheric temperature (K)

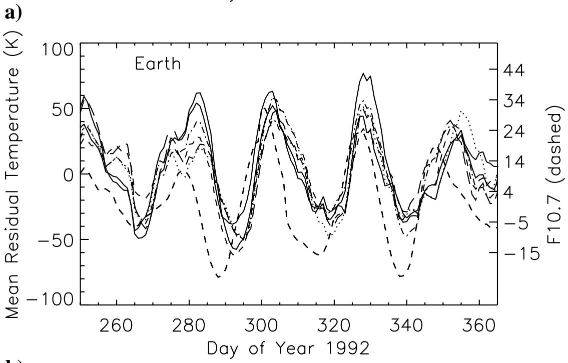
Planet & time period	$\Delta T/\Delta F$	$\Delta T/\Delta F$ ratio to Earth
Earth		
075–150, 2003	2.95	1.00
270–360, 2003	1.73	1.00
100–220, 1979	1.20	1.00
320-75, 1980–1981	1.77	1.00
250–365, 1992	2.46	1.00
All periods	*2.06±0.83*	*1.00*
Mars		
075–150, 2003	0.77	0.26
270–360, 2003	0.59	0.34
All periods	*0.70±0.36*	*0.34*
Venus		
100–220, 1979	<0.15	<0.125
320-75, 1980–1981	<0.20	<0.113
250–365, 1992	<0.21	<0.085
All periods	*<0.20±0.12*	*<0.097*

The potential implications of the different samplings of latitude and local time by the various satellites ought to be mentioned. All of the Earth satellites have eccentric orbits, and in each time interval represented in Figs. 2–6, perigees of each satellite precess over a significant range of different local times and latitudes, and generally quite different among satellites in a given set. However, all of the Earth satellites reflect very similar residual exosphere temperature variations with respect to solar flux, implying that the quasi-27-day variation is only weakly dependent on local time and latitude. This is in agreement with empirical models of Earth's atmosphere [12]. In addition, for comparison with results from Mars and Venus, we averaged the temperature responses derived from orbital drag on different Earth satellites to arrive at a single characteristic response that is a global average in the sense that broad distributions of latitudes and local times are included in the sampling. Thus, we believe that we have come close to a "global response" characterization for Earth. Similarly, for Mars, the circular orbit of MGS experiences drag at all latitudes on both the day and the night sides of the planet. Although we do not have specific knowledge about the latitude and local time dependence of the solar response in Mars's atmosphere, we do not expect it to differ too much from that of Earth, that is, only weak dependences. In any case, we judge that the pole-to-pole and day–night orbital drag experienced by MGS also results in a reasonable global response to the quasi-27-day solar flux variation at Mars. The situation is different at Venus. We could not find any discernible response to solar activity changes in the nighttime data, and therefore have only presented results for daytime, for which the observed response is still difficult to see. Moreover, the data taken at Venus correspond to low latitudes. Thus, in comparison to Earth and Mars, the results shown for Venus in Table 2 should be considered "upper limits," and perhaps should even be reduced by a factor of 2 to represent a day–night average for comparison purposes.

The "average" nature of the responses provided in Table 2 do not in any way diminish the utility of the results presented in this paper, insofar as validation of first-principles models [1–4] is concerned. Although Table 2 provides a useful summary of the different responses of the three planets that first-principles models could strive to reproduce, an alternative method might be followed if greater rigor and accuracy is required. That is, the models for Earth, Mars, and Venus could be sampled and averaged with respect to altitude, latitude, local time, and longitude identically to those of the satellites presented in this paper, and model curves generated for comparison with those in Figs. 2–6 under identical conditions.



a)



b)

Fig. 6 a) Mean residual exosphere temperatures (solid line) and adjusted $F10.7$ (dashed line) at Venus during days 250–365 of 1992. b) The corresponding data at Earth for the six satellites in Table 1: 1972-023E (long-dashed line), 1969-064C (dash-dot-dotted line), 1975-072B (solid line), 1960-Xi1 (dashed line), 1969-015E (dash-dotted line), and 1969-001A (dotted line).

V. Conclusions

The different responses of Mars and Venus to solar flux changes at a quasi-27-day period, as compared to Earth, are likely due to the differing efficiencies of CO_2 cooling and EUV heating in these upper atmospheres. Our results can therefore be used to constrain planetary atmosphere models that seek to self-consistently and interconsistently simulate the thermospheres of these planets. The data in Table 2 might be used to provide crude bounds on the thermosphere responses of Earth, Mars, and Venus to solar flux variability. However, more accurate constraints and improved insight would be gained by modeling the specific data illustrated in Figs. 2–6, as this better retains the value of these data as being contemporaneous between the planets. In particular, due to the different local time and latitude samplings corresponding to each dataset in Figs. 2–6, numerical models attempting to emulate these results may need to similarly sample the model output to optimize the fidelity of the comparison.

The results presented here should also prove valuable in validating and/or updating the parameterization of short-term solar flux variations in empirical models of Earth's, Mars's, and Venus's thermospheres, especially for the purposes of specifying or predicting atmospheric drag on satellites. For this purpose, as well as constraining first-principles models and even other applications, all of the data in Figs. 2–6, as well as the raw density data, are available from the authors upon request.

An important adjunct to the present work will be investigation of the effects of multiyear solar flux changes on the thermospheres of these planets. This work is ongoing and will be reported on in the future.

Acknowledgments

J. Forbes was supported through the Glenn Murphy Endowed Professorship in Aerospace Engineering Sciences, College of Engineering and Applied Science, University of Colorado at Boulder. The contributions to this paper by A. Konopliv were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors thank Rodney Anderson at the University of Colorado for assisting in calculating the orbits of Earth, Mars, and Venus to adjust the 10.7-cm radiofluxes. Xiaoli Zhang's assistance in data analysis and plotting is greatly appreciated.

References

[1] Bougher, S. W., and Roble, R. G., "Comparative Terrestrial Planet Thermospheres 1. Solar Cycle Variation of Global Mean Temperatures," *Journal of Geophysical Research*, Vol. 96, No. A7, 1991, pp. 11045–1105.

[2] Bougher, S. W., Engel, S., Roble, R. G. B., and Foster, B., "Comparative Terrestrial Planet Thermospheres 2. Solar Cycle Variation of Global Structure and Winds at Equinox," *Journal of Geophysical Research*, Vol. 104, No. E7, 1999, pp. 16591–1661.

[3] Keating, G. M., and Bougher, S. W., "Isolation of Major Venus Thermospheric Cooling Mechanism and Implications for Earth and Mars," *Journal of Geophysical Research*, Vol. 97, No. A4, 1992, pp. 4189–4197.

[4] Bougher, S. W., Roble, R. G., and Fuller-Rowell, T., "Simulations of the Upper Atmospheres of the Terrestrial Planets," *Atmospheres in the Solar System: Comparative Aeronomy*, Geophysical Monograph No. 130, American Geophysical Union, 2002, pp. 261–288.

[5] Forbes, J. M., Bruinsma, S., and Lemoine, F. G., "Solar Rotation Effects in the Thermospheres of Mars and Earth," *Science*, Vol. 312, June 2006, pp. 1366–1368.

[6] Bruinsma, S., and Lemoine, F. G., "A Preliminary Semi-Empirical Thermosphere Model of Mars: DTM-Mars," *Journal of Geophysical Research*, Vol. 107, No. E10, 2002.

[7] Lemoine, F. G., MGM1041c Gravity Model, Mars Global Surveyor Radio Science Archival Volume MGS-M-RSS-5-SDP-V1, Geosciences Node, Planetary Data System, Washington University, St. Louis, MO, 28 March 2003.

[8] Konopliv, A. S., Banerdt, W. B., and Sjogren, W. L., "Venus Gravity: 180th Degree and Order Model," *Icarus*, Vol. 139, No. 1, 1999, pp. 3–18.

[9] Hedin, A. E., Niemann, H. B., Kasprzak, W. T., and Seiff, A., "Global Empirical Model of the Venus Thermosphere," *Journal of Geophysical Research*, Vol. 88, No. A1, 1983, pp. 73–83.

[10] Bowman, B. R., and Storz, M. F., "Time Series Analysis of HASDM Thermospheric Temperature and Density Corrections," AIAA Paper 2002-4890, Aug. 2002.

[11] Bowman, B. R., Marcos, F. A., and Kendra, M. J., "A Method for Computing Accurate Daily Atmospheric Density Values from Satellite Drag Data," AAS Paper 2004-179, Feb. 2004.

[12] Jacchia, L. G., "New Static Models of the Thermosphere and Exosphere with Empirical Temperature Profiles," Smithsonian Astrophysics Special Rept. 313, 1970.

[13] Tobiska, W. K., Woods, T., Eparvier, F., Viereck, R., Floyd, L., Bouwer, D., Rottman, G., and White, O. R., "The SOLAR2000 Empirical Solar Irradiance Model and Forecast Tool," *Journal of Atmospheric and Terrestrial Physics*, Vol. 62, No. 14, 2000, pp. 1233–1250.

[14] Brace, L. H., Hoegy, W. R., and Theis, R. F., "Solar EUV Measurements at Venus Based on Photoelectron Emission From the Pioneer Venus Langmuir Probe," *Journal of Geophysical Research*, Vol. 93, No. A7, 1988, p. 7282.

[15] Mouradian, Z., Bocchia, R., and Botton, C., "Solar Activity Cycle and Rotation of the Corona," *Astronomy and Astrophysics*, Vol. 394, No. 3, 2002, pp. 1103–1109.

A. Ketsdever
Associate Editor