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X-RAY AND EUV HEATING OF THE VENUSIAN AND MARTIAN THERMOSPHERE BY THE YOUNG SUN

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Abstract. In view of the low water abundance in the present Venusian and Martian atmospheres several observations by spacecraft and studies suggest that both planets should have lost most of its water over the early active period of the young Sun. During the first Gyr after the Sun arrived at the Zero-Age-Main-Sequence high X-ray and EUV fluxes between 10 - 100 times that of the present Sun were responsible for much higher temperatures in the thermosphere-exosphere environments on both planets. By applying a diffusive-gravitational equilibrium and thermal balance model for investigating radiation impact on the early thermospheres by photodissociation and ionization processes, due to exothermic chemical reactions and cooling by CO_2 IR emission in the 15μm band we found expanded thermospheres with exobase levels between about 200 (present) to 2000 km (4.5 Gyr ago). The higher temperatures in the upper atmospheres of both planets could reach blow-off conditions for H atoms even at high CO_2 mixing ratios of 96 %. Lower CO_2 mixing ratio or higher contents of water vapour in the early atmospheres could have had a dramatic impact on the loss of atmosphere and water on both planets. The duration of this phase of high thermal loss rates essentially depended on the mixing ratios of CO_2, N_2 and H_2O in the early atmospheres and could have lasted between about 150 to several hundred Myr.

1. Introduction

On the basis of the analysis of neutral mass spectrometer data by spacecraft it was found that the Venusian and Martian atmospheres are enriched in D over H relative to Earth by a factor of about 120 and about 5 times, respectively (e.g., McElroy et al., 1982). From these observations various authors conclude that both planets were once more wet. For the prediction of the amount of primordial water on Venus one has to consider two possibilities. The first hypotheses assumes that Venus was formed from condensates in the solar nebula that contained little water (e.g., Lewis, 1974). Grinspoon and Lewis (1988) have also argued that present Venus' water content may be
in a steady state where the loss of hydrogen to space is balanced by a continuous input of water from comets or from delayed juvenile outgassing so that no increase of Venus' past water inventory is required to explain the observed D/H ratio. However, the initial water inventory on early Venus may have been larger, because a substantial amount of water is required to explain the onset of the large greenhouse effect observed at present (e.g., Kasting and Pollack, 1983; Chassefière, 1996). This agrees with the second hypothesis which argues in agreement with previous theories for a water abundance more comparable to that on Earth and Mars (e.g., Wetherill, 1981; Morbidelli et al., 2000).

On Mars, high resolution altimetric data from the Mars Orbiter Laser Altimeter (MOLA) instrument on board of Mars Global Surveyor (MGS) defined a detailed topography of the northern Martian lowlands (Head III et al., 1999), which is consistent with the hypothesis that a lowland-encircling geologic contact may represent the ancient shoreline of standing bodies of water in the Martian past (e.g., Carr, 1987). However, we note that it is difficult to estimate the initial water reservoir on early Venus and Mars from the present D/H ratio, because all estimations depend on the non-steady or steady state of the planet's water contents and possible unknown D/H fractionation processes.

In the present study we apply a thermospheric balance and diffusive equilibrium model for studying the X-ray and EUV (XUV) radiation effects of the young Sun on the early Venusian and Martian thermosphere-exosphere environments as a function of atmospheric CO_2 mixing ratio by using solar XUV fluxes as obtained by multiwavelength observations of Sun-like stars with ages covering 0.13 – 7 Gyr (Ribas et al., 2005).

Finally, we discuss the implications of our study for the evolution of the early Venusian and Martian loss of atmosphere and their expected water inventories.

2. Numerical modelling of the thermosphere-region over Venus' and Mars' history

In the present study we apply a thermospheric model to the CO_2-rich atmospheres of Venus and Mars based on the models of Gordiets et al. (1982) and Gordiets and Kulikov (1985) that have been modified to high XUV flux values expected during the Sun's evolution (see Ribas et al., 2005: present [1 XUV], 3.8 Gyr ago [10 XUV], 4.24 Gyr ago [30 XUV], 4.37 Gyr ago [70 XUV], 4.5 Gyr ago [100 XUV]). Our thermospheric model solves the 1-D time-dependent equations of continuity and diffusion for the main atmospheric species, hydrostatic and heat balance equations, and the equations of vibrational kinetics for radiating molecules from the mesopause up to the exobase.

The model is self-consistent with respect to the neutral gas temperature and vibrational temperatures of the species radiating in the IR and it takes into account: heating due to the CO_2, N_2, O_2, CO, and O photoionization by XUV-radiation ($\lambda \leq 102.7$ nm), heating due to O_2 and O_3 photodissociation by solar UV-radiation, and chemical heating in exothermic 3-body reactions

$$O + O + M \rightarrow O_2 + M, \quad (1)$$

$$O + CO + M \rightarrow CO_2 + M, \quad (2)$$

$$O + O_2 + M \rightarrow O_3 + M, \quad (3)$$

where M are CO_2, N_2 and CO molecules and O and He atoms. Further, the model includes: neutral gas molecular heat conduction, IR-cooling in the vibrational-rotational bands of CO_2 (15 μm), CO, O_3, and in the 63 μm O line, turbulent energy dissipation and heat conduction. The volume heating and cooling rates for the processes used in our simulations and the heating rates owing to photodissociation are discussed in detail by Gordiets et al. (1982) and Gordiets and Kulikov (1985). The lower boundary conditions at the mesopause at about 100 km are

$$\rho = \rho_0, \qquad T = T_0, \quad (4)$$

where T is the temperature, ρ the gas density and T_0 and ρ_0 are taken from observational data (Hedin et al., 1983; Keating et al., 1988). The upper boundary of the model is the exobase level where we assume

$$\frac{\partial T}{\partial z} = 0, \qquad \frac{\partial^2 v_z}{\partial z^2} = 0, \quad (5)$$

here $\mathbf{v}_z$ is the vertical bulk gas velocity. The eddy conduction heating rate q_{ec} is calculated by

$$q_{ec} = \frac{\partial}{\partial z}\left[\rho c_p K_{ehc}\left(\frac{\partial T}{\partial z} + \frac{g}{c_p}\right)\right], \quad (6)$$

where K_{ehc} is the eddy heat conductivity assumed to be equal to the eddy diffusion coefficient and c_p is the specific heat at constant pressure. Because of a stable thermospheric stratification the vertical heat flux owing to eddy conduction which is obtained by integration of Eq. (6) over altitude z is always negative and directed downward to the mesosphere, the net effect is cooling. Furthermore, we include in our model simulations also heating due to dissipation of turbulent energy (Gordiets and Kulikov, 1985; Kulikov et al., 2005).

IR emission of CO_2 in the 15 μm band is the major cooling process in the lower thermospheres of Venus, Earth and Mars (e.g., Gordiets et al., 1982; Gordiets and Kulikov, 1985; Bougher et al., 1999). For the calculation of the heat loss rate q_{CO2} due to IR emission of CO_2 in the 15μm band excitation of the $CO_2(01°0)$ vibration-rotation states in collisions with heavy particles like atomic oxygen and CO_2, N_2, etc., collisional and radiative de-excitation processes and absorption of radiation are taken into account. For the 15μm CO_2-band we use the cool-to-space approximation (e.g., Gordiets et al., 1982) which can be expressed as

$$q_{CO_2} = 1.33 \times 10^{-13} g_w e^{-\frac{960}{T}} n_{CO_2}\left(\sum_M k_M n_M\right) F(\tau, \xi), \quad (7)$$

where $g_w = 2$ is a statistical weight factor for the 01°0 CO_2 molecule states, k_M is the relaxation rate constant for collisions with molecules and atoms having density n_M (CO_2, O, O_2, N_2, etc.), n_{CO2} is the CO_2 number density, and $F(\tau,\xi)$ accounts for the absorption of radiation in the band (Gordiets et al., 1982). Here τ is the reduced optical depths of the atmosphere for the 15 μm radiation at the hight in question, ξ is the ratio of the radiative to the net relaxation rate of the $CO_2(01°0)$ states at the same height.

Our model simulations for present Venus yield an exospheric temperature for medium solar activity conditions of about 270 K which is in good agreement with the global empirical model of the Venus thermosphere inferred from the Pioneer Venus neutral mass spectrometer measurements of Hedin et al. (1983) and the neutral gas mass spectrometer of the PV multiprobe bus as well as with other model simulations. For present Mars our model simulation yields an average exospheric temperature of about 220 - 230 K which is also in a good agreement with aerobreaking data obtained by Mars Global Surveyor (e.g., Keating et al., 1988).

Fig. 1 shows our modelled thermospheric temperature profiles on Venus for a 96 %, and a 10% CO_2 / N_2 atmosphere and various XUV fluxes. Depending on calculated exospheric temperatures and exobase altitudes H atoms could have been lost under diffusion-limited hydrodynamic blow-off conditions even for a 96 % CO_2 atmosphere during about 250 Myr after the Sun arrived at the ZAMS. For a 10 % CO_2 and 90 % N_2 atmosphere the thermospheric temperatures could reach the critical temperature at the exobase for atomic hydrogen of about 4000 K around 3.8 Gyr ago and exospheric temperatures in excess of 20000 K about 4 Gyr ago.

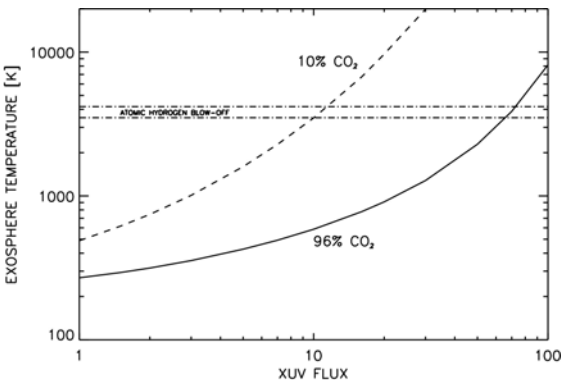

Fig. 1: Modelled Venusian exospheric temperatures for a 96 % CO_2 atmosphere (solid line) and for an atmosphere with 10 % (dotted line) CO_2 as a function of the solar XUV flux. The dashed-dotted lines mark the blow-off region for atomic hydrogen.

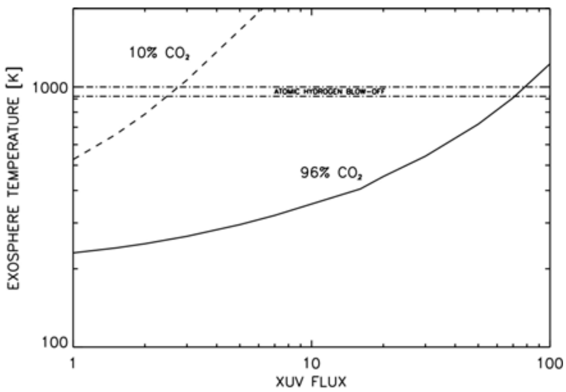

Fig. 2: Modelled Martian exospheric temperatures for a 96 % CO_2 atmosphere (solid line) and for an atmosphere with 10 % (dotted line) CO_2 as a function of the solar XUV flux. The dashed-dotted lines mark the blow-off region for atomic hydrogen.

If one considers an atmosphere with lower CO_2 mixing ratios and higher N_2 values during this active solar period and high exospheric temperatures of more than about 20000 K as shown in Fig. 1, one obtains a Jeans escape flux for atomic oxygen of more than about 4.5×10^{10} cm^{-2} s^{-1}, resulting in loss rates $\geq 1.5 \times 10^{29}$ s^{-1}. This loss rate is about 10^4 times larger than the present non-thermal O loss rates (Kulikov et al., 2005) and could result in an atmospheric loss of an equivalent amount of about 2 - 3 bar over 100 Myr.

Fig. 2 shows modelled thermospheric temperature profiles on Mars for a 96 %, and a 10 % CO_2/N_2 atmosphere as a function of solar XUV flux. Depending on initial CO_2 mixing ratios and exobase altitudes atomic hydrogen could have been under diffusion-limited hydrodynamic blow-off conditions even for a 96 % CO_2 atmosphere for about 230 Myr after the Sun arrived at the ZAMS.
If one assumes that early Mars had a lower CO_2/N_2 mixing ratio during the outgassing period one can see in Fig. 2 that the exobase temperatures could have reached several thousand K, so that an equivalent amount of several bar of heavy atomic species like O, C or N could have been lost via Jeans escape.

3. Implications for atmospheric evolution

Our investigation show the importance of a high CO_2 abundance for the evolution and atmospheric stability of young terrestrial planetary atmospheres and their water inventories and is in agreement with the recent study of Tian et al. (2005) who considered CO_2 and hydrogen-rich atmospheres for early Earth 3.5 - 4 Gyr ago (6 - 10 XUV periods).

Kasting and Pollack (1983) studied the hydrodynamic loss of water from a primitive H_2O-rich Venusian atmosphere as a function of the H_2O mixing ratio at the mesopause (cold-trap). The hydrogen escape flux calculated by Kasting and Pollack (1983) depends sensitively on the H$_2$O number density at the mesopause. They found that for H_2O mixing ratios $\geq 7 \times 10^{-4}$ atomic hydrogen becomes the major species at the exobase which moves than to great distances, so that the exosphere becomes unstable to expansion, Jeans escape becomes inappropriate and hydrodynamic conditions have to be considered. The escape fluxes
in such cases depend on the XUV flux value and H_2O mixing ratios.

On early Venus H could escape at H_2O mixing ratios of 0.0063 at 10 XUV with about 3.5×10^{11} cm^{-2} s^{-1} and at 100 XUV of about 3.8×10^{12} cm^{-2} s^{-1}. If the water mixing ratios were higher (0.055 -0.46) because of the runaway greenhouse stage H escape fluxes in the orders of about 1- 3.5×10^{12} cm^{-2} s^{-1} could be reached for 8-16 times higher XUV fluxes (Kasting and Pollack, 1983) and of about 1.3 - 2.7×10^{13} cm^{-2} s^{-1} for 100 XUV (Kulikov et al., 2005).

By using these H escape fluxes, one finds that the full amount of a terrestrial ocean could have escaped over a time period of about 50 Myr if the H_2O mixing ratio was about 0.46 and the solar XUV flux was about 70 - 100 times that of the present solar value. If the H_2O mixing ratio was about 0.063 and the XUV flux about 16 times that of the present solar value, a terrestrial ocean could have been lost from Venus during 900 Myr. However, if an water ocean evaporated on early Venus, there are two potential sinks for the remaining oxygen.

(1) Oxidation of the crust: the incorporation of about 100 bar of O_2 by FeO should impose a permanent extrusion of non-oxidized material with a rate which is about 15 times higher than on Earth (Lewis and Prinn, 1984), which is unlikely due to the weak plate tectonic activity on Venus (Rosenqvist and Chassefière, 1995).

(2) O loss to space: Kulikov et al. (2005) applied a numerical test particle model for the simulation of the O^+ pick up ion loss from an unmagnetized Venus over its history and found a total loss of oxygen from several tens of bar to about 300 bar. Their obtained values depend strongly on the expected solar wind conditions of the young Sun and assumed planetary obstacle distances.

However, the situation on early Mars, which did not experience a runaway greenhouse effect could have been different. Rosenqvist and Chassefière (1995) modelled the photochemistry of Martian CO_2 atmospheres with surface pressures between 0.1 - 10 bar. They found that the water vapor profile influences the O_2 production which depends itself on the temperature profile. Furthermore it was found that water vapor could be depleted in the middle and upper atmosphere on early Mars due to a cool temperature climate (Rosenqvist and Chassefière, 1995; Lammer et al., 2002). These atmospheric conditions could result in much lower H_2O mixing ratios < 10^{-6} at the mesopause compared to early Venus which experienced a runaway greenhouse effect.

In such a case Mars, would not have lost much of its dissociated H atoms due to diffusion-limited hydrodynamic escape. But as shown in Fig. 2 lower CO_2/N_2 mixing ratios on early Mars shortly after its volatile outgassing could have had a major impact on the thermal loss of the main atomic atmospheric species (O, N, C) combined with the impact erosion and loss of O due to dissociative recombination in the dense solar XUV-produced early Martian ionosphere. One should note that thermal and photochemical loss process are independent from an expected early Martian magnetosphere because these atomic species escape as neutrals.

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References:

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

Carr, M. H. Water on Mars. Nature, 326, 30-34, 1987.

Chassefière, E. Hydrodynamic escape of oxygen from primitive atmospheres: applications to the cases of Venus and Mars. Icarus, 124, 537-552, 1996.

Gordiets, B. F., Yu. N. Kulikov, M. N. Markov, and M. Ya. Marov. Numerical modelling of the thermospheric heat budget. J. Geophys. Res., 87, 4504 - 4514, 1982.

Gordiets, B. F., and Yu. N. Kulikov. On the mechanisms of cooling of the nightside thermosphere of Venus. Adv. Space Res., 5, 113-117, 1985.

Grinspoon, D. H., and J. S. Lewis. Cometary water on Venus - Implications of stochastic impacts. Icarus, 74, 21-35, 1988.

Head III, Jr., J. W., H. Hiesinger, M. A. Ivanov, M. A. Kreslavsky, S. Pratt, and B. J. Thomson. Possible ancient oceans on Mars: evidence from Mars Orbiter Laser Altimeter Data. Science, 286, 2134-2137, 1999.

Hedin, A. E., H. B. Nieman, W. T. Kasprzak, and A. Seiff. Global empirical model of the Venus thermosphere. J. Geophys. Res., 88, 73-83, 1983.

Kasting, J. F., and J. B. Pollack. Loss of water from Venus I. Hydrodynamic escape of hydrogen, Icarus, 53, 479-508, 1983.

Keating, G. M. and 27 co-authors. The structure of the upper atmosphere of Mars: In situ accelerometer measurements from Mars Global Surveyor. Science, 279, 1672-1678, 1988.

Kulikov, Yu. N., H. Lammer, H. I. M. Lichtenegger, N. Terada, I. Ribas, C. Kolb, D. Langmayr, R. Lundin, E. F. Guinan, S. Barabash, and H. K. Biernat. Atmospheric and water loss from early Venus. Planet. Space Sci., submitted, 2005.

Lammer, H., F. Selsis, G. J. Molina-Cuberos, W. Stumptner, A. Bèrces, T. Kerékgyártó, and G. Rontó. Was the ancient Martian surface sterilized by radiation? ASP Conf. Series, 269, 151-161, 2002.

Lewis, J. S. The temperature gradient in the solar nebula. Science, 186, 440-443, 1974.

McElroy, M. B., M. J. Prather, and J. M. Rodriguez. Escape of hydrogen from Venus. Science, 215, 1614-1615, 1982.

Morbidelli, A., J. Chambers, J. I. Lunine, J. M. Petit, F. Robert, G. B. Valsecchi, and K. Cyr. Source regions and timescales for the delivery of water to Earth. Meteoritics and Pl. Science, 35, 1309-1320, 2000.

Ribas, I., E. F. Guinan, M. Güdel, and M. Audard. Evolution of the solar activity over time and effects on planetary atmospheres. I. High-energy irradiances (1-1700 Å). ApJ., 622, 680-694, 2005.

Rosenqvist, J., and E. Chassefière. Inorganic chemistry of O_2 in a dense primitive atmosphere. Planet. Space Sci., 43, 3-10, 1995.

Wetherill, G. W. Solar wind origin of ^{36}Ar on Venus. Icarus, 46, 70-80, 1981.