"Physics of Auroral Phenomena", Proc. XXIX Annual Seminar, Apatity, pp. 229 - 233, 2006

Polar Geophysical Institute

SOLAR RADIATION AND PARTICLE INDUCED EFFECTS ON THE EARLY MARTIAN ATMOSPHERE AND LOSS

Yu. N. Kulikov[1], H. Lammer[2], H. I. M. Lichtenegger[2], T. Penz[2], and H. K. Biernat[2]

[1] *Polar Geophysical Institute (PGI), Russian Academy of Sciences, Khalturina Str. 15, 183010 Murmansk, Russian Federation*
[2] *Space Research Institute, Austrian Academy of Sciences, Schmiedlstr. 6, A-8042 Graz, Austria*

Emails: kulikov@pgi.ru; helmut.lammer@oeaw.ac.at; herbert.lichtenegger@oeaw.ac.at; thomas.penz@oeaw.ac.at; helfried.biernat@oeaw.ac.at

Abstract. The evolution of the Martian atmosphere with regard to its H_2O inventory is influenced by the thermal loss and non-thermal atmospheric loss processes of H, H_2, O, N, C, CO, CO_2, H^+, O^+, H_2^+, $N2^+$, CO^+, CO_2^+, and O_2^+ into space, as well as by chemical weathering of the surface soil. The epochs related to escape of the atmosphere and water from Mars over long-term periods can be divided into 3 epochs, the present Mars, the period between the present and 3.5 Gyr ago and the first billion years. The evolution of all escape processes depend on the history of the intensity of the solar X-ray and EUV (XUV)radiation and the solar wind density. Thus, we use actual data from the observation of solar proxies with different ages from the Sun in Time program for reconstructing the Sun's radiation and particle environment from the present to 4.6 Gyr ago. We compare different model investigations for the non-thermal escape processes (ion pick up, sputtering, ionospheric clouds triggered by the Kelvin Helmholtz plasma instability) of the Martian atmosphere over long-time periods and discuss the effect on the total loss to the Martian CO_2 and/or H_2O inventory. We apply a thermospheric model to the CO_2-rich atmosphere of Mars that have been modified to high XUV flux values expected during the Sun's evolution. During the first Gyr after the Sun arrived at the Zero-Age-Main-Sequence high XUV 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 15 μm band we found expanded thermospheres with exobase levels between about 200 (present) to 2000 km (4.5 Gyr ago). Our model results indicate that the high temperature in the thermosphere-exosphere environment on early Mars could reach "blow-off" conditions for H atoms even at high CO_2 mixing ratios of 96 %. Furthermore, we show that lower CO_2 / N_2 or CO_2 mixing ratios in general, or higher contents of H_2O-vapor in the early Martian atmosphere could have had a dramatic impact on the loss of atmosphere and water on early Mars. 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 atmosphere. Lower CO_2 mixing ratios on early Mars shortly after its volatile out-gassing could have had a major impact on the thermal loss of the main atomic atmospheric species (O, N, C) combined with 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 is independent from an early Martian magnetosphere because these atomic species escape as neutrals. Furthermore, a combination between an expanded thermosphere-exosphere region and a stronger early solar wind could have also enhanced ion pick up loss during the period where the Martian magnetic dynamo decreased.

1. Introduction

The evolution of the Martian atmosphere and the evidence of the existence of an early hydrosphere are of great interest in studies regarding the evolution of the planet's water inventory and the search for life carried out by current and future Mars missions. Although the Martian climate is at present too cold and the atmosphere too thin so that liquid water can not be stable on the surface, there are many indications that the situation was different during the Noachian epoch. Chassefière (1996) showed that oxygen produced by photodissociation of H_2O vapor in an earlier stage of terrestrial planetary evolution may be lost partly due to hydrodynamic escape, although in relatively modest amounts. If hydrodynamic escape of hydrogen on early Mars equivalent to a few percent of a terrestrial ocean occurred at a relatively slow rate during the first Gyr of a planet's lifetime, less than 10 % of the remaining oxygen would be expected to be dragged to space by the hydrogen wind. This result applies to the case of a continuous supply of water by comets during the heavy bombardment, when no more than about 0.3 times (≈ 80 bar) of the terrestrial water ocean is expected to have been accreted. This value is in agreement with the upper water content estimate obtained by Lunine et al. (2003). However, if an expected amount of about 15 - 70 bar of water on early Mars has been lost through the hydrodynamic escape of H produced from H_2O photodissociation, than one has to find the sinks for the remaining oxygen produced from such huge amounts of photodissociated H_2O vapor. Rosenquvist and Chassefière (1995) studied the inorganic chemistry of O_2 in dense primitive atmospheres and pointed out that carbon in primitive atmospheres whatever its form is (CO or CH_4, etc.) can react with oxygen to produce CO_2. They conclude that these processes may also be strong potential sinks for oxygen. However, if there is not enough carbon, which can react with the remaining oxygen in the atmosphere, the oxygen would accumulate. One should note that these processes do not remove oxygen from the atmosphere but only convert it into CO_2 and thus do not reduce the surface pressure. One should note that the remained oxygen should have contributed to the total surface pressure on early Mars as long as it is retained in the atmosphere. After all this "extra" oxygen was lost to space or oxidized to the surface, outgassed atmospheric species like CO_2 (Manning et al., 2006) or oxygen which was converted into CO_2 (Rosenquvist and Chassefière, 1995) started to determine the surface pressure. The aim of this work is to investigate possible scenarios which could be responsible for the loss of the early Martian atmosphere, including the possible protecting effects of the early planetary magnetosphere. In Section 2, we apply a thermospheric balance and diffusive equilibrium model to study the early Martian thermosphere-exosphere and the O^+ ion loss due to the solar wind induced pick up process related to the evolving solar radiation and particle environment during the Noachian epoch, 3.8 - 4.5 Gyr ago. Finally we discuss the possible scenarios which could have removed several bar to tens of bar of the Martian atmosphere and its hydrosphere.

2. Heating of the Martian thermosphere due to solar X-ray and EUV (XUV) radiation

Kulikov et al. (2006) and Lammer et al. (2006a) applied a thermospheric model to the CO_2 atmospheres of Venus and Mars. For the investigation of the XUV heating of the early Martian upper atmosphere due to the active young Sun we apply the same model which is based on the thermospheric models of Gordiets et al. (1982) and Gordiets and Kulikov (1985) but have been modified to XUV flux values from the present solar up to 100 times, as expected for the Sun 4.5 Gyr ago (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 CO_2, O, CO, N_2, O_2, Ar, He, NO, and H_2O, 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, neutral gas molecular heat conduction, IR-cooling in the vibrational-rotational bands of CO2 (15 μm), CO, O_3, and in the 63 μm O line, turbulent energy dissipation and heat conduction (Gordiets et al., 1982; Gordiets and Kulikov, 1985; Kulikov et al., 2006). As shown by Gordiets et al. (1982) for the present time solar radiation level, solar heating of the Earth's upper thermosphere by XUV radiation is balanced primarily by thermospheric IR radiation. In the Martian CO_2 atmosphere, 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 and Keating, 1999; Bougher et al., 1999), while cooling due to the downward thermal conduction flux in the altitude region where thermospheric temperature is nearly constant is not significant and can be neglected. It is conventional to define the solar ultraviolet heating efficiency, as the fraction of the solar energy absorbed at a given altitude which appears locally as heat. Knowledge of this parameter is of fundamental importance to studies of the thermospheric energy budget but is poorly known for the Martian thermosphere (Lichtenegger et al., 2006). However, to study the effect of the heating efficiency to the thermospheric and exobase temperatures we model in the present study thermospheric temperature profiles for a heating efficiency range with a minimum value of about 8 % and an upper limit of about 32 %. Fig. 1 shows our modelled thermospheric temperature profiles for high XUV radiation levels (10, 50, and 100 times the average present solar value). The temperature profiles are calculated for low and high solar XUV heating efficiency values of 8 and 32 %, correspondingly. One can see that if one considers a low heating efficiency case the exobase temperature T_{exo} grows by approximately a factor of 3 from about 355 K to about 1230 K for XUV fluxes increasing from 10 to 100 times that of the present Sun. And only for higher XUV fluxes, close to 100 XUV T_{exo} is above the blow-off temperature for atomic hydrogen and is still below the blow-off temperature of about 2000 K for H_2. In the upper limit of the heating efficiency cases shown in Fig. 1, substantially higher exobase temperatures result. In 100 XUV case T_{exo} reaches the value of about 4800 K that is above the blow-off temperature for H, H_2 and He. The simulation results also show that atomic hydrogen will be in blow-off condition for the 50 XUV case. One should note that in a hydrogen-rich early

Martian atmosphere the exobase moves to much larger distances compared to the exobase calculated for the CO_2 atmosphere considered in the present study that correspond to a CO_2-rich atmosphere. In such a case dissociated hydrogen would dominate in the upper atmosphere and could escape in a diffusion-limited regime from the planet along with a hydrodynamic wind.

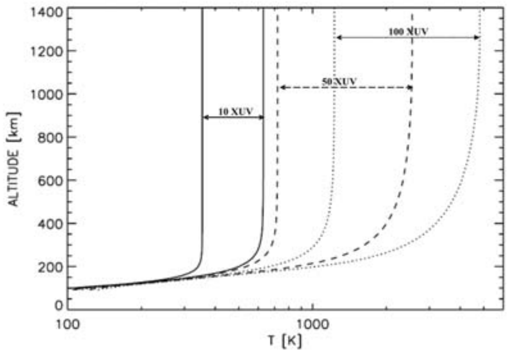

Fig. 1: Modelled Martian temperature profiles in a 96 % CO2 thermosphere as a function of altitude for 10 XUV (≈ 3.8 Gyr ago), 50 XUV (4.33 Gyr ago), and 100 XUV (≈ 4.5 Gyr ago) flux values for a low heating efficiency of 8 % (lower temperature range) and high heating efficiency of 32 % (upper temperature range).

Fig. 2 shows the atomic oxygen number density profiles including thermal and “hot” photochemically produced [$O_2^+ + e^- \rightarrow O^{hot} + O^{hot} + \Delta E$] components during the Noachian epoch (3.8 - 4.6 Gyr ago). The solid curve demonstrates the importance of the contribution of the O^{hot} component above about 700 km for 10 XUV flux level.

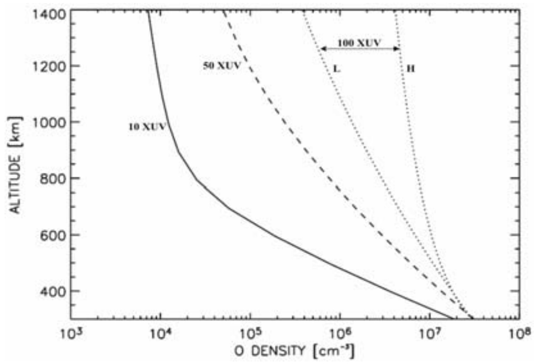

Fig. 2: Atomic oxygen total number density vertical profiles during the Noachian epoch. The profiles include both thermal (cold) and hot (photochemically produced) components. The solid curve shows the O profile for the 10 XUV case, the dashed curve is for the 50 XUV level and the dotted curve are for 100 XUV solar flux. “L” and “H” denote low and high heating efficiency for the 100 XUV flux value.

However, for higher XUV flux values (≤ 50 XUV) the contribution of the O^{hot} becomes negligible. As one can see at 100 XUV flux level the heating efficiency has a very strong effect on the thermospheric temperature and as a consequence on the exobase altitude and thermospheric expansion.

3. Atmospheric erosion of the heated and extended early Martian atmosphere

Mars lacks at present a detectable magnetic field of a global scale (Acuna et al., 1999; Connerney et al., 2004). On the other hand at smaller spatial scales the Martian crust shows a variation of remnant magnetism, which is on average about 10 times more magnetized than that of the Earth`s (Connerney et al., 2004). Thus, the lack of a present-day global magnetic field which would protect the upper atmosphere against solar wind erosion does not exclude that Mars once had an active dynamo, where the remanence was acquired either by thermoremanent magnetization or by an other process like chemical remanent magnetization. Models of core evolution are consistent with both an early magnetic field and a late onset magnetic field (Connerney et al., 2004; Lillis et al., 2006). All of these models cannot predict the strength of the magnetic field, but an early dynamo would most likely be driven by thermal convection while a later onset dynamo would most likely be driven by more efficient chemical compositional convection and latent heat due to inner core freezing (Connerney et al., 2004).

Unfortunately there is yet no observational constraint on the timing of the Martian dynamo. Therefore, we study both cases:

i.) An early Martian dynamo with a minimum and maximum expected magnetic moment $M_{Mars} = 0.1 – 10\ M_{Earth}$ (see Schubert and Spohn, 1990).

ii.) A case corresponding to a later onset of the Martian dynamo after 200 - 250 Myr after the planet's origin, without magnetic protection of the upper Martian atmosphere against the minimum, moderate, and maximum solar wind mass flux of the young Sun (see Wood et al., 2002; 2005).

For studying the erosion the upper atmosphere by O^+ ion pick up we use a numerical test particle model that includes particle motion in the electric and magnetic fields based on the Spreiter-Stahara gas-dynamic model (Spreiter and Stahara, 1980). This model reproduces successfully several ion distributions obtained by Pioneer Voyager on Venus (Luhmann, 1993; Lammer et al., 2006b) and the Soviet Phobos 2 spacecraft plasma measurements on Mars (Lundin et al., 1989; 1990; 1991; Lichtenegger and Dubinin, 1998; Lichtenegger et al., 2002; Lammer et al., 2003).

The total production rate of planetary O^+ ions is calculated by summing photoionization, electron impact and charge exchange rates and is based on the energy dependent charge exchange cross sections used by Kallio et al. (1997) and on the electron impact ionization frequencies given by Cravens et al. (1987). Further, the electron temperature is approximated according to Zhang et al. (1993) and for the calculation of the O^+ ion pick up fluxes 4.5 Gyr ago (100 XUV), 4.37 Gyr ago (70 XUV), and 4.33 Gyr ago (50 XUV) we use the modelled neutral O densities shown in Fig. 2.

The O^+ ion pick up loss rates shown in Table I assume a protection of the early Martian atmosphere against the solar wind mass flux of the young Sun during the first 220 Myr after the planet's origin. The subsolar magnetopause stand-off distance r_s is calculated by determining the magnetic and solar wind ram pressure balance condition at the subsolar point

$$r_s = \left[\frac{\mu_0^2 f_0^2 M_{\rm Mars}^2}{4\pi^2(2\mu_0 n_{\rm sw} m v_{\rm sw}^2 + B_{\rm IMF}^2)}\right]^{1/6} \qquad (1)$$

The value for the intrinsic Martian magnetic moment $M_{\rm Mars}$ at the corresponding time period is taken from Schubert and Spohn (1990) and the magnetopause stand-off distance according to the minimum, moderate and maximum solar wind mass flux of the young Sun decreases during the considered time period from about 13, 10, and 7 Martian radii $r_{\rm Mars}$ above the surface to about 1.9, 1.3, and 0.8 $r_{\rm Mars}$. $B_{\rm IMF}$ is the Interplanetary Magnetic Field (IMF), m is a proton mass, μ_0 and f_0 are magnetic permeability and magnetospheric form-factors, respectively. $n_{\rm sw}$ and $v_{\rm sw}$ are the solar wind density and velocity. One can see that the loss rates for the low heating efficiency case are negligible even if one assumed the maximum solar wind mass flux case for the young Sun of Wood et al. (2002).

Stand-off distances	Low heating efficiency	High heating efficiency
$r_{s_{min}} \sim 1.9\, r_{\rm Mars}$	1×10^{23}	2×10^{28}
$r_{s_{mod}} \sim 1.3\, r_{\rm Mars}$	9.5×10^{23}	5.7×10^{28}
$r_{s_{max}} \sim 0.8\, r_{\rm Mars}$	4×10^{25}	3.3×10^{29}

Table I: O^+ ion pick up escape rates in units of [s^{-1}] corresponding to 70 XUV flux value about 220 Myr after the Sun arrived at the ZAMS and subsolar magnetopause stand-off distances r_s above the surface of about 1.9, 1.3, and 0.8 Martian radii corresponding for minimum, moderate and maximum solar wind plasma conditions (Wood et al., 2002). The value for the intrinsic Martian magnetic moment at the corresponding time period is taken from Schubert and Spohn (1990). The left column corresponds to the low heating efficiency of 8 % and the right column to the high heating efficiency of 32 % in a 96 % CO_2 atmosphere as considered.

A higher heating efficiency results in a hotter and therefore more expanded upper atmosphere and higher loss rates in the order of about 10^{29} s^{-1}. The result presented in Tables I indicate that a strong early magnetic dynamo would have protected the early Martian atmosphere against solar wind erosion so that it remains a mystery why the present Martian surface pressure is only about 7 - 10 mbar and not higher. If one assumes the "highly unlikely" case of the maximum possible solar wind mass flux of Wood et al. (2002; 2005) the upper atmosphere may have lost during the 70 - 50 XUV period about 2 bar. Finally we investigate cases where we assume an early Martian dynamo and a weak magnetic moment MMars = 0.1MEarth during the first 100 Myr (100 XUV) after the Sun arrived at the ZAMS.

Table II shows the results of O+ ion pick up loss rates for subsolar magnetopause stand-off distances of about 1.5, 0.9, and 0.4 rMars corresponding for minimum, moderate and maximum solar wind mass flux conditions (Wood et al., 2002; 2005). As one can see our results in Table II show that Mars could lose about 10 - 25 bar due to ion pick up for higher heating efficiencies even if one assumes the minimum solar wind mass flux obtained by Wood et al. (2002; 2005).

Stand-off distances	Low heating efficiency	High heating efficiency
$r_{s_{min}} \sim 1.5\, r_{\rm Mars}$	$9 \times 10^{26} \sim 0.015$	$7.5 \times 10^{29} \sim 12$
$r_{s_{mod}} \sim 0.9\, r_{\rm Mars}$	$2.5 \times 10^{27} \sim 0.04$	$1 \times 10^{30} \sim 16$
$r_{s_{max}} \sim 0.4\, r_{\rm Mars}$	$1.5 \times 10^{28} \sim 0.25$	$1.5 \times 10^{30} \sim 24$

Table II: O^+ ion pick up escape rates in units of [s^{-1}] and [bar] corresponding to 100 XUV flux values during the first 100 Myr after the Sun arrived at the ZAMS and a weak initial Martian magnetic moment of about $M_{\rm Mars}$ = $0.1 M_{\rm Earth}$ and subsolar magnetopause stand-off distances of about 1.5, 0.9, and 0.4 Martian radii corresponding for minimum, moderate and maximum solar wind conditions (Wood et al., 2002; Lammer et al., 2003). The left column corresponds to the low heating efficiency of 8 % and the right column to the high heating efficiency of 32 % in a 96 % CO_2 atmosphere as considered in our simulations.

On the other hand one can see in Table II, a low heating efficiency yields negligible total atmospheric loss rates during the most active period of the young Sun. Model simulations for the low heating efficiency in an unprotected early Martian upper atmosphere would yield O^+ pick up loss rates during the first 200 Myr depending on the chosen solar wind mass flux from 0.5 bar (minimum) up to 10 bar (maximum). A somewhat higher heating efficiency would result in a more expanded atmosphere and much enhanced loss rates of tens of bar during the early Noachian epoch.

4. Conclusion

Assuming that impact erosion is more or less balanced by impact atmospheric delivery the results of our study indicate that Mars could not lose its initial atmosphere over its history if the upper atmosphere was protected during the first 200 Myr after the planet's origin by a strong early magnetic dynamo. The intrinsic planetary magnetic field would have protected the extended upper atmosphere from the XUV and solar wind induced erosion. We found that a weak early Martian dynamo $\leq 0.1\ M_{\rm Earth}$ or a late onset of the dynamo after the first 200 Myr combined with exobase temperatures of more than 1000 K could have been responsible for the erosion of an early Martian atmosphere, containing several bar to tens of bar of oxygen which may have accumulated after a hydrogen blow-off phase during the accretion period.

Acknowledgements. The authors thank the Austrian Academy of Sciences, "Verwaltungsstelle für Auslandsbeziehungen" and by the Russian Academy of Sciences for supporting working visits to the PGI in Murmansk and Apatity, Russian Federation.

References

Acuna, M.~H., and the MGS/MAG team Global distribution of crustal magnetism discovered by the Mars Global Surveyor MAG/ER experiment. Science, 284, 790-793, 1999.

Bougher, S. W., and G. M. Keating. Structure of the Mars upper atmosphere: MGS Aerobraking data and model interpretation. The Fifth International Conference on Mars, July 19-24, 1999, Pasadena, California, abstract no. 6010., 1999.

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.

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

Connerney, J. E. P., Acuna, M. H., Ness, N. F., and T. Spohn. Mars crustal magnetism. Space Sci. Rev., 111, 1–33, 2004.

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.

Kallio, E., Luhmann, J. G., and S. Barabash. Charge exchange near Mars: The solar wind absorption and energetic neutral atom production. J. Geophys. Res., 102, 22183 -22197, 1997.

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., in press, 2006.

Lammer, H., Kulikov, Yu. N., Lichtenegger, H. I. M. Thermospheric X-ray and EUV heating by the young Sun on early Venus and Mars. Space Sci. Rev., in press, 2006a.

Lammer, H., Lichtenegger, H. I. M., Biernat, H. K., Erkaev, N. V., Arshukova, I. L., Kolb, C., Gunell, H., Lukyanov, A., Holmstrom, M., Barabash, S., Zhang, T. L., and W. Baumjohann. Loss of hydrogen and oxygen from the upper atmosphere of Venus. Planet. Space Sci., in press, 2006b.

Lichtenegger, H. I. M., and E. M. Dubinin. Model calculations of the planetary ion distribution in the Martian tail. Earth Planets Space, 50, 445-452, 1998.

Lichtenegger, H. I. M., Lammer, H., and W. Stumptner. Energetic neutral atoms at Mars: III. Flux and energy distributions of planetary energetic H atoms. J. Geophys. Res., 107, 1279, doi:10.1029/2001JA000322, 2002.

Lichtenegger, H. I. M., H. Lammer, Yu. N. Kulikov, S. Kazeminejad, G. H. Molina-Cuberos, R. Rodrigo, B. Kazeminejad, G. Kirchengast. Effects of low energetic neutral atoms to Martian and Venusian exospheric temperature estimations. Space Sci. Rev., submitted, 2006.

Luhmann, J. G. A model of the ionospheric tail rays of Venus. J. Geophys. Res., 98, 17615-17621, 1993.

Lunine, J. I., Chambers, J., Morbidelli, A., and L. A. Laurie Leshin. The origin of water on Mars. Icarus, 165, 1–8, 2003.

Lundin, R., Zakharov, A., Pellinen, R., Hultquist, B., Borg, H., Dubinin, E.~M., Barabash, S., Pissarenko, N., Koskinnen, H., and I. Liede. First results of the ionospheric plasma escape from Mars. Nature, 344, 609-612, 1989.

Manning, C. V., McKay, C. P., and K. J. Zahnle. Thick and thin models of the evolution of carbon dioxide on Mars. Icarus, 180, 38-59, 2006.

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.

Schubert, G., and T. Spohn. Thermal history of Mars and the sulfur content of its core. J. Geophys. Res., 95, 14095–14104, 1990.

Spreiter, J. R., and S. S. Stahara. Solar wind flow past Venus: Theory and comparisons. J. Geophys. Res., 98, 17,251-17,262, 1980.

Wood, B. E., Müller, H.-R., Zank, G., and J.L. Linsky. Measured mass loss rates of solar-like stars as a function of age and activity. ApJ, 574, 412-425, 2002.

Wood, B. E., Müller, H.-R., Zank, G. P., Linsky, J. L., and S. Redfield. New mass-loss measurements from astrospheric Ly-alpha absorption. ApJ, 628, L143 -L146, 2005.

Zhang, M. H. G., Luhmann, J. G., Nagy, A. F., Spreiter, J. S., and S. S. Stahara. Oxygen ionization rates at Mars and Venus: relative contributions of impact ionization and charge exchange. J. Geophys. Res., 98, 3311-3318, 1993.