

MOMENTUM TRANSPORT IN THE SOLAR WIND EROSION OF THE MARS IONOSPHERE. H. Pérez-de-Tejada, Institute of Geophysics, National University of Mexico, México, D.F.

Introduction: Measurements in the Mars plasma environment indicate that a friction layer develops between the solar wind and that planet's ionosphere. The observed features include a velocity boundary layer in the solar wind that streams around the flanks of the Mars ionosphere, and enhanced planetary particle fluxes in that region. Information on the flow dynamics and ion composition in the Mars plasma environment has been obtained with measurements conducted with the Phobos spacecraft [1]. Flow speed profiles derived from data obtained downstream from Mars show a sharp decrease of the solar wind velocity to the low values that are seen across the wake. Around that region there is also a sharp change in the composition of the particle population. In particular, solar wind protons are dominant in the outer parts of the plasma environment, where the flow speed remains high (~400 km/s), and strong fluxes of planetary O⁺ ions are detected as the spacecraft approaches and moves through the wake where the speed of the proton population has decreased to very low (~ 40 km/s) values. An important implication of the smaller flow speeds measured within the boundary layer is that the solar wind momentum is used to accelerate planetary pickup ions and ionospheric plasma. In particular, the low speeds of the solar wind within the velocity boundary layer implies the removal of most of the incident momentum which can then be employed to produce a plasma flow in the upper ionosphere. It is suggested that a cold plasma flow is present in the tenuous Mars upper ionosphere and that its momentum is provided by the solar wind within the adjacent velocity boundary layer. Following an earlier analysis [2, 3] we will estimate the erosion of the present day ionosphere and the amount of material that could have been removed in the early Mars atmosphere.

Momentum Flux Balance: The thickness of the velocity boundary layer that is necessary to produce the observed changes in the plasma properties through cross-flow transport of solar wind momentum can be derived from the conservation relation

$$\int_0^s [m_{sw} n'_{sw} U_{sw}^2 - m_{sw} n_{sw} U_{sw}^2] dz = \int_{-z}^0 m_i n_i U_i^2 dz \quad (1)$$

where the left hand side indicates the momentum removed from the solar wind and the right hand side depicts the same momentum assimilated by the ionospheric plasma. The density n_{sw} and flow speed u_{sw} apply within the boundary layer in the solar wind

(primed quantities refer to freestream conditions) while n_i and u_i refer to the ionospheric plasma. An approximate solution of this equation was described in [2] in terms of the equivalent momentum flux thickness δ_{sw} and δ_i that replace the integration interval of both integrals (the procedure implies that the deficiency of momentum flux within the boundary layer is replaced by the momentum present in a layer of thickness δ_{sw}). From the solution derived using this technique it is possible to obtain the following relation for the $\delta = \delta_{sw} / \delta_i$ ratio.

$$\delta = (u_i / u'_{sw})^2 (n_i m_i / n'_{sw} m_{sw}) [1 - n''_{sw} u''_{sw}{}^2 / n'_{sw} u'_{sw}{}^2] \quad (2)$$

where the double prime quantities indicate representative values derived from the velocity boundary layer and that are used here within δ_{sw} . The second term in the square bracket indicates the fraction of the solar wind momentum that remains within the boundary layer if there are non-zero n''_{sw} and u''_{sw} values. Equation (2) is alternative to an expression for the ionospheric flow speed u_i that was derived in [2] and that was then used with empirical values of the geometry of the boundary layer around the Venus and Mars ionospheres. Since there was no adequate information on the width of the velocity boundary layer around both planets the calculations led to u_i values given in terms of the δ_{sw} / δ_i ratio. A better use of the same procedure can now be prepared by calculating the δ_{sw} value that is suitable to explain the minimum ionospheric escape flux; that is, it is possible to estimate the thickness of the boundary layer that would be required if the bulk of the upper ionospheric plasma is subject to escape as a result of solar wind momentum transfer.

Erosion in the Present Ionosphere: Equation (2) can be employed by using the values of the solar wind parameters reported in [1]; namely, $u'_{sw} = 400$ km/s, $n'_{sw} = 5$ cm⁻³, and $u''_{sw} = 40$ km/s, $n''_{sw} = 1$ cm⁻³. Calculations for an assumed ionospheric escape flow can then be prepared by using $u_i = 5$ km/s (Mars escape speed) with $m_i = 16 m_{sw}$ for a dominant O⁺ planetary ion population. The results of that calculation lead to values of the δ_{sw} / δ_i ratio as a function of the plasma density n_i in the upper ionosphere. Even though there is no definite information on this latter quantity it is possible to assume that $n_i \approx 300$ -600 cm⁻³ is adequate for the 300-800 km altitude range of the upper ionosphere (values up to 700 cm⁻³ at ~ 800 km altitude

have been inferred from the Phobos observations. The escape particle flux within the ionosphere should then be $\sim 2 \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ which is nearly one order of magnitude larger than the peak ion fluxes reported in [1] from the Phobos measurements across the wake (the detected ion fluxes correspond to particles that move with speeds much larger than the escape flow).

From equation (2) we can thus estimate that $0.1 \leq \delta \leq 0.3$, and hence that $\delta_{\text{sw}} \approx 150 \text{ km}$ for the assumed $\delta_i \approx 500 \text{ km}$ ionospheric width based on the Phobos observations. The implication here is that a narrow velocity boundary layer in the solar wind is required to carry off an ionospheric flow suitable to the low densities observed in the Martian upper ionosphere. The total particle loss eroded from the ionosphere around the planet should be $\sim 2 \cdot 10^{25} \text{ s}^{-1}$ and a total mass loss $\sim 0.5 \text{ kg}$ (for a O^+ population) which is comparable to that estimated from the Phobos measurements [1]. Since the total mass contained in the Mars atmosphere is $\sim 3 \cdot 10^{16} \text{ kg}$ (for a 7 mbar pressure at the surface) the predicted escape flux would remove that material in $\sim 10^9$ years.

Erosion in the Early Mars Ionosphere: Different δ_{sw} values can be predicted for a denser ionosphere that could have existed in the Mars far past. In this case it is possible to assume that the plasma densities were comparable to those currently existing in the Earth or Venus ionospheres even though the configuration of the Mars ionosphere should have been very different. It is useful, however, to consider the implications of assuming that the density in the early Mars upper ionosphere reached values larger than 10^3 cm^{-3} as it is currently the case in the Venus upper ionosphere. As in that planet the thickness of the ionosphere at the terminator may have reached 1000 km so that if $n_i = 2000 \text{ cm}^{-3}$ we have $\delta = 1$ in equation (2) and thus $\delta_{\text{sw}} = 1000 \text{ km}$ around the terminator. This thickness of the velocity boundary layer is not contradictory to that inferred from the PVO plasma data for the boundary layer present around the Venus ionosphere. Measurements show that this feature is nearly 1000 km thick in the downstream vicinity of the terminator [3] and thus represents a viable view of what could have occurred in a dense Mars ionosphere. The large δ_{sw} value expected in the early Mars conditions results from the high total plasma content that may

have existed in the upper ionosphere. With densities larger than 10^3 cm^{-3} and $\delta_i \geq 10^3 \text{ km}$ we find that equation (2) leads to δ_{sw} values that are over an order of magnitude larger than those inferred from the Phobos measurements and in addition that are restricted by geometric constraints. For example, with $n_i = 10^4 \text{ cm}^{-3}$ and $\delta_i = 10^3 \text{ km}$ we obtain $\delta_{\text{sw}} = 5000 \text{ km}$ which is far larger than the values inferred from measurements of the boundary layer around the Venus ionosphere. It is unlikely that the density and the thickness of the early Mars upper ionosphere exceeded those seen in the Venus ionosphere but it is possible that with comparable values the velocity boundary layer in both cases had a similar geometry.

From equation (2) it can also be estimated that with fixed values of the $\delta = \delta_{\text{sw}}/\delta_i$ ratio the flow speed u_i decreases with larger ionospheric densities n_i and can thus become smaller than the escape speed. With $\delta = 1$ the ionospheric flow can escape from Mars if $n_i \leq 2 \cdot 10^3 \text{ cm}^{-3}$ but with larger densities the flow speed is smaller than the escape velocity and the flow remains captive to the gravitational field. When $\delta = 2$ the ionospheric flow can escape from Mars up to $n_i = 5 \cdot 10^3 \text{ cm}^{-3}$ which implies a dense population in the upper ionosphere. This case may represent the upper limit of a suitable boundary layer since $\delta_{\text{sw}} = 2000 \text{ km}$ (obtained with $\delta_i = 1000 \text{ km}$) is already larger than the values inferred from observations around the Venus ionosphere. Independent of these numbers it is therefore possible that an ionospheric density within $10^3 \text{ cm}^{-3} \leq n_i \leq 2 \cdot 10^3 \text{ cm}^{-3}$ and the value $\delta \approx 1$ could fit better the geometry suggested for the Mars early ionosphere. Within this range of values we would expect a total particle flux $\sim 2 \cdot 10^{26} \text{ s}^{-1}$ moving with the escape speed and, as a result, an effective mass loss $\sim 7 \text{ kg/s}$. This amount is one order of magnitude larger than that suggested for the present day conditions and implies the removal of a mass comparable to that of a few meter-deep global layer of water that could have been eroded over the $4.5 \cdot 10^9$ years of martian history.

References: [1] Lundin R. et al. (1990) *GRL*, 17, 873. [2] Perez-de-Tejada H. (1986) *JGR.*, 91, 6765. [3] Perez-de-Tejada H. (1998) *JGR.*, 103, 31499.