Solar Wind Interaction with Venus and Mars

Y. J. Ma[1], A. F. Nagy[2] , C. T. Russell[1], D. Najib[2] , G. Toth[2]

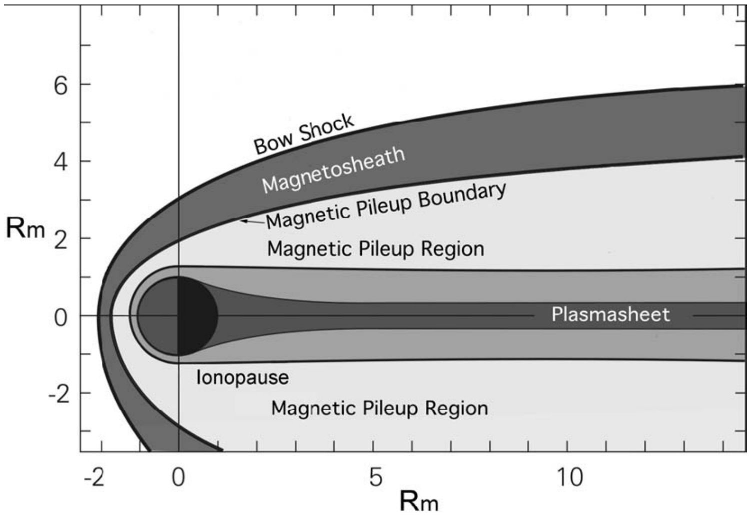
[1]Institute of Geophysics and Planetary Physics, UCLA

[2]Atmospheric, Oceanic, and Space Sciences, University of Michigan

Physical Parameters of Representative Non-magnetic Solar System Bodies

	Venus	Mars	Europa	Titan
radius	6052 km	3396 km	1569 km	2575 km
distance	118×10^6 km 0.79 AU	228×10^6 km 1.52 AU	6.7×10^5 km 9.39 R_J	1.22×10^6 km 20.28 R_S
gravity	8.87 m/sec^2	3.72 m/sec^2	1.3 m/sec^2	1.35 m/sec^2
mass	48.7×10^{23} kg	6.42×10^{23} kg	4.8×10^{22} kg	1.35×10^{23} kg
M_s	6.5	7.2	3.7	0.9
M_A	6.2	15.3	0.2	1.1

Solar Wind Interaction with an Unmagnetized Planet



From *Nagy et al.*, 2004

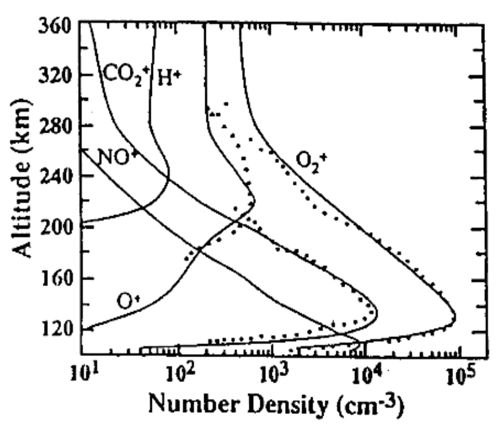
Relevant Mars Missions:

Relevant Past Missions:

Viking 1 and 2 Landers, Phobos and MGS

Current Mission:

Mars Express



Measured and calculated ion densities for the dayside ionosphere of Mars.

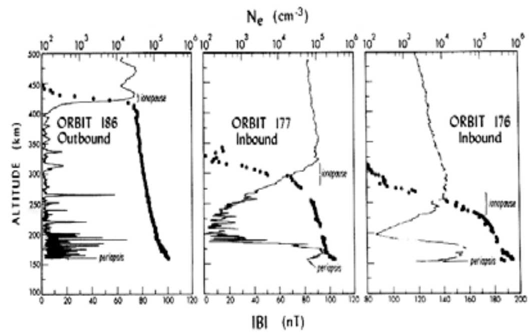
Relevant Venus Missions:

Relevant Past Mission:

Pioneer Venus Orbiter

Current Mission:

Venus Express



Magnetized ionosphere vs. unmagnetized ionosphere.

Numerical Studies of Venus

MHD models:

- **1D multi-species model:** *Shinagawa and Cravens*, [1988]
- **2D model:** *Shinagawa* [1996]
- **3D model**: *Wu.* [1992], *Tanaka* [1993], *McGary and Pontius* [1994], *Cable and Steinolfson* [1995], *Murawski and Steinolfson* [1996], *Kallio et al.*, [1998]
- **3D 2-species model:** *Tanaka and Murawski* [1997], *Tanaka* [2000]
- **3D multi-fluid model:** *Terada et al.*, [2009]

Hybrid models:

- **2D:** *Terada et al.*, [2002, 2004]
- **3D:** *Kallio et al.*, [2006, 2008], *Jarvinen et al.*, [2008], *Liu et al.*, [2009]

Numerical Studies of Mars

MHD model:

2D model: *Shinagawa and Bougher* [1999]

2D two-fluid MHD model: *Sauer and Dubinin* [2000]

3D model: *Bauske et al.* [2000]

3D multi-species model: *Liu et al.* [1999, 2001], *Ma et al.*, [2002, 2004, 2007]

3D non-ideal, multi-fluid MHD model: *Harnett and Winglee* [2003, 2005, 2007, 2009], *Najib et al.*, [2008, 2009]

Hybrid model:

3D: *Kallio and Janhunen* [2002, 2006, 2008]

3D: *Simon et al.* [2006]

3D: *Modolo et al.* [2005]

Multi-Species Single Fluid MHD Equations

➢**Continuity Equations:**

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i \mathbf{u}) = S_i - L_i$$

$$S_i = m_i n_i (\nu_{ph,i} + \sum_{s=ions} k_{si} n_s)$$

$$L_i = m_i n_i (\alpha_{R,i} n_e + \sum_{t=neutrals} k_{it} n_t)$$

➢**Momentum Equation:** $\left(\rho = \sum_{i=ions} \rho_i \right)$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + p\mathbf{I} + \frac{B^2}{2\mu_0}\mathbf{I} - \frac{1}{\mu_0}\mathbf{B}\mathbf{B} \right) = \rho \mathbf{G} - \sum_{i=ions} \rho_i \sum_{t=neutrals} \nu_{it} \mathbf{u} - \sum_{i=ions} L_i \mathbf{u}$$

Multi-Species Single Fluid MHD Equations

➢**Magnetic Induction Equation:**

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{uB} - \mathbf{Bu}) = 0$$

➢**Energy Equation** $\left(\varepsilon = \frac{1}{2}\rho u^2 + \frac{1}{\gamma - 1} p + \frac{1}{2\mu_0} B^2 \right)$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left(\mathbf{u}\left[\varepsilon + p + \frac{1}{2\mu_0} B^2 \right] - \frac{1}{\mu_0} (\mathbf{B} \cdot \mathbf{u})\mathbf{B} \right) =$$

$$\rho \mathbf{u} \cdot \mathbf{G} - \sum_{i=ions} \sum_{t=neutrals} \frac{\rho_i \nu_{it}}{m_i + m_t} [3k(T_n - T_i) - m_i u^2]$$

$$-\frac{1}{2} \sum_{i=ions} L_i \mathbf{u}^2 + \frac{k}{\gamma - 1} \sum_{i=ions} \left(\frac{S_i T_n - L_i T_i}{m_i} - \frac{\rho_i}{m_i} \alpha_{R,i} n_e T_e \right)$$

Multi-species Global MHD Model for Venus and Mars

- **Four-species single-fluid MHD model**
  - **Calculate densities of H^+, O_2^+, O^+, CO_2^+**
  - **Use single momentum and energy equations considering the effect of ion-neutral collisions.**
- **Spherical grids**:
  - **Computational domain:** –16R$_p$ ≤ X ≤ 8 R$_p$, –10R$_p$ ≤ Y, Z ≤ 10 R$_p$
  - **Radial resolution is 10 km to 600km**
  - **Angular resolution is 2.5^0 to 5.0^0**
- **Inner Boundary Conditions**
  - **Inner boundary at 100 km**
  - **[O2+] , [O+] and [CO2+] are in photochemical equilibrium (SZA and optical depth considered).**
  - **Zero gradient for U and B**

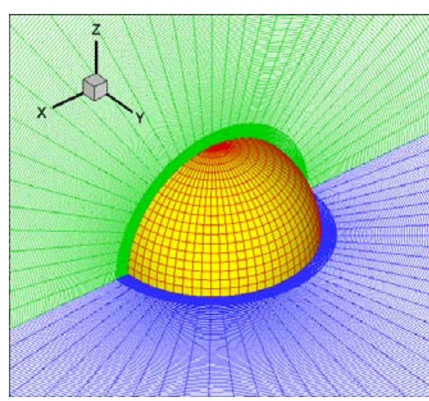
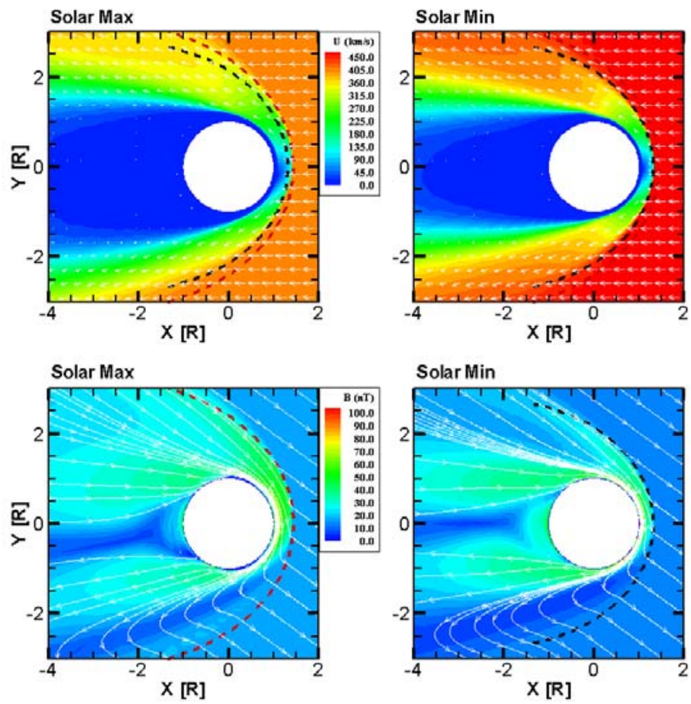


Illustration of the grid system used in the calculation (total 3.5×10[6] cells, a typical run requires 2000 process-hours).

Table: List of chemical reactions and rates considered in the Mars model

Reaction	Rate coefficient	References
$CO_2 + hv \rightarrow CO_2^+ + e$	7.30×10^{-7} s^{-1} (solar max) 2.47×10^{-7} s^{-1} (solar min)	Schunk&Nagy, 2000
$O + hv \rightarrow O^+ + e$	2.73×10^{-7} s^{-1} (solar max) 8.89×10^{-8} s^{-1} (solar min)	Schunk&Nagy, 2000
$H + hv \rightarrow H^+ + e$	8.59×10^{-8} s^{-1} (solar max) 5.58×10^{-8} s^{-1} (solar min)	Fox [private communication]
$CO_2^+ + O \rightarrow O_2^+ + CO$	1.64×10^{-10} $cm^{-3}s^{-1}$	Schunk&Nagy, 2000
$CO_2^+ + O \rightarrow O^+ + CO_2$	9.60×10^{-11} $cm^{-3}s^{-1}$	Schunk&Nagy, 2000
$O^+ + CO_2 \rightarrow O_2^+ + CO$	1.1×10^{-9} $(800/Ti)^{0.39}$ $cm^{-3}s^{-1}$	Fox and Sung, 2001, JGR
$O^+ + H \rightarrow H^+ + O$	6.4×10^{-10} $cm^{-3}s^{-1}$	Schunk&Nagy, 2000
$H^+ + O \rightarrow O^+ + H$	5.08×10^{-10} $cm^{-3}s^{-1}$	Fox and Sung, 2001, JGR
$O_2^+ + e \rightarrow O + O$	7.38×10^{-8} $(1200/Te)^{0.56}$ $cm^{-3}s^{-1}$	Schunk&Nagy, 2000
$CO_2^+ + e \rightarrow CO + O$	$3.10\times10^{-7}(300/Te)^{0.5}$ $cm^{-3}s^{-1}$	Schunk&Nagy, 2000

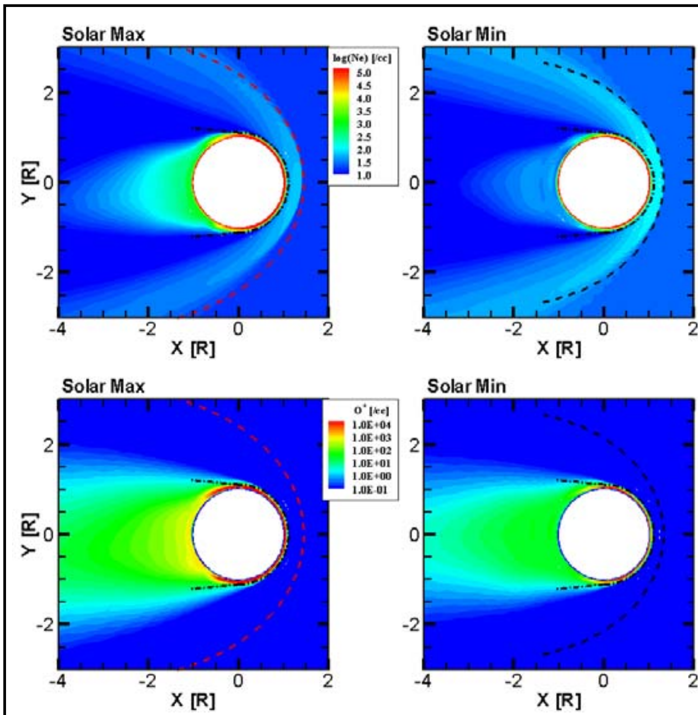
Model Results for Venus



Subsolar shock location
Solar max: 1.44 R_V
Solar min : 1.33 R_V

Without ionosphere
Subsolar shock location
Solar max: 1.32 R_V
Solar min : 1.25 R_V

Contour of plasma speed and magnetic field in the equatorial plane for solar max (left panels) and solar min (right panels) cases. The red dashed line is the average bow shock location at solar max condition from Zhang et al., (1990), taken to be R= 2.40/(1+0.66*cos(SZA)); while the black dashed line is the mean bow shock locations at solar min condition from Zhang et al. (2008), taken to be R= 2.14/(1+0.62*cos(SZA)).



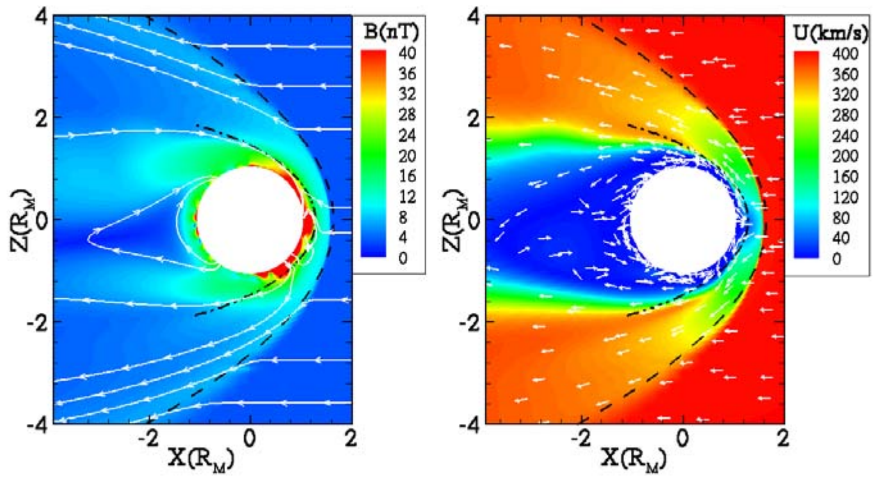
Contour of the electron number density and O^+ in the equatorial plane for solar max and solar min cases. The black dash-dot lines indicate the Ion Composition Boundary (ICB) for solar minimum condition from Martinecz et al., (2008).

Ion Escape fluxes

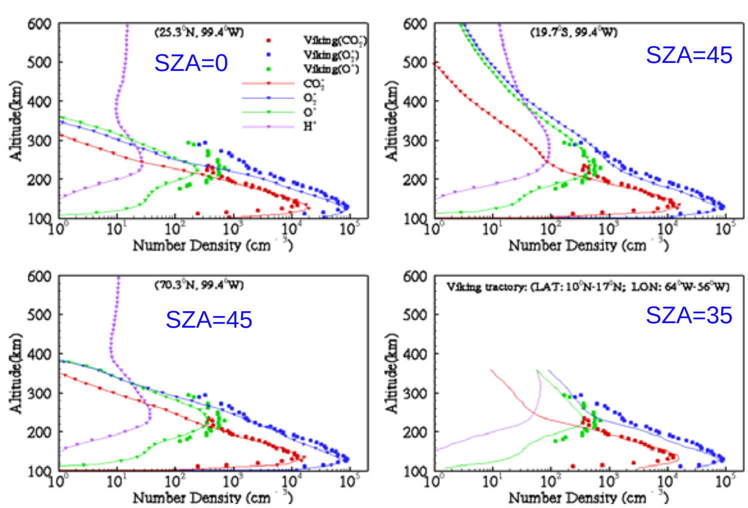
	Solar max flux(s^{-1})	Solar min flux(s^{-1})
O^+	3.9×10^{25}	4.3×10^{25}
O_2^+	1.2×10^{25}	1.8×10^{25}
CO_2^+	1.4×10^{22}	1.0×10^{22}
total	5.1×10^{25} 1.68 kg/s	6.1×10^{25} 2.06 kg/s

Model Results for Mars

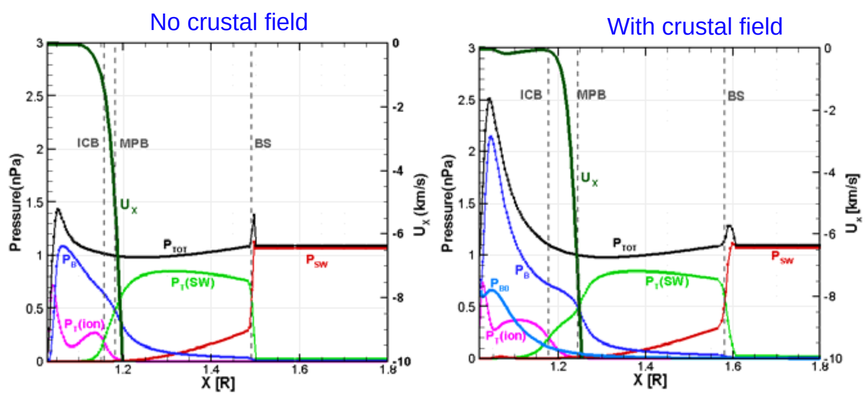
The calculated magnetic field and velocity in the meridianal plane. The color plots show the magnitudes; the white lines marked with arrows indicate the vector direction of the magnetic field and the arrows show the direction (not the magnitude) of the velocity. The dashed line represents the observed mean bow shock and the dash-dot line is the mean MPB locations. (Ma et al., 2004)



The calculated solar cycle minimum density profiles for case4 along radial lines for different latitudes in the X-Z plane compared with Viking observation. (Ma et al., 2004)



Effect of crustal fields



Locations of Subsolar Boundaries.

	No crustal field	With crustal field
BS	1.49 R_M	1.58 R_M
MPB	1.18 R_M	1.24 R_M
ICB	1.16 R_M	1.18 R_M

	Solar cycle	Crustal sources	IMF	Subsolar position	Subsolar BS(R_M)	Averaged terminator BS(R_M)	Subsolar MPB(R_M)
Case1	Maximum	Included	3nT Parker spiral	180^0W 0^0N	1.58	2.68	1.24
Case2	Maximum	Included	B_y=3nT	180^0W 0^0N	1.59	2.73	1.24
Case3	Minimum	Included	3nT Parker spiral	180^0W 0^0N	1.54	2.58	1.22
Case4	Minimum	Included	3nT Parker spiral	99.4^0W 25.3^0N	1.43	2.44	1.13
Case5	Minimum	Not included	3nT Parker spiral	N/A	1.39	2.33	1.11

Related parameters of selected cases and the calculated subsolar bow shock location. Observed Subsolar BS location:(1.64±0.08)R_M(*Vignes, et. al*, 2000), terminator BS location: (2.62±0.33)R_M(*Vignes, et. al*, 2002) and subsolar MPB location: (1.29±0.04)R_M (*Vignes, et. al*, 2000).

Table 1. Input Parameters Used for the Different Calculations

	Solar Wind Density, cm^{-3}	Solar Wind Velocity, km/sec	Solar Condition	"Position" of Crustal Field
Case 1	2	300	solar minimum	0°
Case 2	2	300	solar minimum	90°
Case 3	2	300	solar minimum	180°
Case 4	4	400	solar minimum	0°
Case 5[a]	2	300	solar minimum	0°
Case 6	4	400	solar maximum	0°
Case 7[b]	20	1000	solar maximum	0°

[a]Case 5 is the same as case 1 except that charge exchange and impact ionization of the corona were not included.
[b]The magnetic field was set to B_y = 20 nT for case 7.

Table 2. Calculated Escape Rate[a]

	O^+	O_2^+	CO_2^+	Total
Case 1	3.3×10^{23}	1.00×10^{23}	5.7×10^{22}	4.9×10^{23}
Case 2	4.7×10^{23}	2.8×10^{23}	1.1×10^{23}	8.6×10^{23}
Case 3	4.4×10^{23}	2.5×10^{23}	1.2×10^{23}	8.1×10^{23}
Case 4	7.2×10^{23}	1.9×10^{23}	1.3×10^{23}	1.0×10^{24}
Case 5	1.3×10^{23}	9.3×10^{22}	4.9×10^{22}	2.7×10^{23}
Case 6	1.8×10^{24}	4.1×10^{23}	1.8×10^{23}	2.4×10^{24}
Case 7	2.3×10^{25}	3.3×10^{24}	4.1×10^{24}	3.0×10^{25}

[a]Escape rates in sec^{-1}.

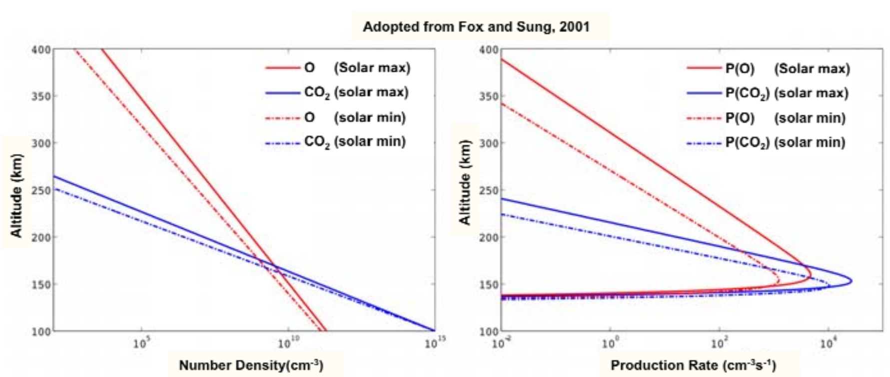
Martian Escape rates, from *Ma and Nagy*, [2007]

Summary

- Our 4-species MHD model applies to both Venus and Mars. This model uses a spherical grid structure with a good radial resolution to represent the ionosphere.
- The MHD model results for Venus are consistent with the PVO and VEX measured bow shock and ICB locations. The model results show that a realistic ionosphere and related physical processes are critical in determining the shock location.
- The MHD model results for Mars are consistent with the MGS measured bow shock and ICB locations. Bow shock location of Mars does not have an strong solar cycle dependence, instead, the orientation of the crustal sources play important roles in determine the shock locations.
- According to our calculation, plasma escape rate for Venus is at least an order of magnitude more than that of the Mars. The calculated fluxes are in reasonable agreement with the ones measured by ASPERA.

Thank You!

Model Input for Solar max and Solar min Cases



Solar max case

n_{SW} = 17.0 cm^{-3}; $\mathbf{V}_{SW}$ = 400 km/s; $\mathbf{B}_{IMF}$= 15.0 nT(36^0 parker spiral), T_p = 2.5e5 K

=>P_D=4.5 nPa, M_f=4.5

Solar min case

n_{SW} = 25.0 cm^{-3}; $\mathbf{V}_{SW}$ = 450 km/s; $\mathbf{B}_{IMF}$= 9.6 nT(36^0 parker spiral), T_p = 3.0e5 K

=>P_D=8.4 nPa, M_f=6.4

Terminator Shock Locations – Mars vs. Venus

Venus

PVO $2.39 \pm 0.21\ R_v$ (Solar max) Slavin et al., [1991]

PVO $2.14\ R_v$ (Solar min) Zhang et al., [2007]

Mars

Phobos $2.66 \pm 0.49\ R_M$ (Solar max) Slavin et al., [1991]

MGS $2.62 \pm 0.33\ R_M$ (Solar med) Vignes et al., [2000]