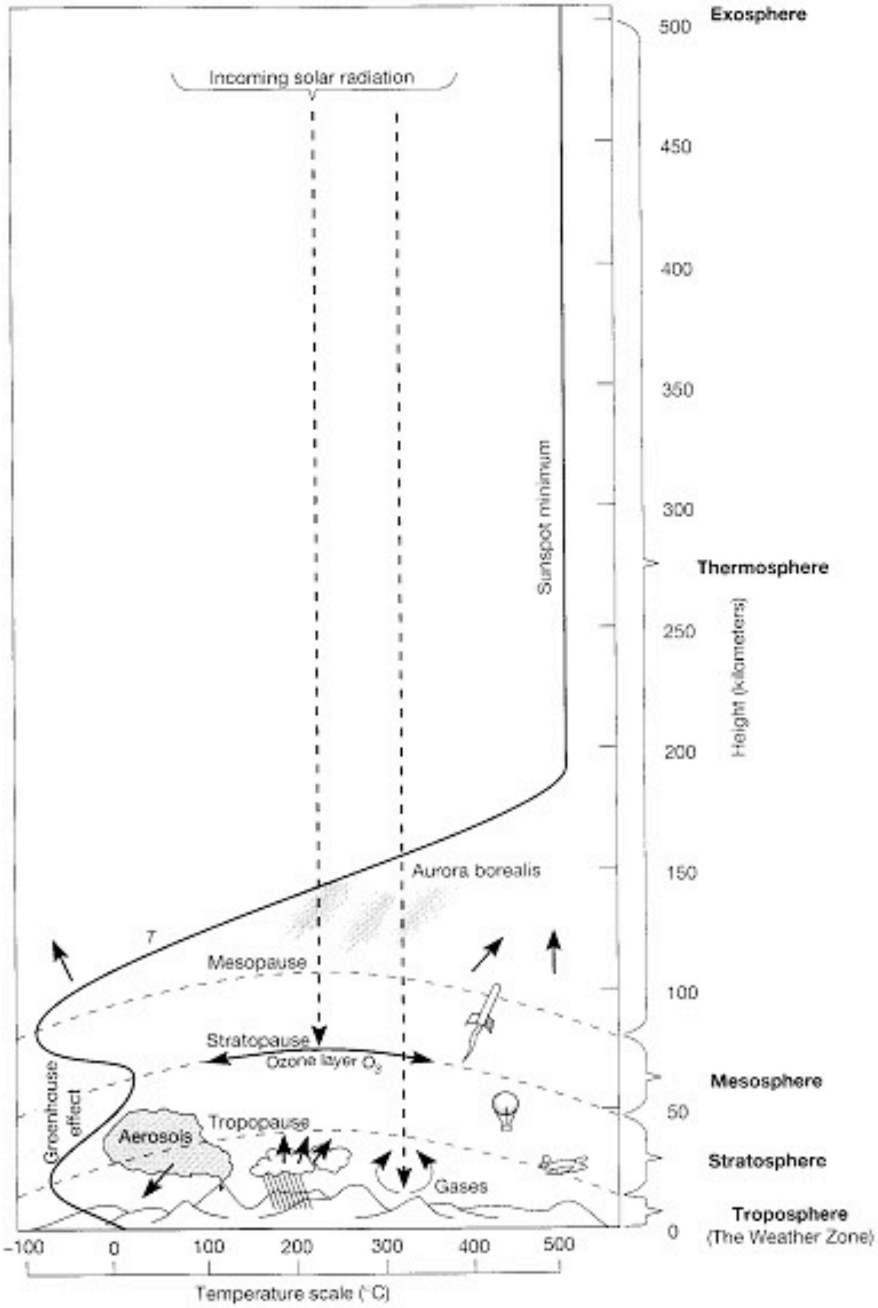
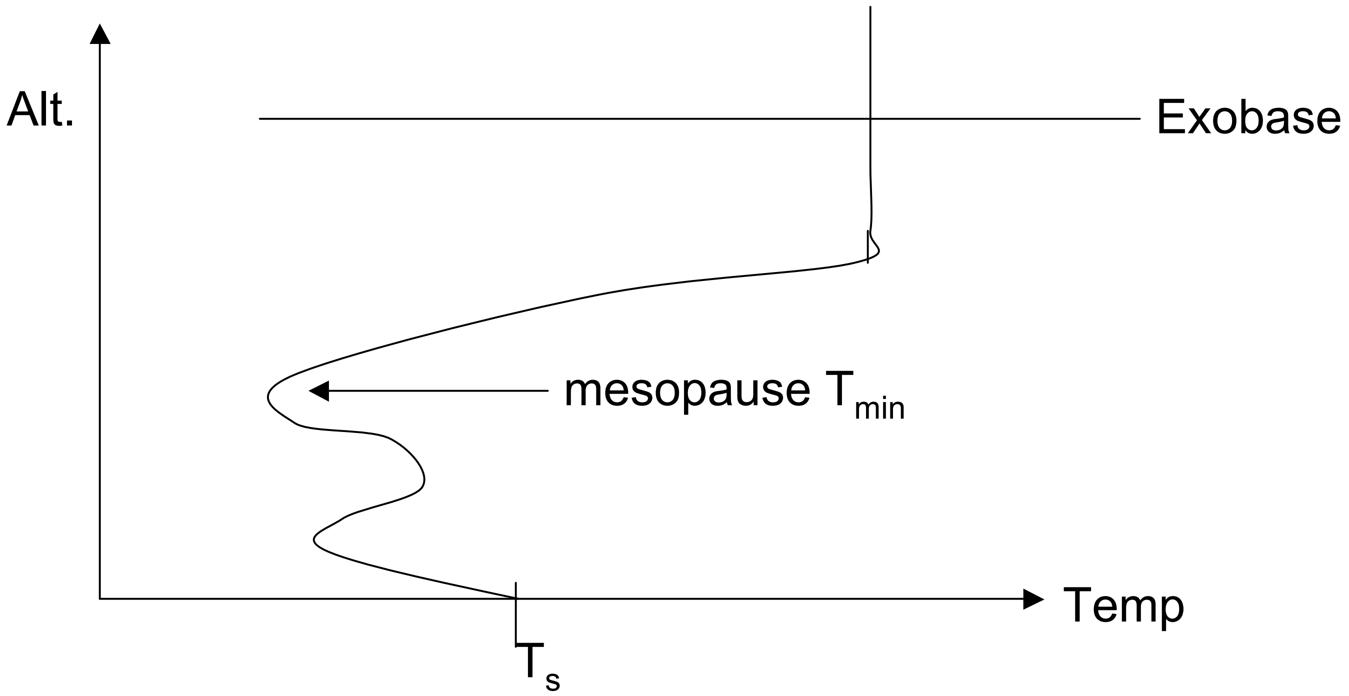
Exospheres


Incoming solar radiation
Sunspot minimum
Aurora borealis
T
Mesopause
Stratopause
Ozone layer O_3
Tropopause
Greenhouse effect
Aerosols
Gases
-100
0
100
200
300
400
500
Temperature scale (°C)
500
450
400
350
300
250
200
150
100
50
0
Height (kilometers)
Exosphere
Thermosphere
Mesosphere
Stratosphere
Troposphere
(The Weather Zone)

Exospheres



Below mesopause – atmosphere heated from below

Above mesopause – atmosphere heated from above

EUV radiation absorbed

Lower thermosphere: convection is principle process of heat transport

Upper thermosphere: conduction is principle process of heat transport

⇒Leads to isothermal region (thermopause)

At altitudes > thermopause

⇨ Mean free path becomes large

⇨ Collisions become negligible

⇨ For some constituents $v_{Th} > v_{esc}$

exosphere ⟶ Cross-section for neutral collision exceeds neutral scale height

Exobase: mean free path ≈ local scale height

Exosphere:

1) velocity distributions are non-Maxwellian due to escape of high velocity particles (loss of tail of the distribution)

2) density does not strictly follow barometric formula
   ⟶ must be derived by considering the individual ballistic components of the atmospheric gas

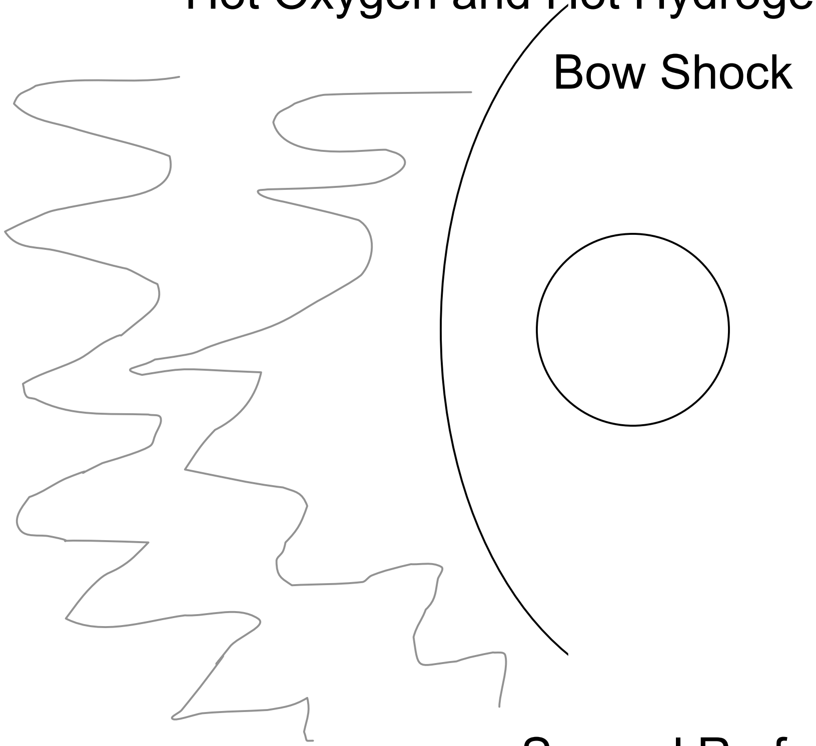
3) average neutral on a ballistic (collisionless) trajectory

Exosphere not really important at Earth, but is at planets which are weakly magnetized

→ Venus, Mars

Ion Pick-up

Hot Oxygen and Hot Hydrogen Neutral Corona



Several R_M from surface

Origin: Dissociative Recombination

$$O_2^+ + e^- \rightarrow \underbrace{O^* + O^*}$$

→ Energetic Neutrals

$$H_2^+ + e^- \rightarrow \overbrace{H^* + H^*}$$

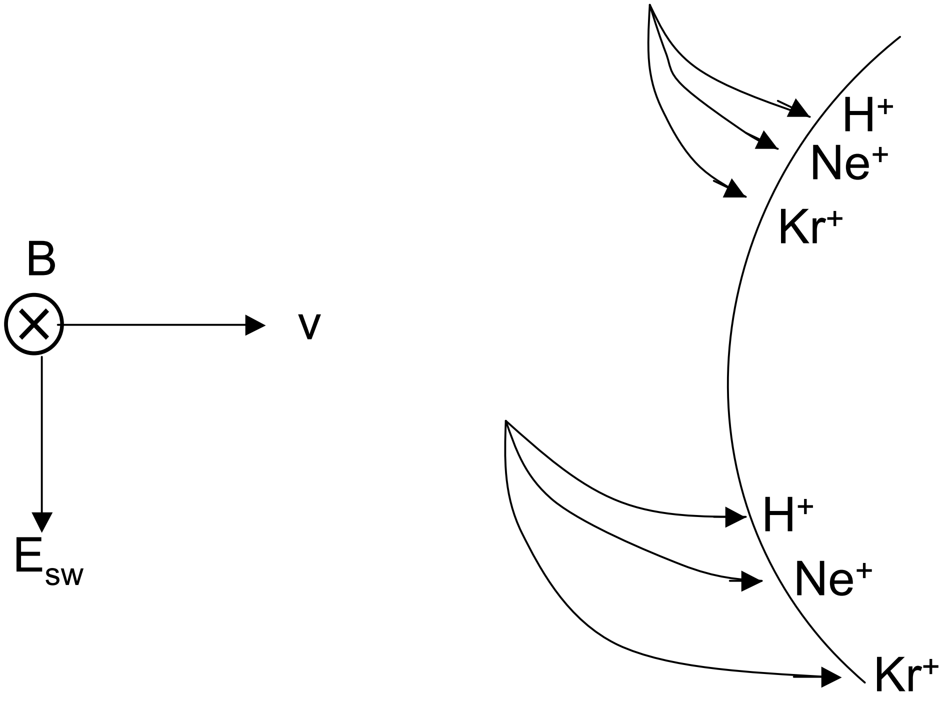
Once neutrals are ionized they are

⇒ picked up by the solar wind (pick-up ions)

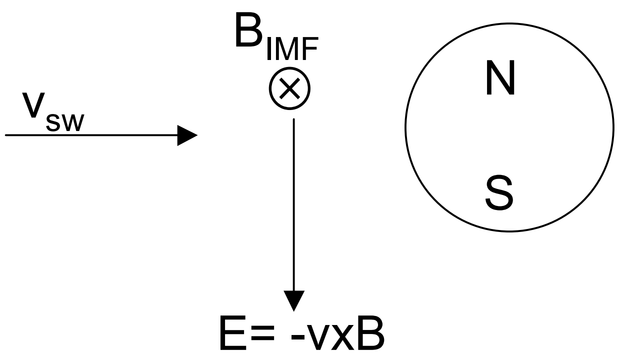
⇒ mass loads the solar wind

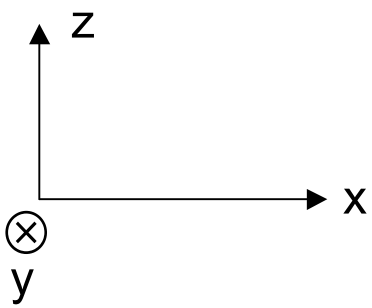
⇒ changes the dynamic pressure

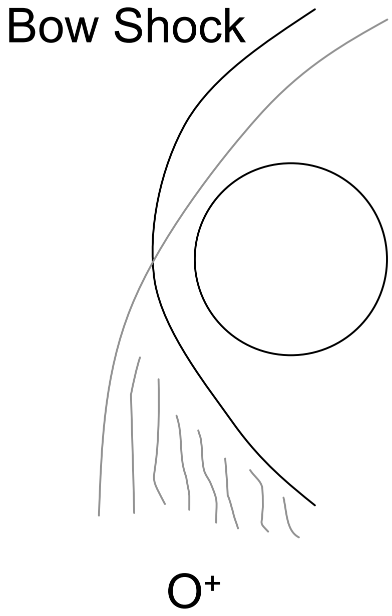
The pick-up process is through the solar wind convection electric field



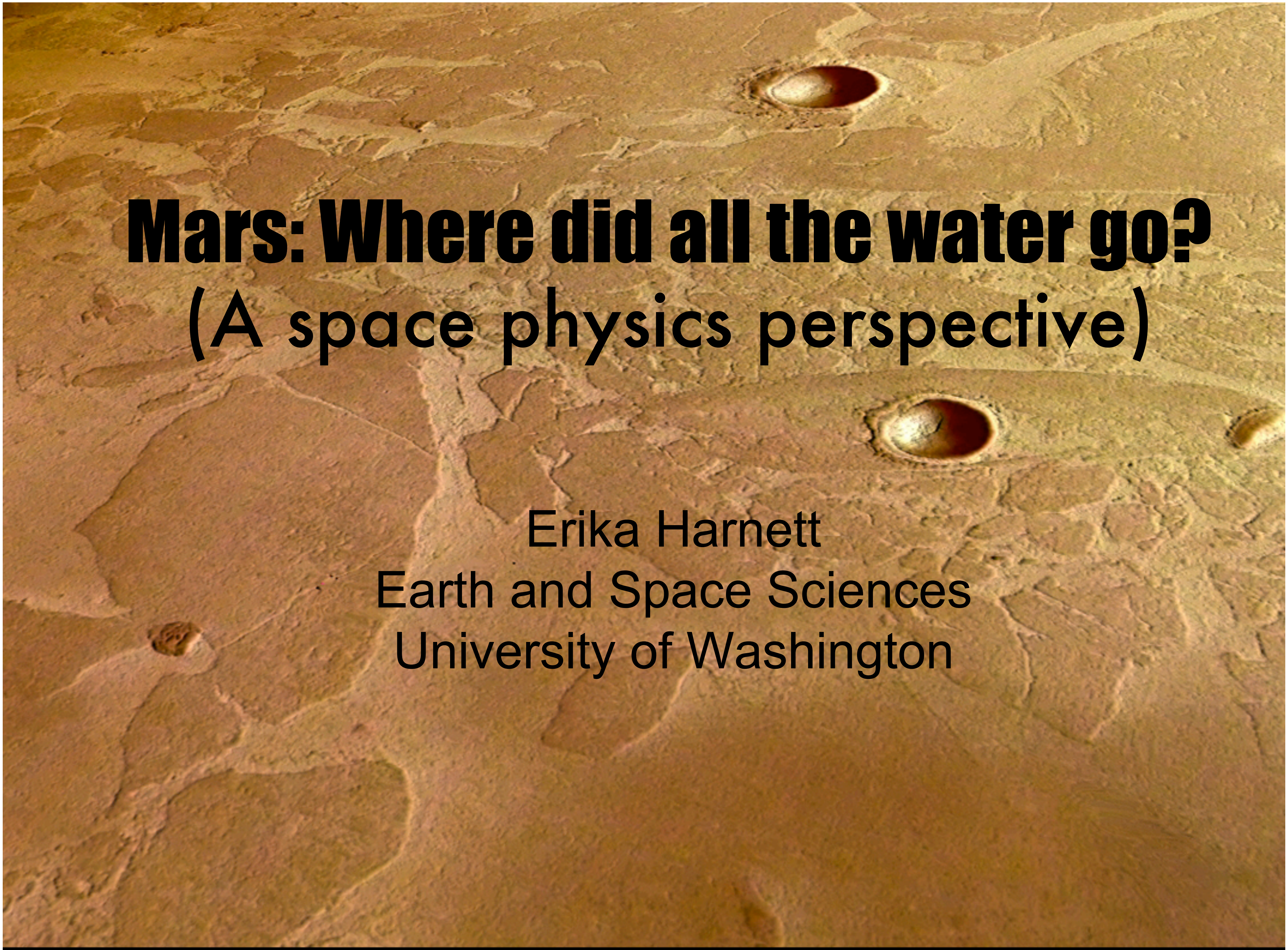
Ion gyro-radius a function of mass







⇒ Assymetric Bow Shock

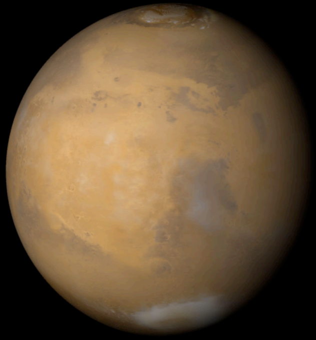


copyright: ESA/DLR/FU Berlin (G. Neukum)

Mars: Where did all the water go?
(A space physics perspective)

Erika Harnett
Earth and Space Sciences
University of Washington

A Short History of Mars

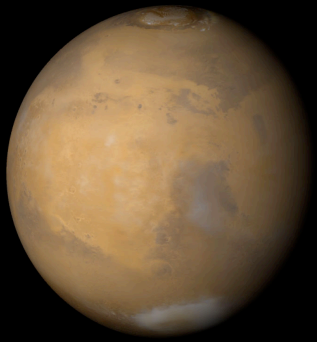


Noachian Era : 4.5 Ga – 3.5 Ga
(end = end of heavy bombardment)

- Active erosion
- Intense volcanic activity
- Lakes and Oceans?
- Dynamo magnetic field disappeared
- Impacts drove 80-95% of atmospheric loss

Manning et al., 2006; and references therein

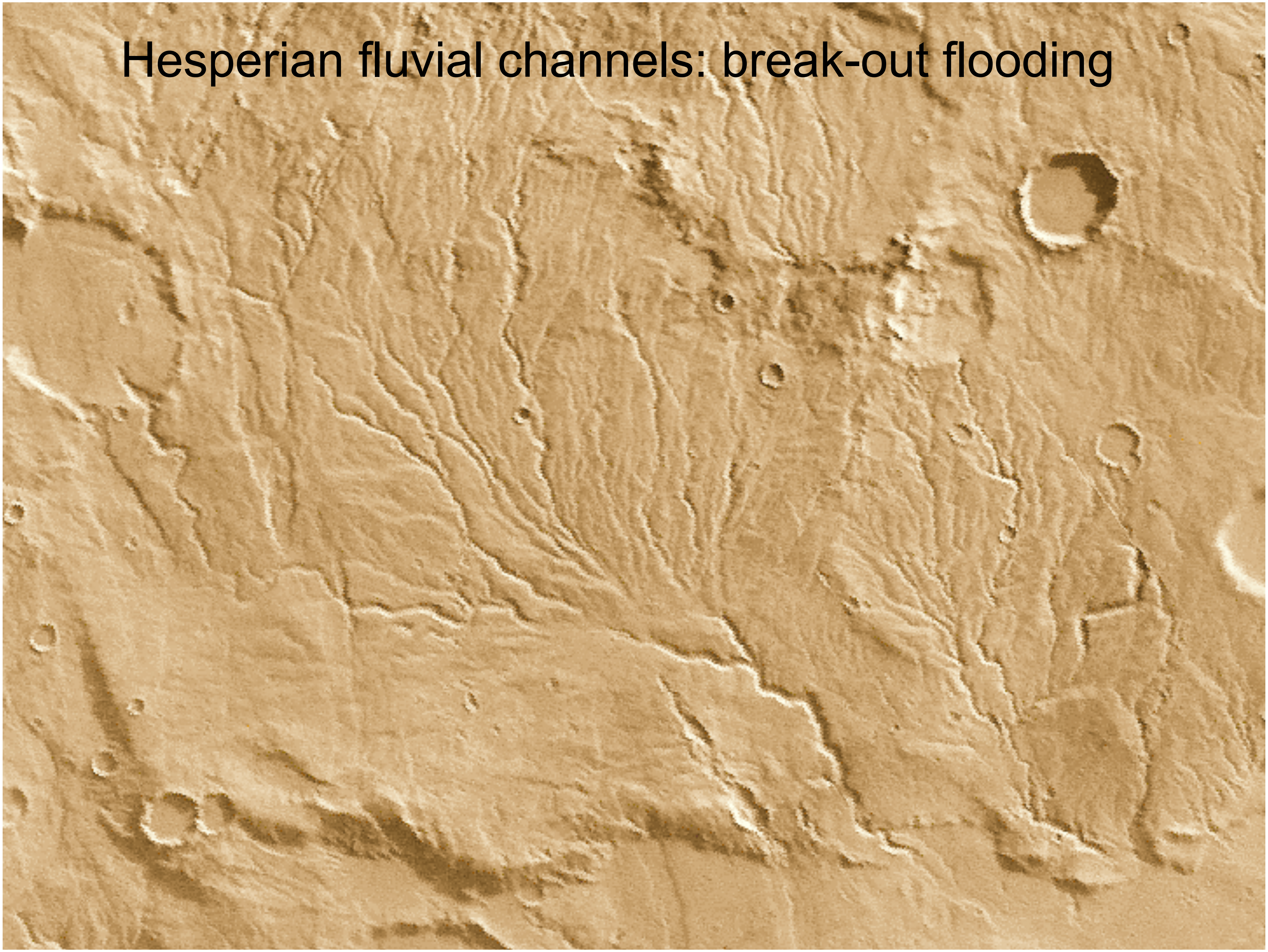
A Short History of Mars



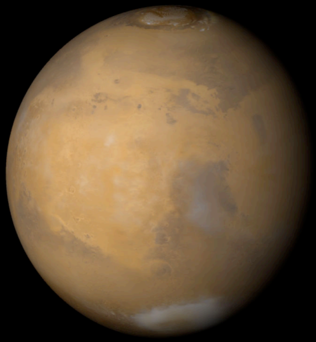
Hesperian Era : 3.5 Ga – 2 Ga
(end = disappearance of liquid water)

- Transition Era
- River forming activity
- Migration of water to polar caps and underground
- Partial resurgence of a dynamo magnetic field
- Atmospheric loss through mass selective method

Hesperian fluvial channels: break-out flooding



A Short History of Mars

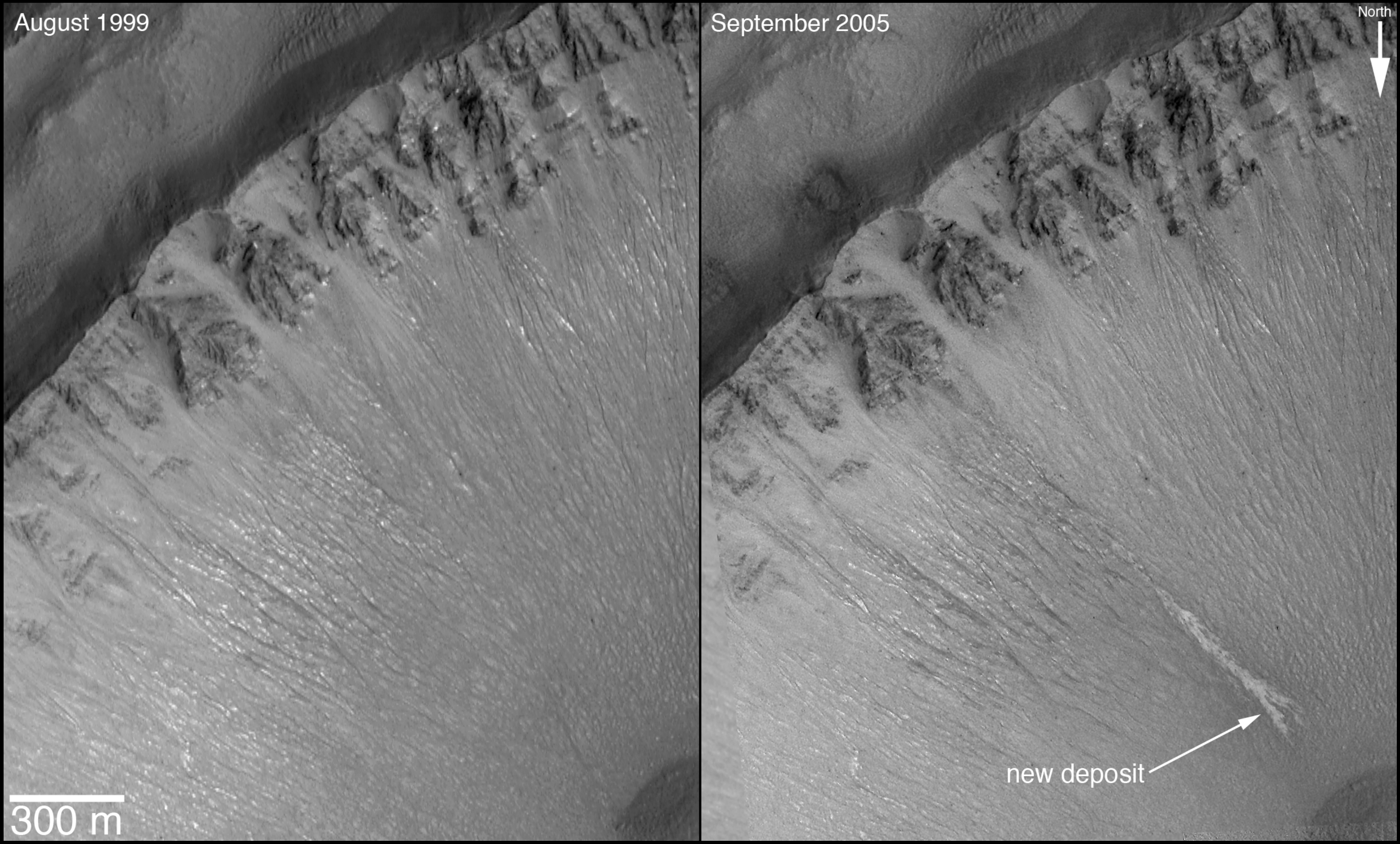


Amazonian Era : 2 Ga – present

- Dusty, dry conditions
- Occasional volcanic activity
- Occasional break-outs of water – impact driven

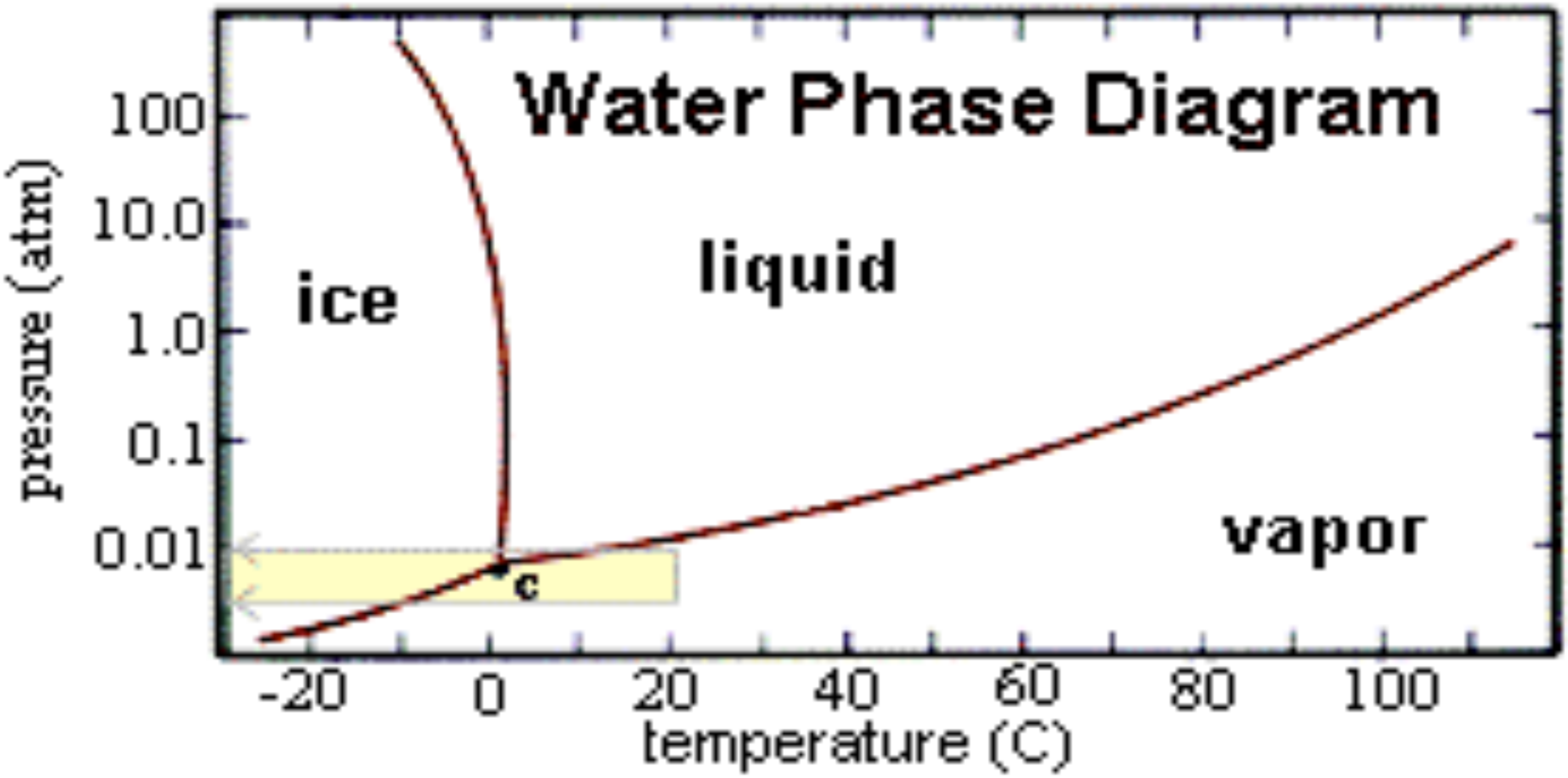
Water on Mars ?

Current ‘seepage channels’

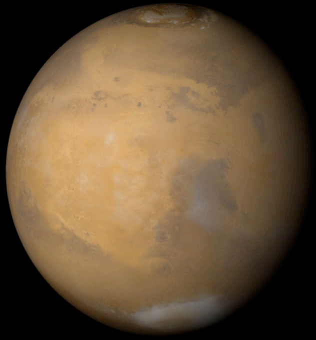


MGS: NASA/JPL/Malin Space Science Systems

Water on Mars ?



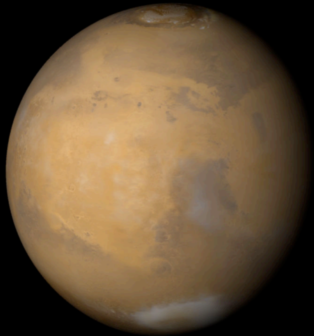
Atmospheric Composition



Venus	Earth	Mars
96.5% CO_2, 3.5% N, traces of SO_2, Ar, H_2O	77% N, 21% O, traces of Ar ,CO_2	95.3% CO_2, 2.7% N, 1.6% Ar, traces of O, H_2O

What was the past atmospheric composition like?

Atmospheric Composition



Past liquid water: 150 mb of CO_2
Current : 7-8 mb of CO_2

Old Convensional Wisdom:

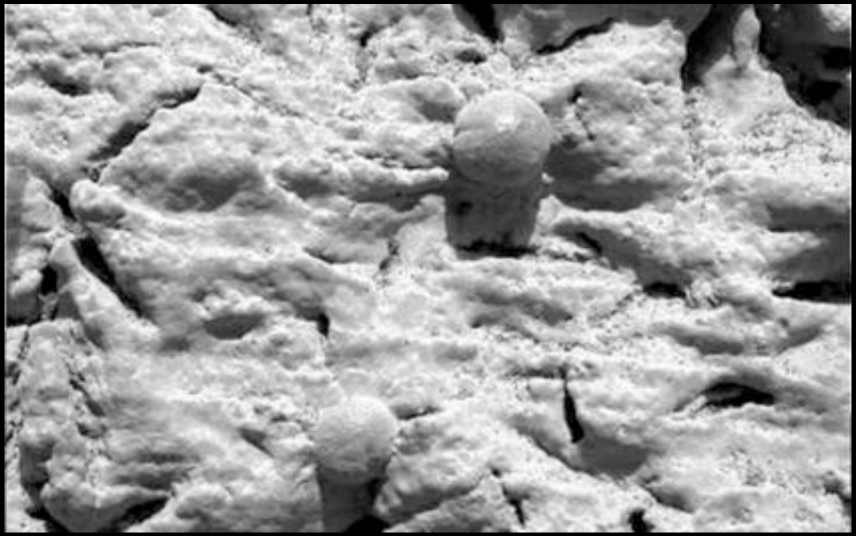
More CO_2 → greenhouse effect → carbonate rock (not seen)

Then MER landed!

Blueberries = concretions

Form in aquious fluids

In every layer looked at in
Eagle crater



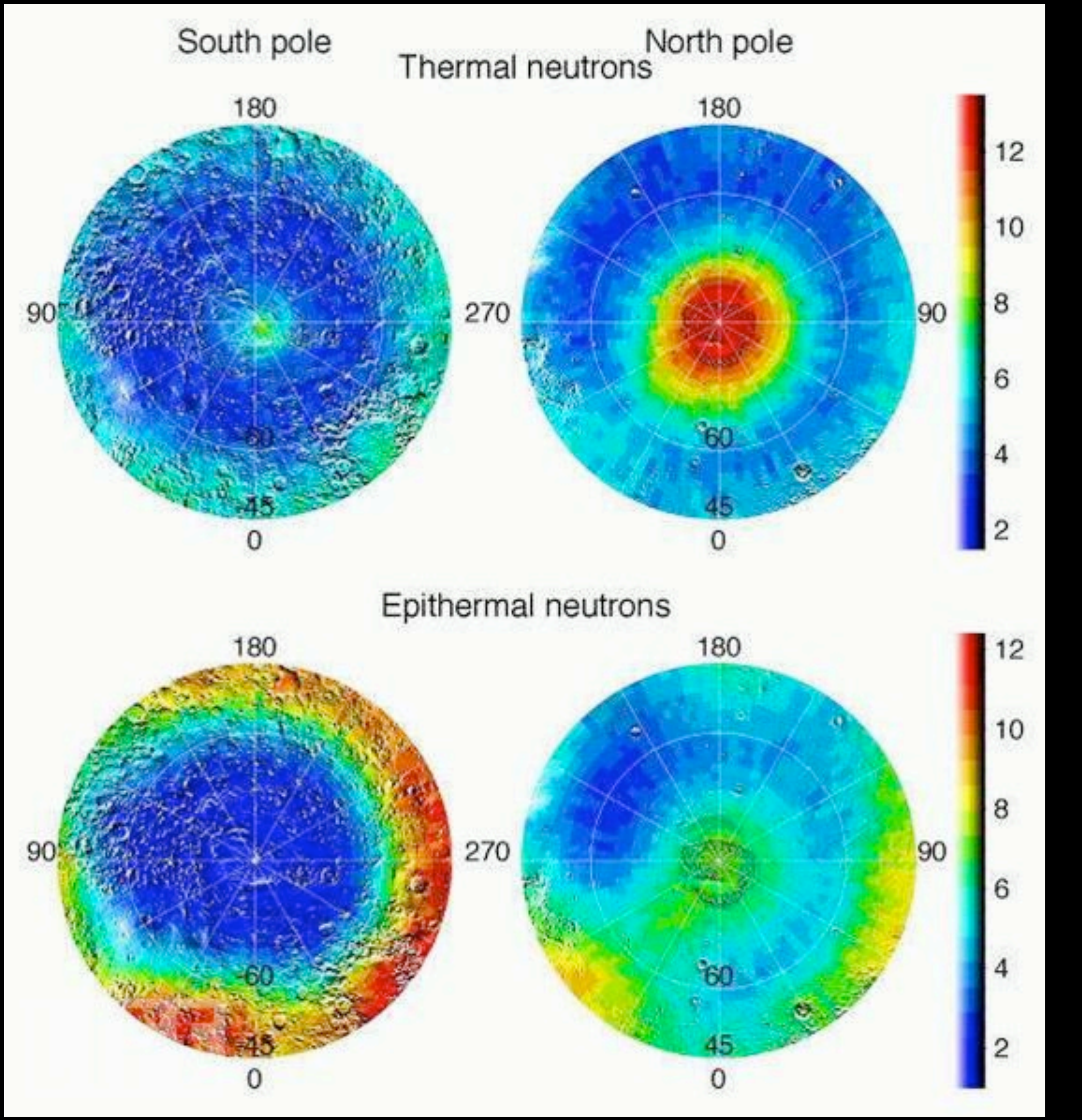
Surrounding rock is Jarosite : requires a pH < 5 to form
on Earth typically forms for pH 1-3

VERY acidic water – can't form carbonate rock in CO_2 atmosphere

(e.g Fairen et al., Nature, 2004)

But what about Phoenix?

Landed in the north pole region Mars

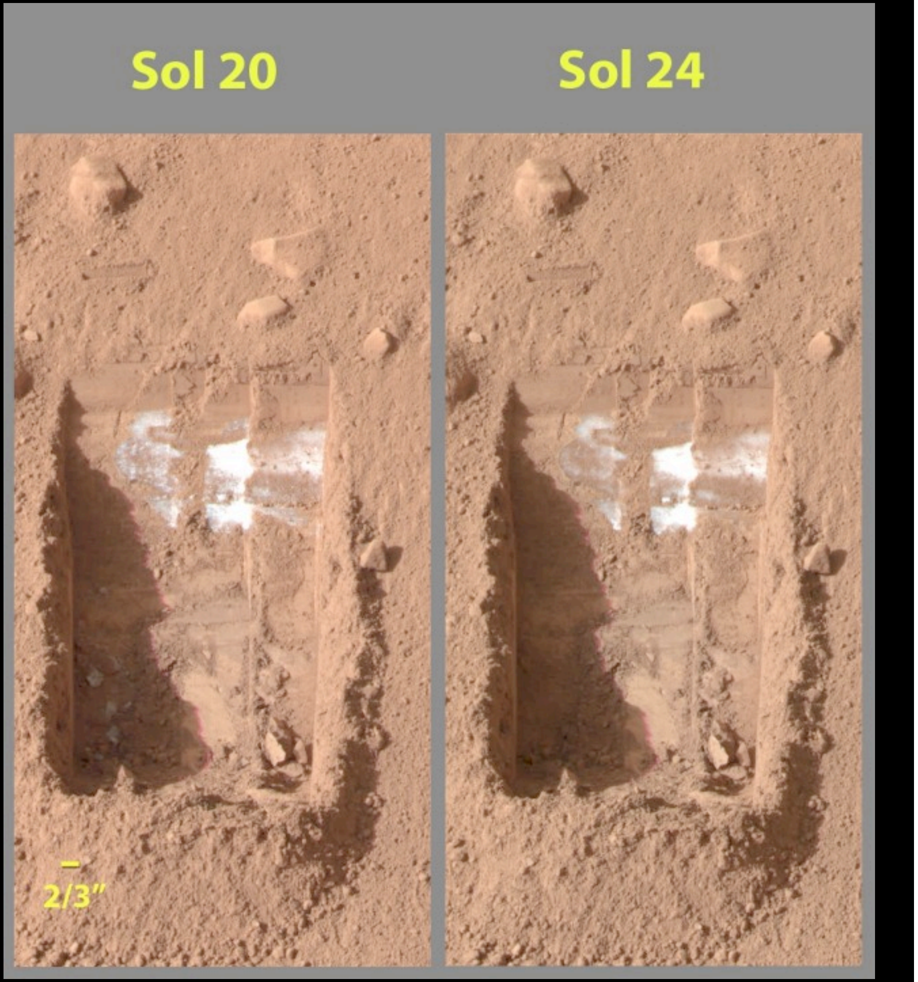


But what about Phoenix?

The soil was:

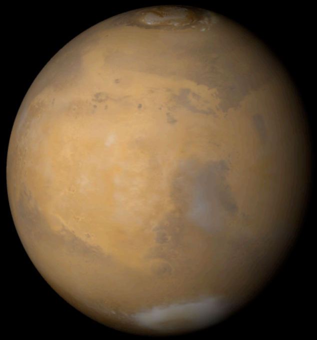
- alkaline (pH = 7.7)
- contained $CaCO_3$ and ClO_4,
- aqueous minerals,
- and salts up to several weight percent.

"Their formation likely required the presence of water."



(Smith et al., Hecht et al., Science, 2009)

Loss/Hiding mechanisms

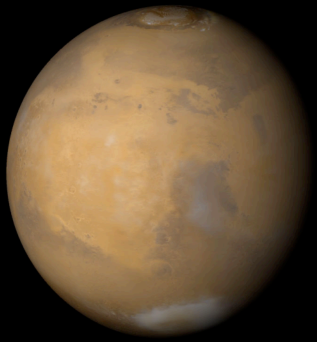


In the polar caps – water cap, CO_2 frost
– 2.7 km thick in the north
– 3.1 km thick in the south

Locked up in permafrost/soil – 10s of meters of water buried

Lost to space – Isotopic fractionization of H, C, N, Ar, Xe
– Can be modified by surface reservoirs

Loss mechanisms



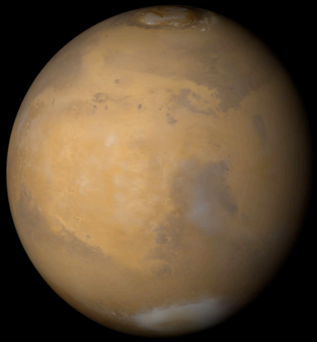
Thermal Mechanisms

Hydrodynamic Outflow - Early (chief) loss mechanism for all terrestrial planets

Impact erosion - Also a source of volatiles

Thermal/Jeans Escape - Dominate mechanism for neutrals

Loss mechanisms



Non-Thermal Mechanisms

Photochemical Escape : Very important in current atmosphere

- EUV + chemistry

$$CO_2^+ + O \Rightarrow O_2^+ + CO$$

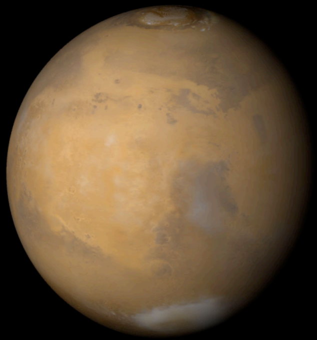
$$O_2^+ + e \Rightarrow 2\ O^*$$

Ion Pick-up : Carried downstream or reimpact the atmosphere

Sputtering : May have been very important in early atmosphere

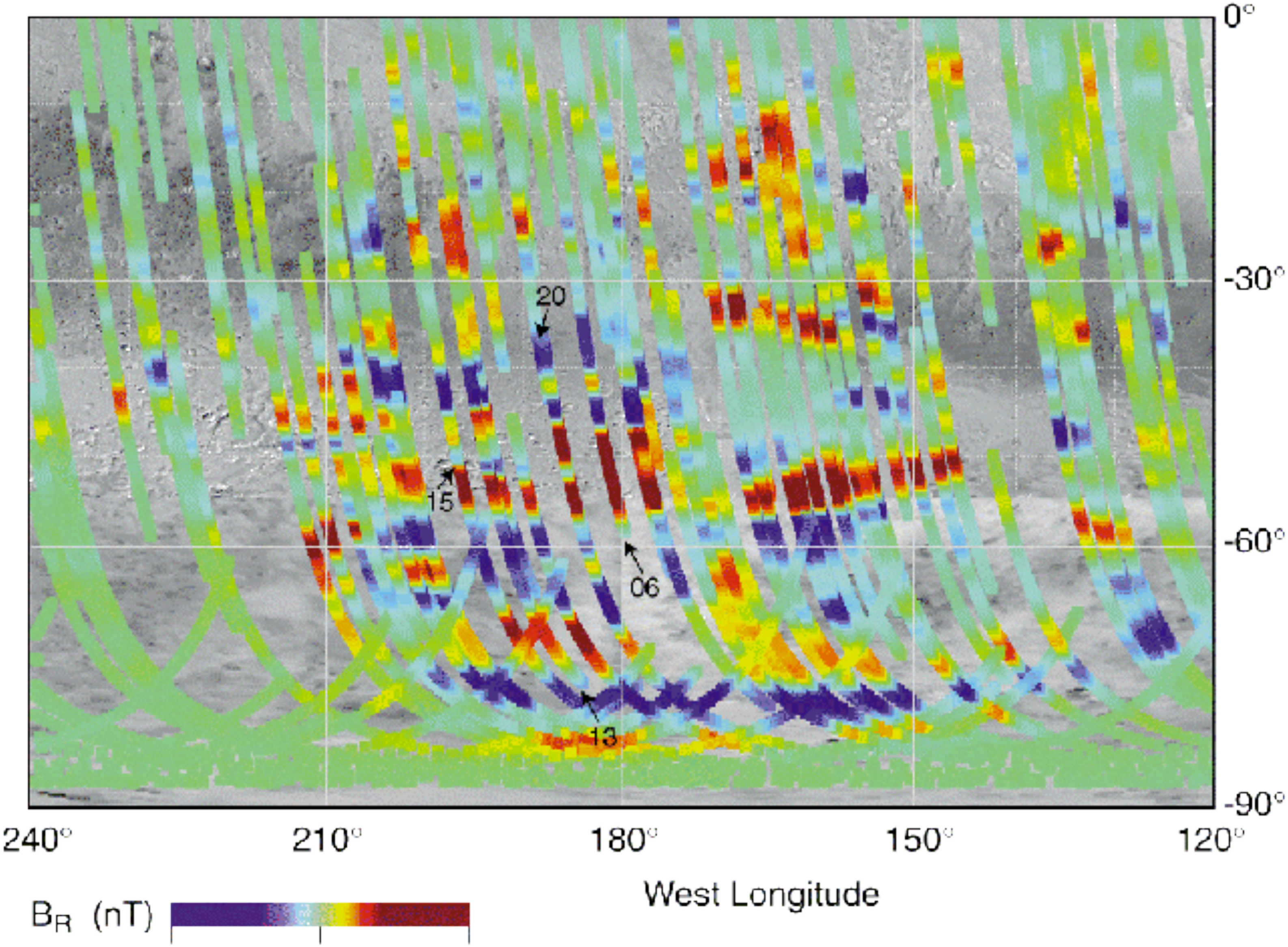
Bulk Removal : Wave/plasma instabilities at solar wind/ionosphere boundary

Loss History



- 4.6 Gya – original atmosphere delivered by impactors and outgassing
- Hydrodynamic escape stripped early atmosphere until most of H gone
- Impact erosion took over as dominate lost process until 3.5 Gya, - also lead to recovery of volatiles
- Secondary atmosphere protected by global magnetic field (?), supplemented by outgassing
- Jeans' escape and photochemical processes dominate for neutrals
- Solar wind loss mechanisms dominate for ions

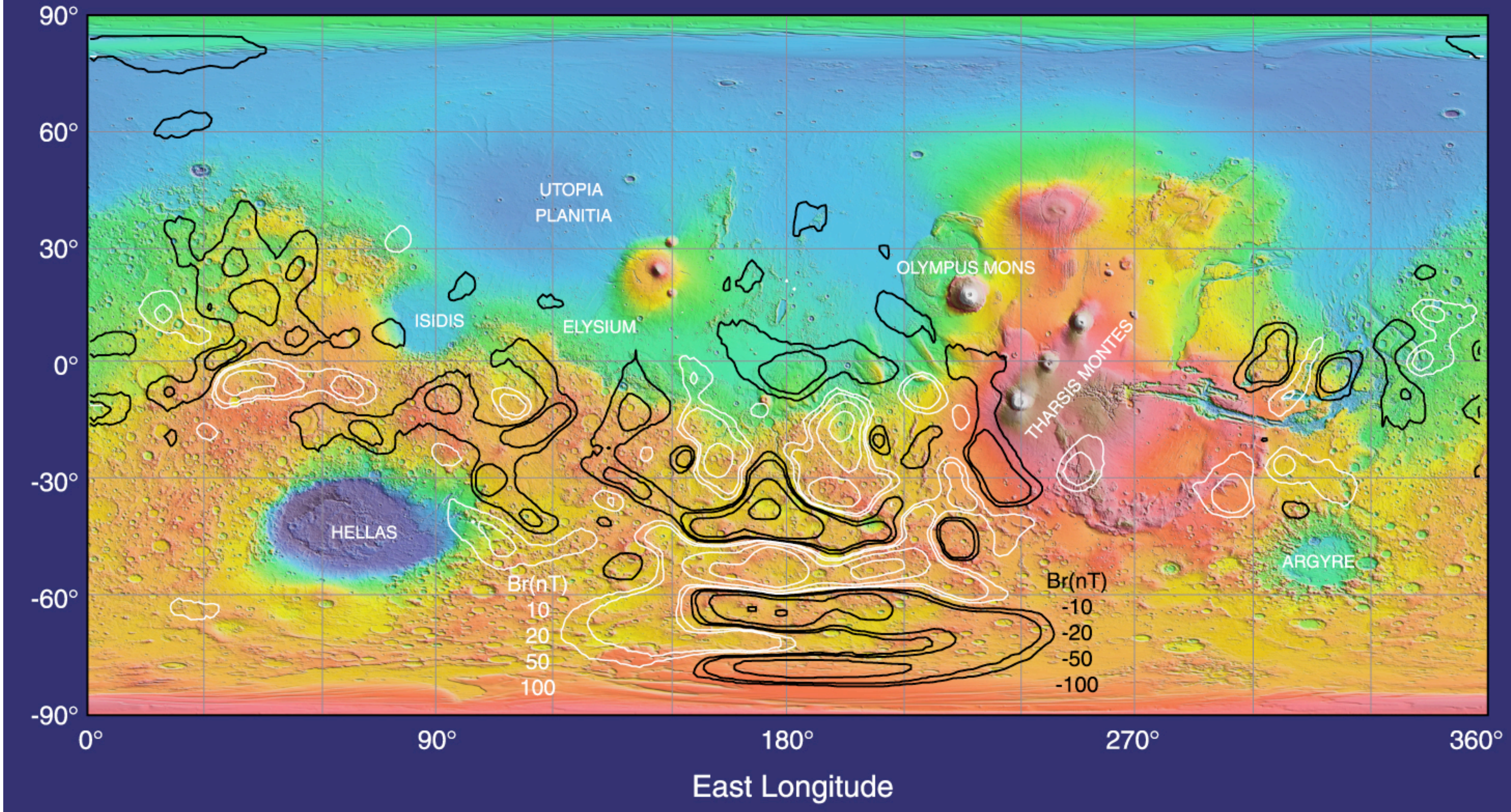
What about magnetic field?



Acuna et al., Connerney et al. *Science* 1999

Mars Global Surveyor

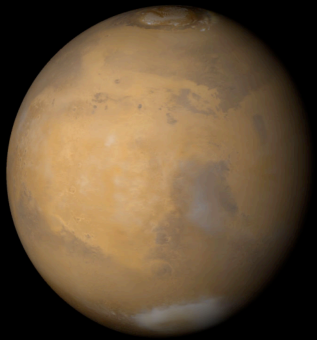
Mars Crustal Magnetism - MAG/ER
Topography - MOLA

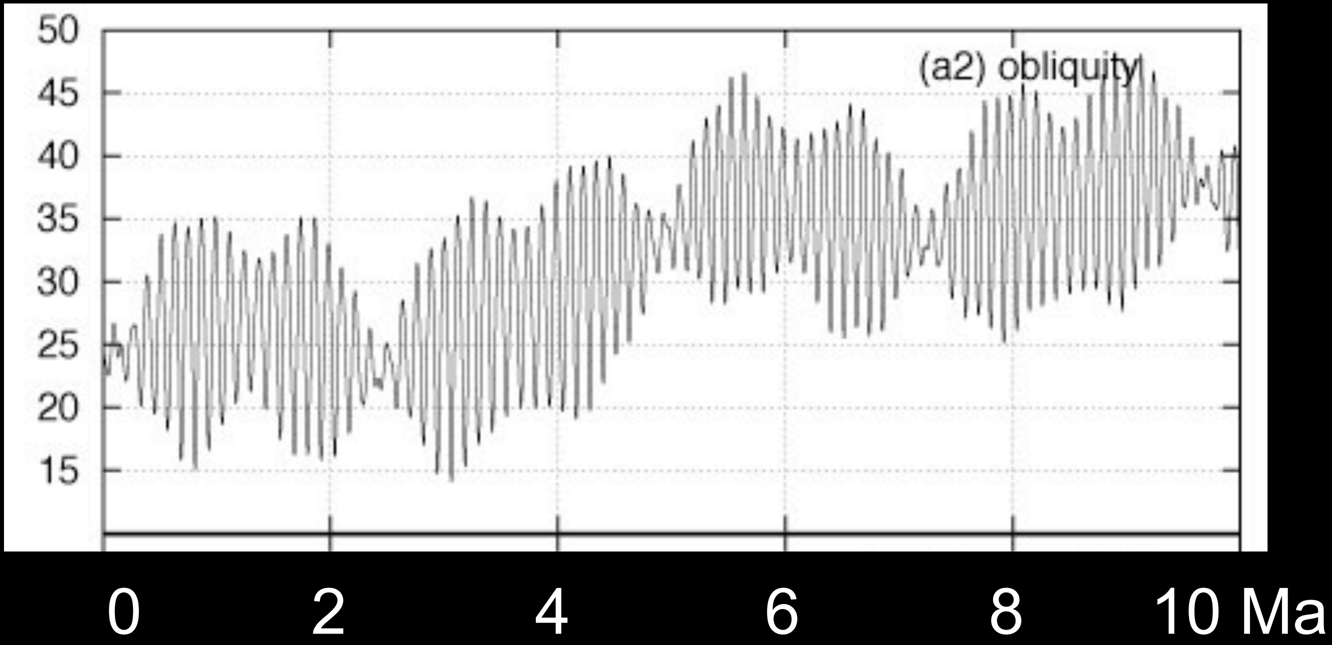


Connerney et al., *Geophys. Res. Lett., 28,* 4015-4018, 2001.

ConJ20011591.002

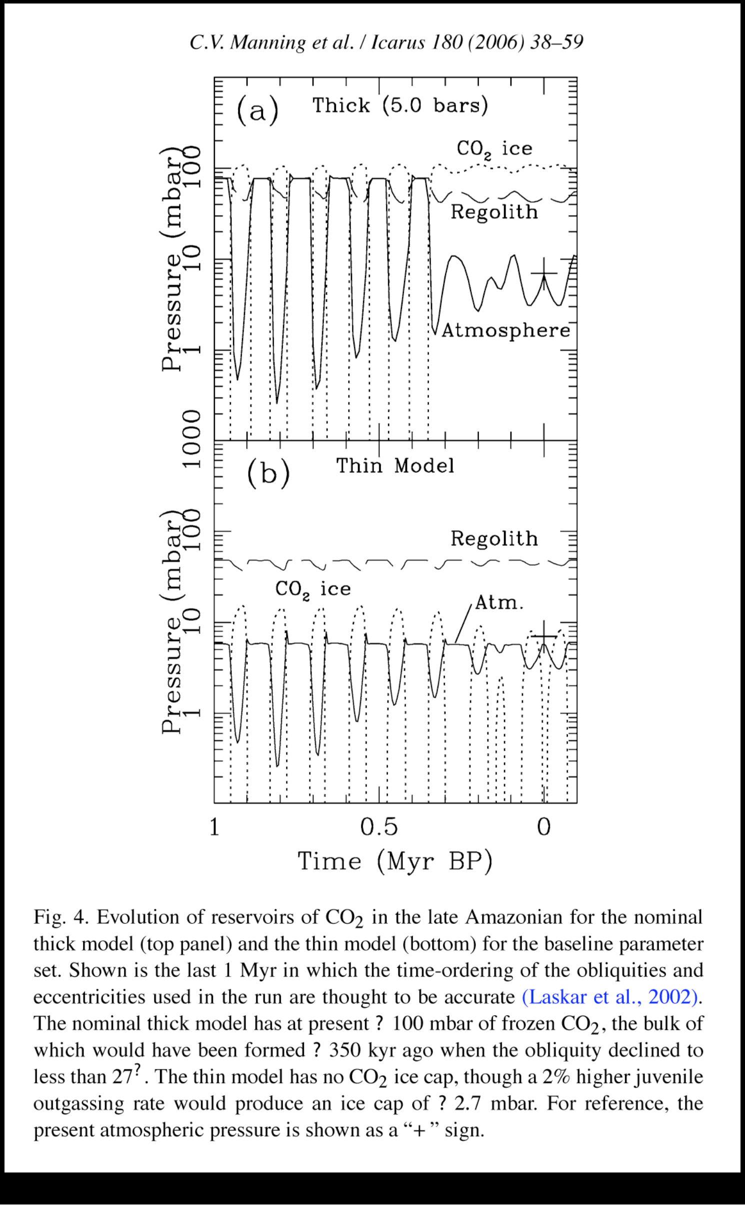
Obliquity History





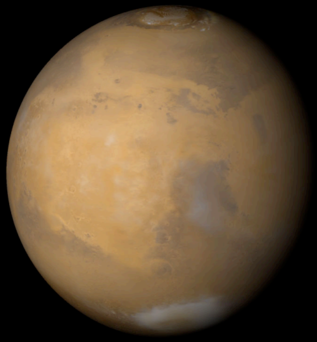
J. Laskar, B. Levrard, J. Mustard, *Nature*, 2002

Obliquity History



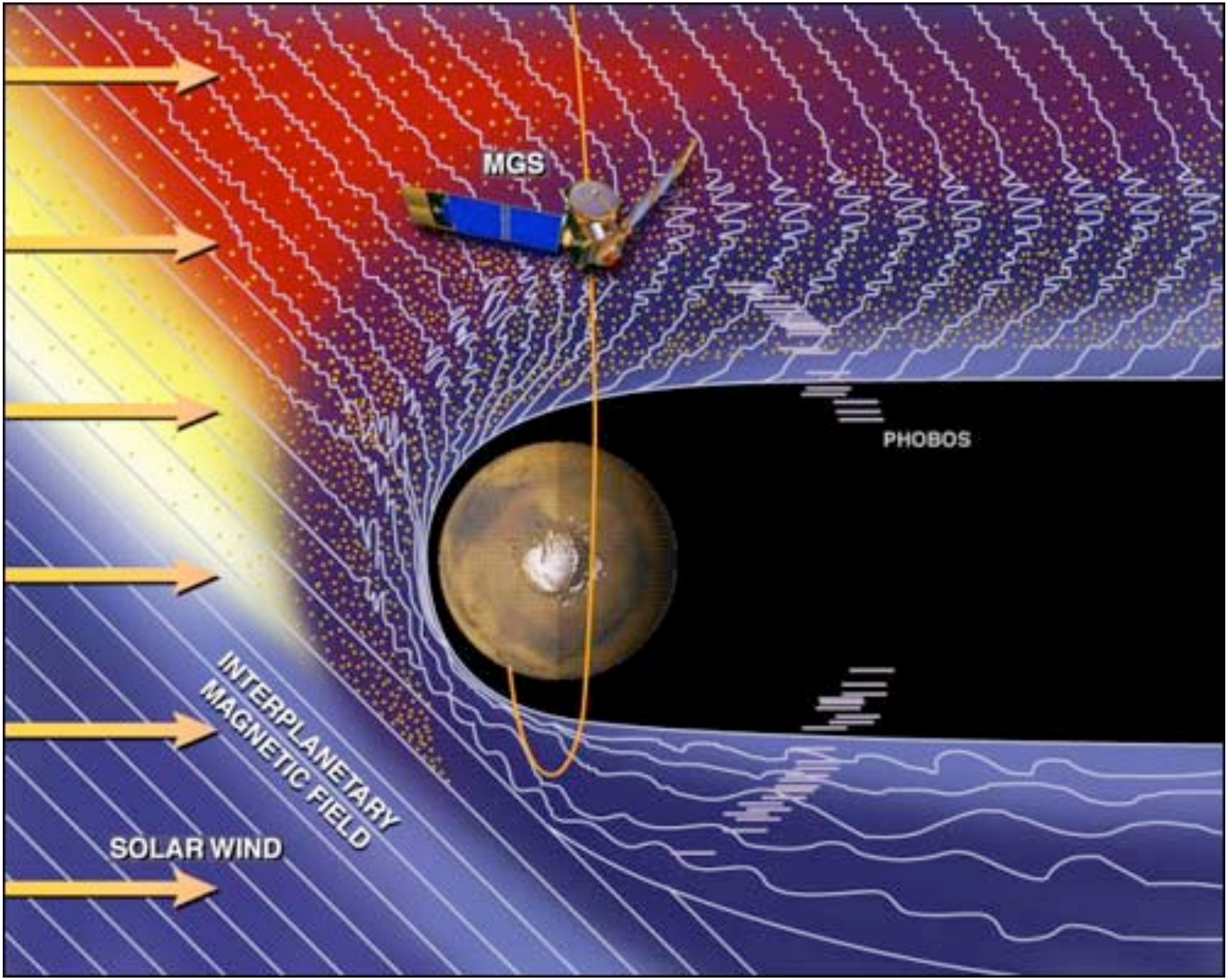
C.V. Manning et al. / Icarus 180 (2006) 38–59

Fig. 4. Evolution of reservoirs of CO_2 in the late Amazonian for the nominal thick model (top panel) and the thin model (bottom) for the baseline parameter set. Shown is the last 1 Myr in which the time-ordering of the obliquities and eccentricities used in the run are thought to be accurate (Laskar et al., 2002). The nominal thick model has at present ? 100 mbar of frozen CO_2, the bulk of which would have been formed ? 350 kyr ago when the obliquity declined to less than $27^?$. The thin model has no CO_2 ice cap, though a 2% higher juvenile outgassing rate would produce an ice cap of ? 2.7 mbar. For reference, the present atmospheric pressure is shown as a “+ ” sign.

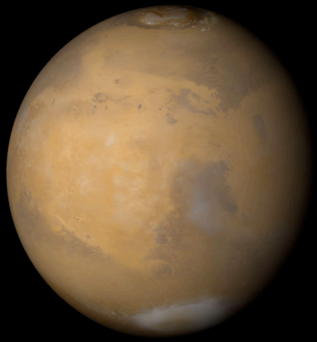


- Thick initial atmosphere result in large swings in greenhouse warming due to obliquity variations

- Atmosphere would change little in response to obliquity variations if initially thin


MGS
PHOBOS
INTERPLANETARY MAGNETIC FIELD
SOLAR WIND

Past Conditions



- EUV flux variation – larger in past
  - → inflated ionosphere
  - → increased scale heights
  - → extended corona

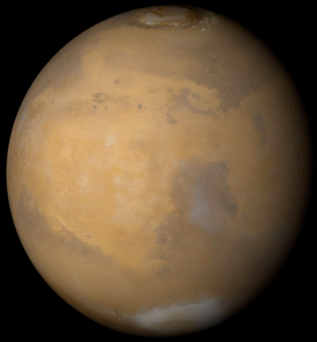
- Solar wind “elevated”
  - → more loss but also delivers volatiles
  - → larger IMF ⇒ reduces pick-up

- Planetary magnetic fields?

- Obliquity changes?

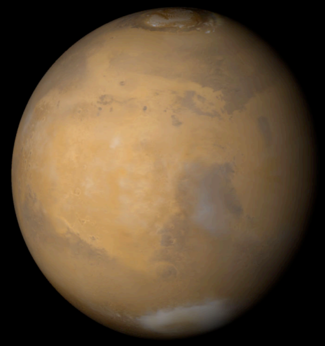
Don’t know about past solar wind – use storms as analogs

Past Conditions vs. Storm Conditions



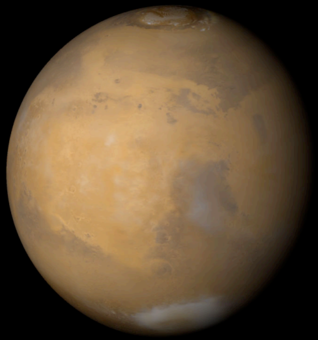
	1+Gya	Storm
UV to X-ray Flux	3 - 50x	10-100x
Solar wind speed	4x	2-5x
Solar wind density	15-40x	5x
IMF strength	10x	5x

3D Multi-Fluid Model



- Multiple ion species
- Conservation of mass
- Conservation of momentum
- Conservation of energy
- Induction equation
- Charge neutrality
- Generalized Ohm’s Law

3D Multi-Fluid Model



$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \cdot (\rho_\alpha \; \boldsymbol{V}_\alpha) = 0$$

$$\rho_\alpha \frac{d\boldsymbol{V}_\alpha}{dt} = q_\alpha n_\alpha (\boldsymbol{E} + \boldsymbol{V}_\alpha \times \boldsymbol{B}(\boldsymbol{r})) - \nabla P_\alpha - \left(\frac{GM_E}{R_e{}^2} \right) \rho_\alpha \vec{\boldsymbol{r}}$$

$$\frac{\partial P_\alpha}{\partial t} = -\gamma \nabla \cdot (P_\alpha \; \boldsymbol{V}_\alpha) + (\gamma - 1) \boldsymbol{V}_\alpha \cdot \nabla P_\alpha$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0$$

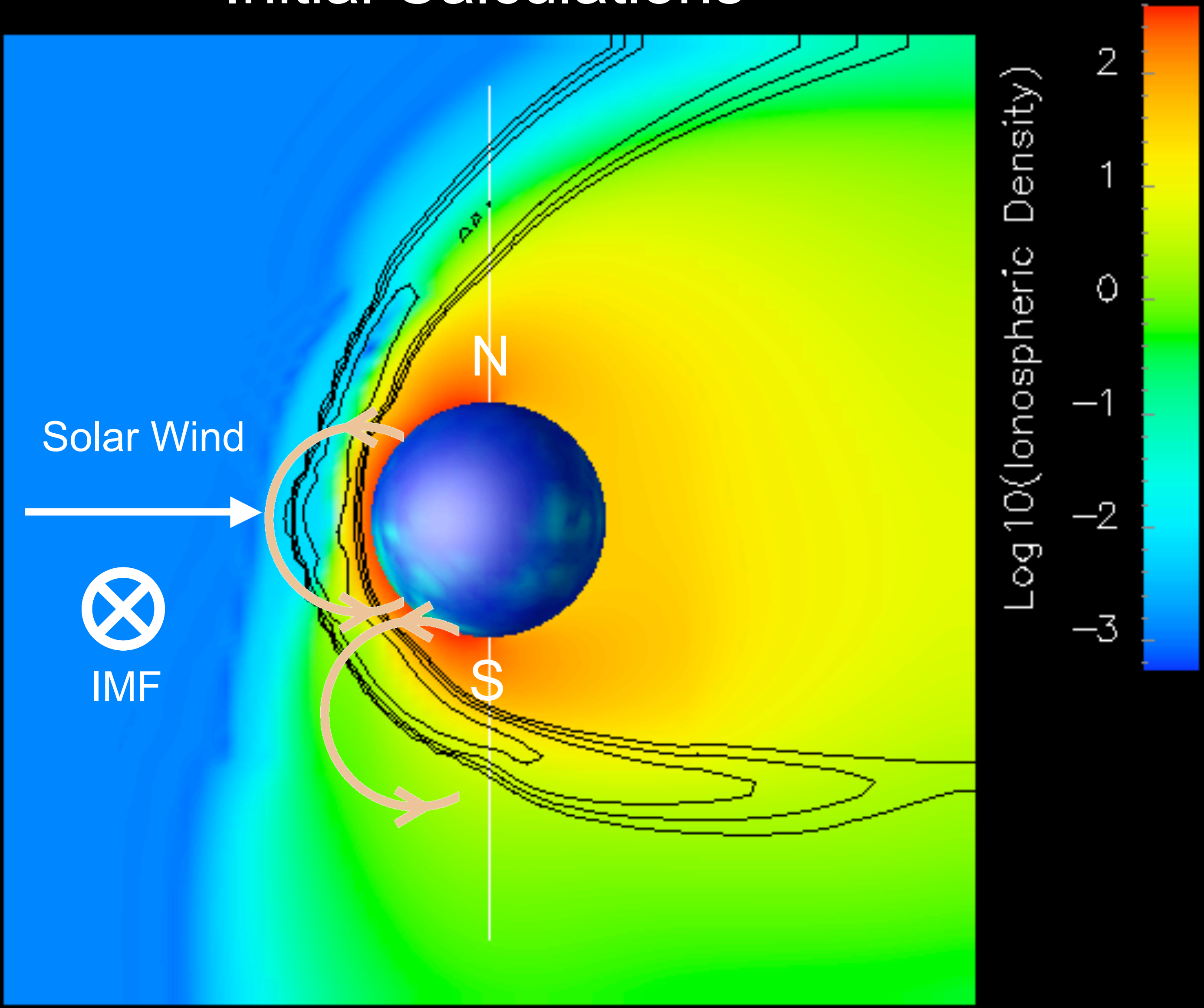
$$n_e = \sum_i n_i, \quad \boldsymbol{V}_{de} = \sum_i \frac{n_i}{n_e} \boldsymbol{V}_i - \frac{\boldsymbol{J}}{\mathrm{en_e}}, \quad \boldsymbol{J} = \frac{1}{\mu_0} \nabla \times \boldsymbol{B}$$

$$\frac{\partial P_e}{\partial t} = -\gamma \nabla \cdot (P_e \; \boldsymbol{V}_{de}) + (\gamma - 1) \boldsymbol{V}_{de} \cdot \nabla P_e$$

$$\boldsymbol{E} \quad = -\sum_i \frac{n_i}{n_e} \boldsymbol{V}_i \times \boldsymbol{B} + \frac{\boldsymbol{J} \times \boldsymbol{B}}{\boldsymbol{e n_e}} - \frac{1}{e n_e} \nabla P_e$$

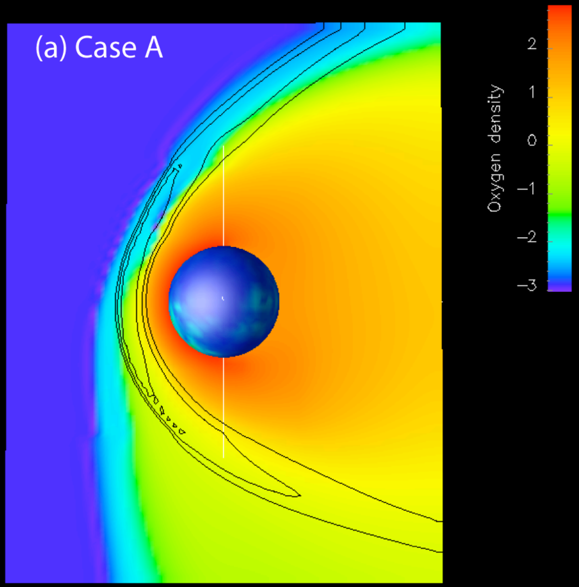
Initial Calculations

Solar Wind
Density : 2 cm^{-3}
Speed : 400 km/s
IMF: 2nT in By

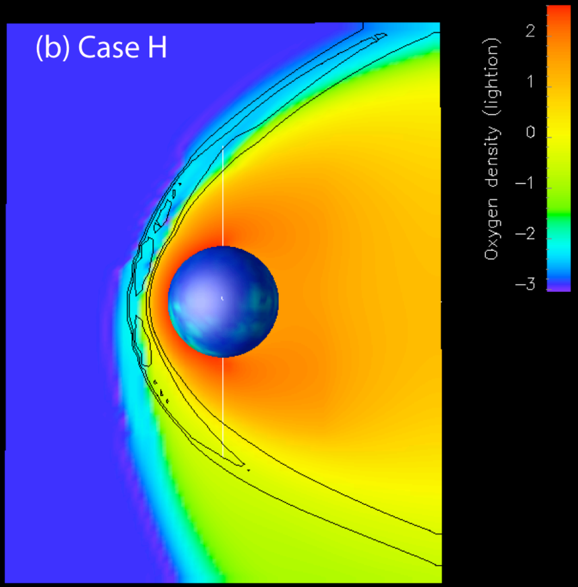


Mass effects are crucial to get loss rates and precipitation rates right

O_2^+ ionosphere
400 km/s wind

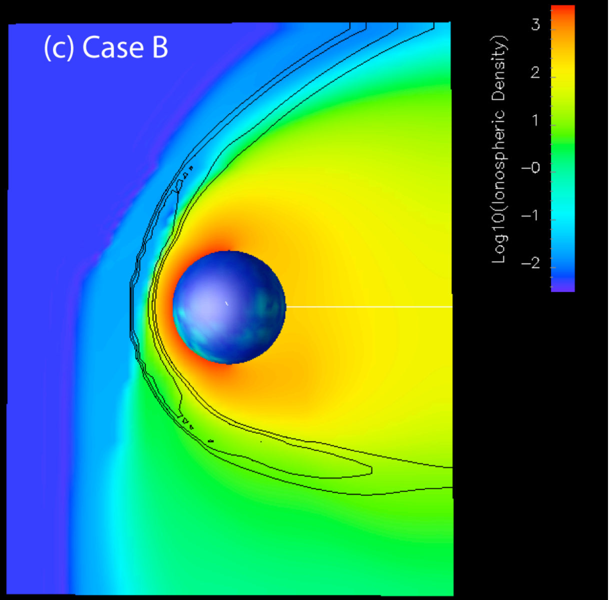


O^+ ionosphere
400 km/s wind



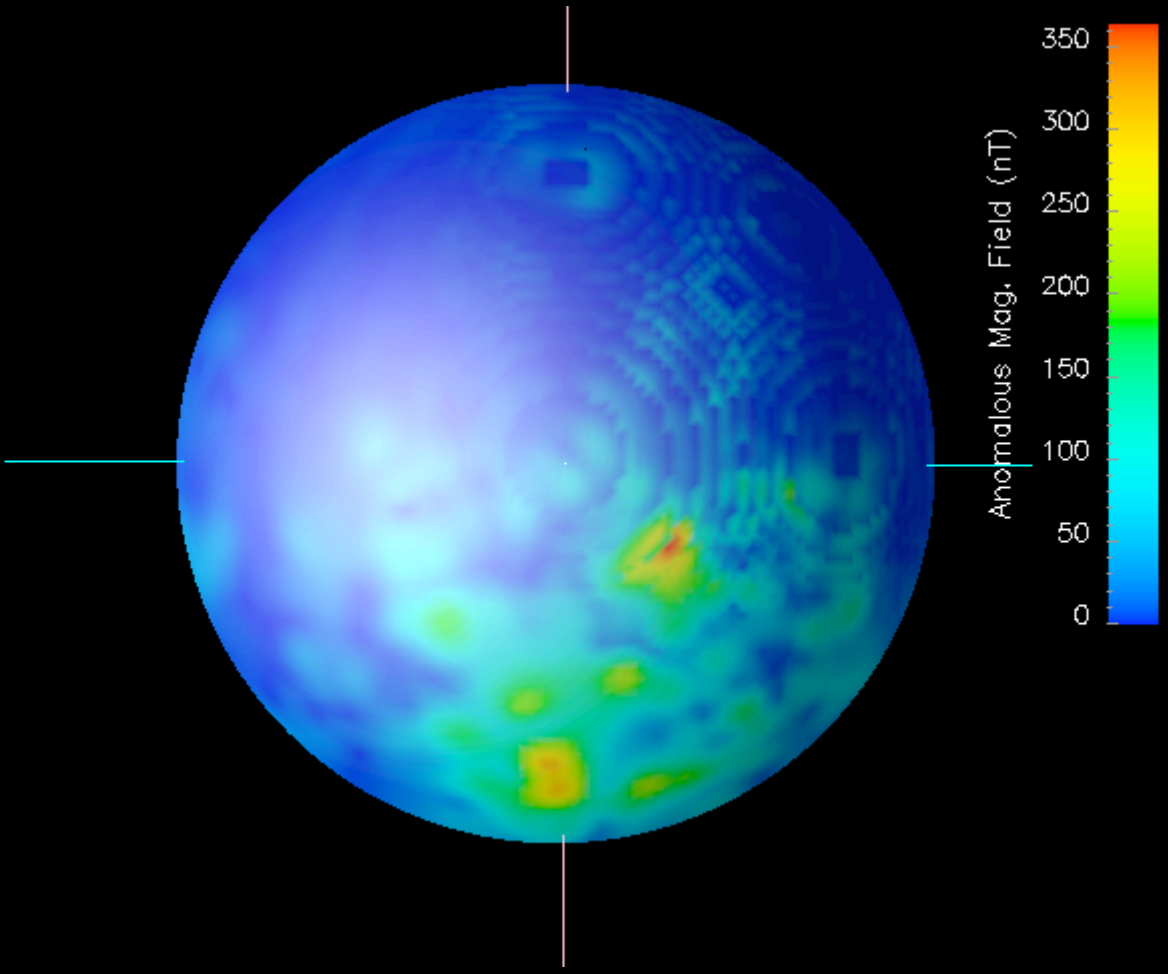
30% decrease in solar wind precipitation and ionospheric loss

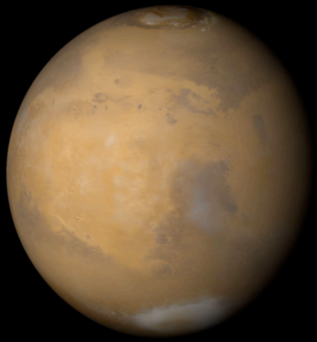
O_2^+ ionosphere
800 km/s wind



2 times ionospheric loss

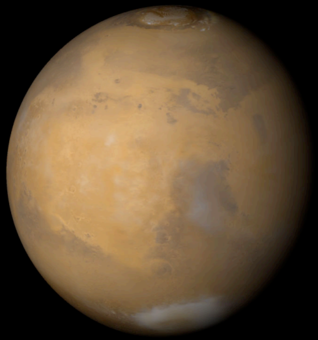
Martian Magnetic Field

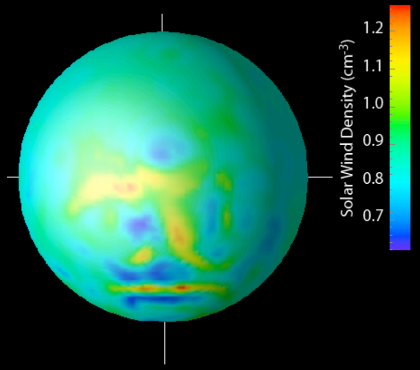




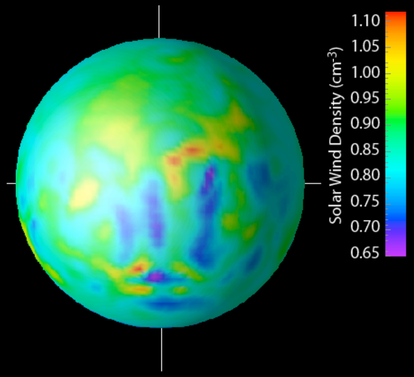
Provided by J. Cain

Dependence on anomaly location?

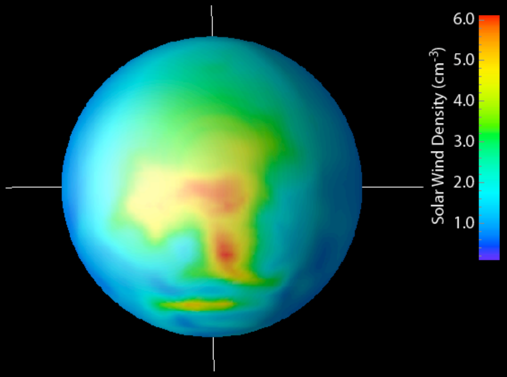




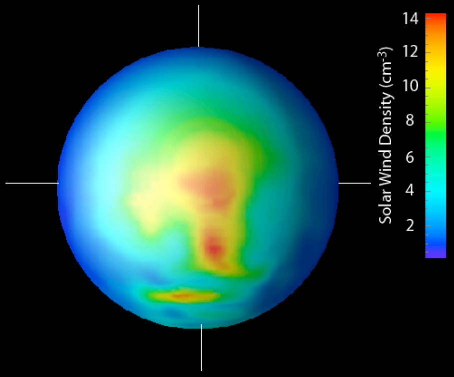
Nominal, By



Nominal, Bz



High pressure, By

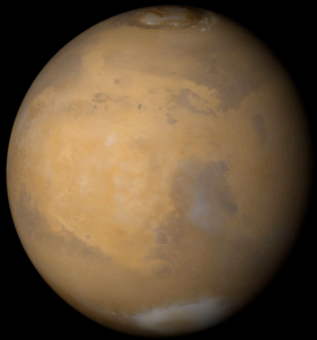


Active Sun, By

- Deflected plasma funneled somewhere else?

- Grid resolution?

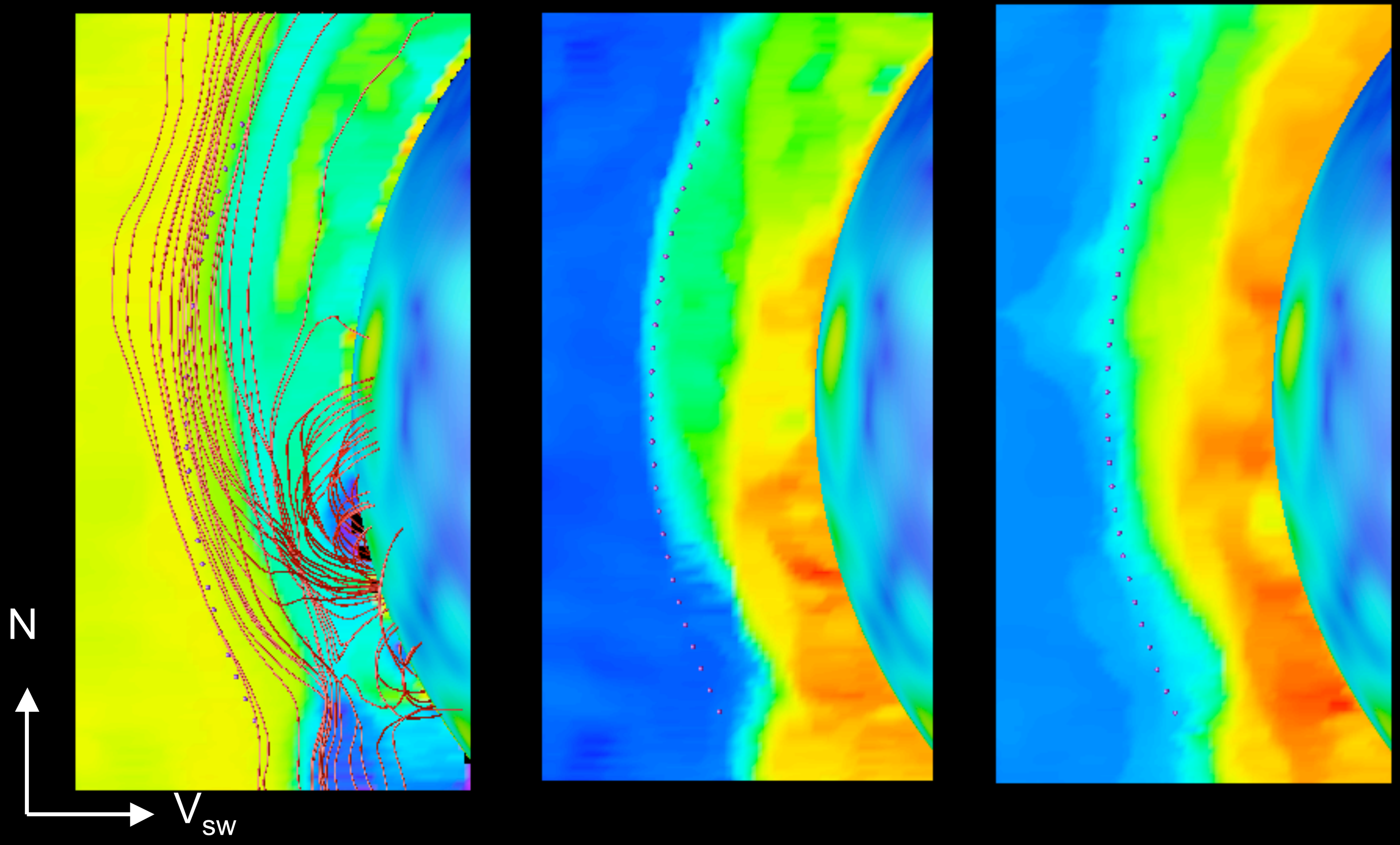
High Resolution Simulations



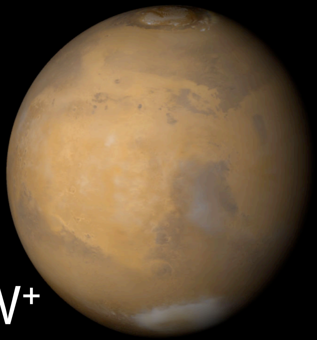
Solar Wind Density

Hydrogen Density

Oxygen Density



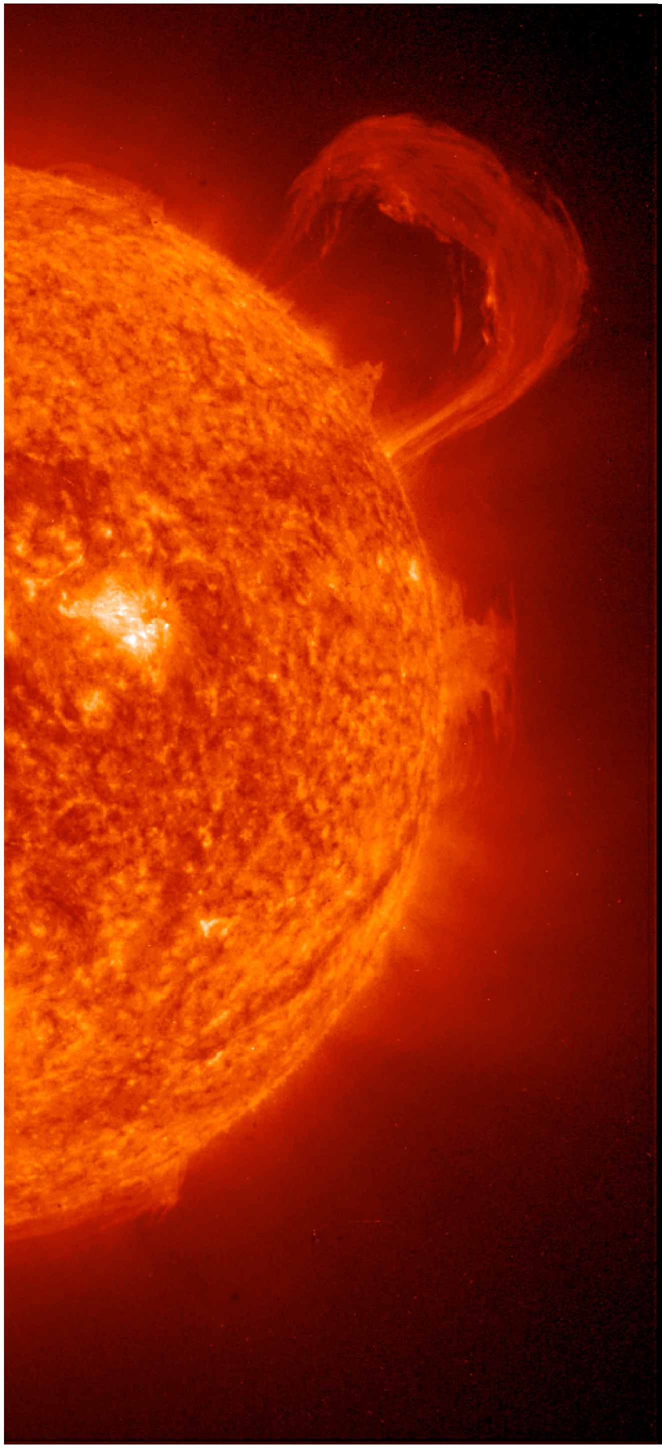
High Resolution Simulations
Loss Rates vs. Anomaly Location



	O_2^+	H^+	SW^+
Dawn	-1.9 ± 0.1	-0.57 ± 0.03	0.47 ± 0.02
Dusk	-2.1 ± 0.1	-0.75 ± 0.04	0.25 ± 0.01
Night	-2.6 ± 0.1	-0.76 ± 0.04	1.05 ± 0.05

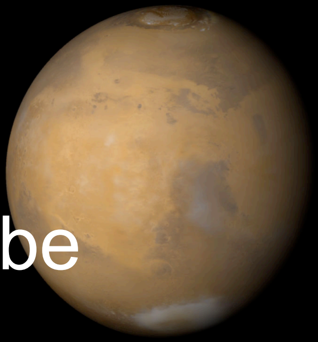
All numbers: x 10^{25} ion s^{-1}

Phobos2 measurement – 3×10^{25} O^+ ions s^{-1}

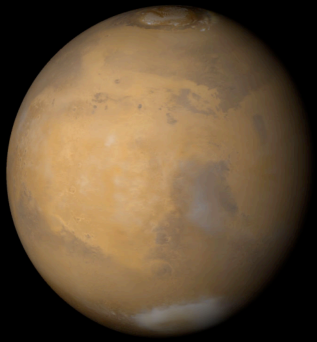


Conclusions

- ***Possibly meters of water lost to space***
- Composition of the ionosphere is important
- Obliquity changes must be considered



Precipitation Rates



Dusk - Asymmetric bow shock

Multi-Fluid Equations

$$\frac{\partial \rho_\alpha}{\partial t} + \nabla \bullet \left(\rho_\alpha \mathrm{v}_\alpha\right) = 0$$

$$\rho_\alpha \frac{d\mathbf{v}_\alpha}{dt} + \nabla P_\alpha = q_\alpha n_\alpha \left(\mathbf{E} + \mathbf{v}_\alpha \times \mathbf{B}\right) + g(r)\rho_\alpha \mathbf{r}$$

$$\frac{\partial P_\alpha}{\partial t} = -\gamma \nabla \bullet \left(P_\alpha \mathbf{v}_\alpha\right) + (\gamma - 1)\mathbf{v}_\alpha \bullet \nabla P_\alpha + \Sigma Q$$

$$\frac{\partial P_e}{\partial t} = -\gamma \nabla \bullet \left(P_e \mathbf{v}_e\right) + (\gamma - 1)\mathbf{v}_e \bullet \nabla P_e + \Sigma Q$$

$$\frac{d\boldsymbol{V}_e}{dt} = 0 \quad \Rightarrow \quad \boldsymbol{E} + \boldsymbol{V}_e \times \boldsymbol{B} + \frac{1}{en_e} \nabla P_e = 0$$

$$n_e = \sum_i n_i, \quad \boldsymbol{V}_e = \sum_i \frac{n_i}{n_e} \boldsymbol{V}_i - \frac{\boldsymbol{J}}{\mathrm{en_e}}, \quad \boldsymbol{J} = \frac{1}{\mu_0} \nabla \times \boldsymbol{B}$$

$$\boldsymbol{E} = -\sum_i \frac{n_i}{n_e} \boldsymbol{V}_i \times \boldsymbol{B} + \eta J + \frac{\boldsymbol{J} \times \boldsymbol{B}}{\mathrm{en_e}} - \frac{1}{en_e} \nabla P_e$$

$$\rho_\alpha \frac{d\boldsymbol{V}_\alpha}{dt} = \boldsymbol{J} \times \boldsymbol{B} - \nabla P_\alpha - \nabla P_e + en_\alpha \left(\boldsymbol{V}_\alpha - \sum_i \frac{n_i < \boldsymbol{V}_i >}{n_e}\right) \times \boldsymbol{B}$$