Solar Wind or Planetary Magnetosphere Interactions with the Atmospheres of Unmagnetized Bodies: Solar and Space Physics and Aeronomy inextricably intertwined

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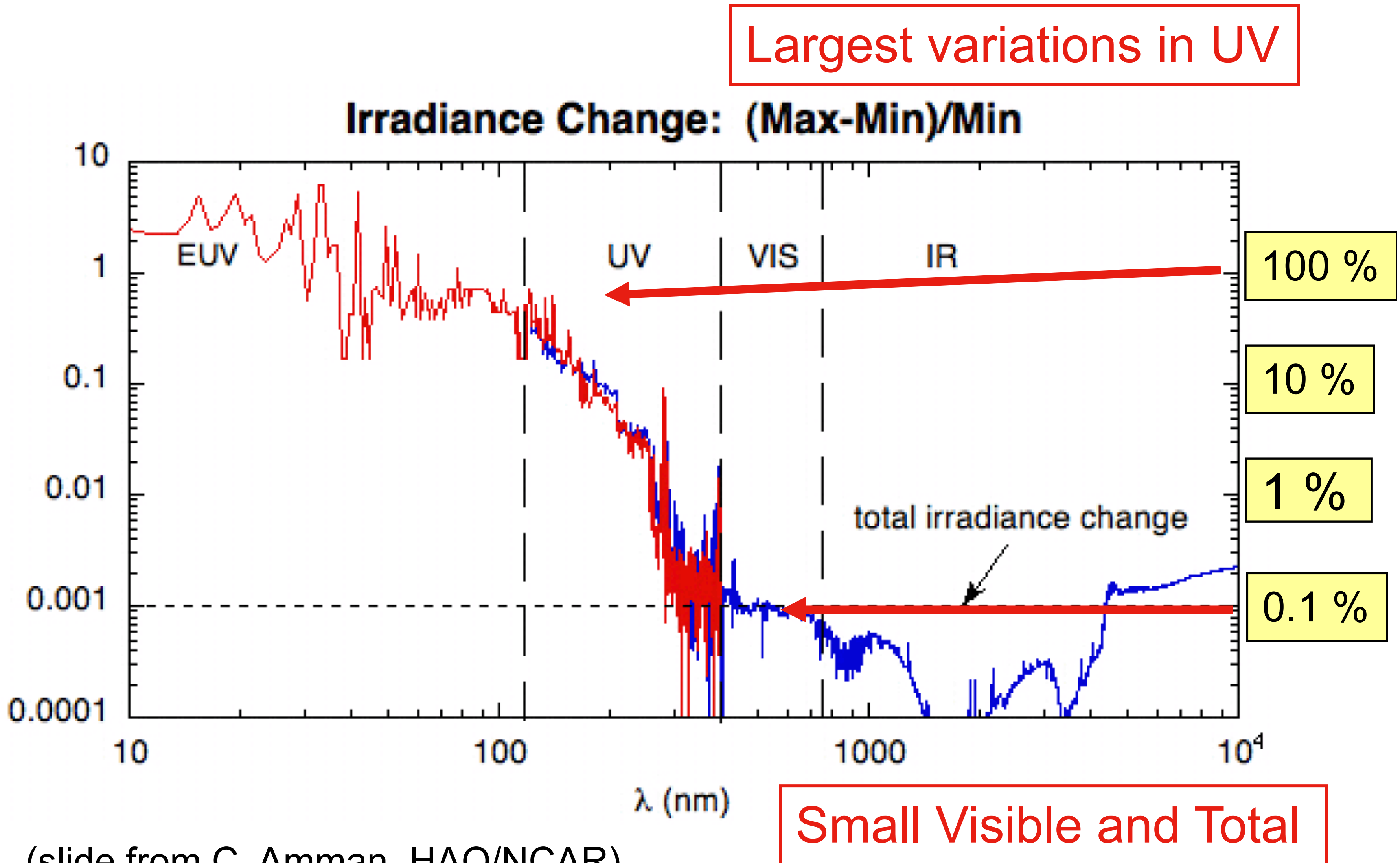
Unmagnetized Planet-Plasma Interaction Process Determiners:

- The external medium, including variability
- Sources of atmospheric heating and ionization, including variability
- Comparative Scales: Planet radius, Atmosphere scale height, ion gyroradius…
- Atmospheric properties including composition/chemistry, dynamics

….Examples provided by Venus, Mars and Titan ….

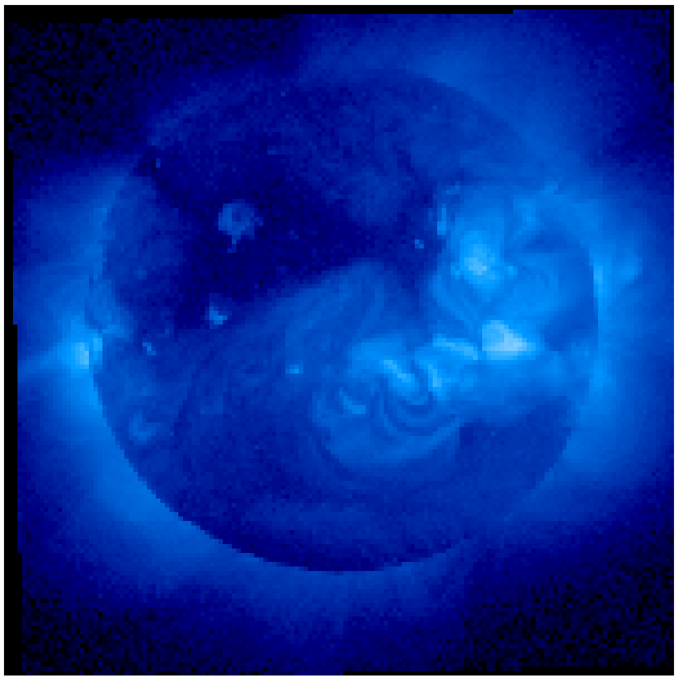
Solar photoemissions play a major role in plasma interactions because they heat atmospheres, make conducting obstacles, and allow ionized constituents to be affected by electromagnetic fields



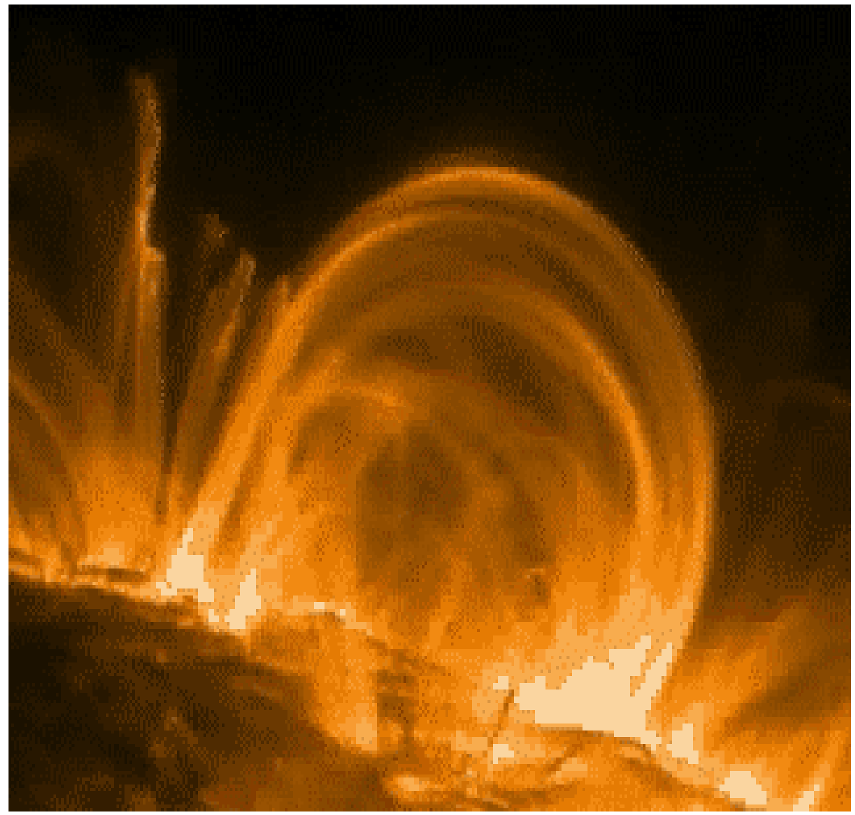
(slide from C. Amman, HAO/NCAR)

The varying solar x-ray and EUV emissions, the main photo-ionizing agents, come in part from magnetic field-controlled coronal loops arching above active regions

Note these wavelengths are Important to planetary atmospheres

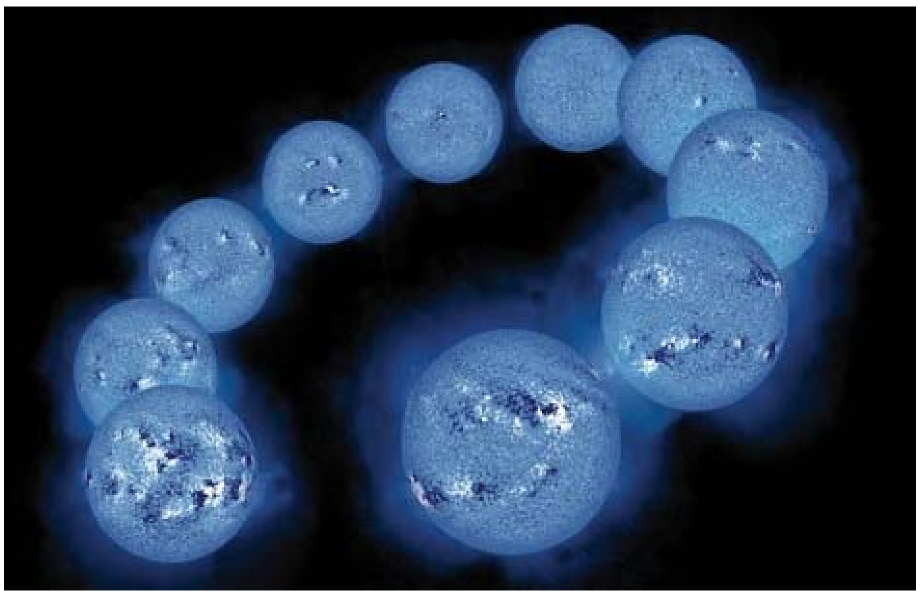


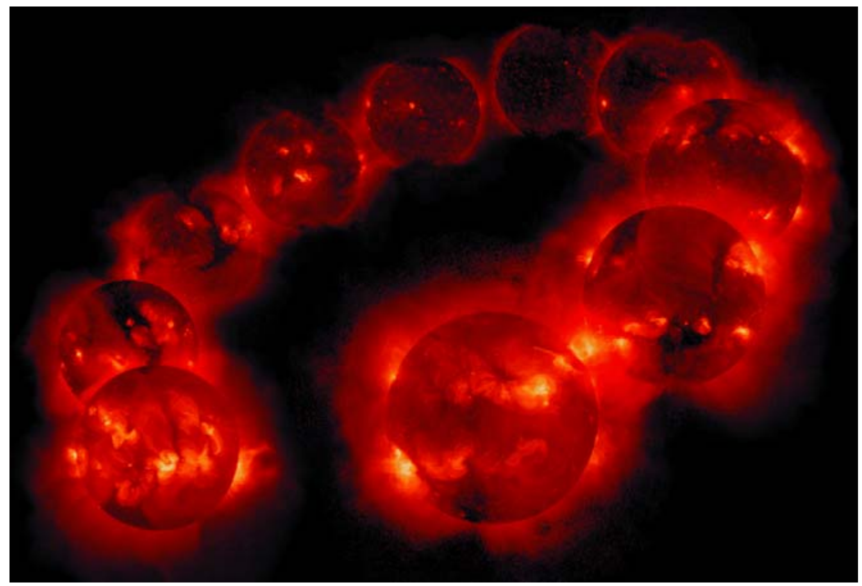
Yohkoh SXT soft x-ray image



TRACE EUV image

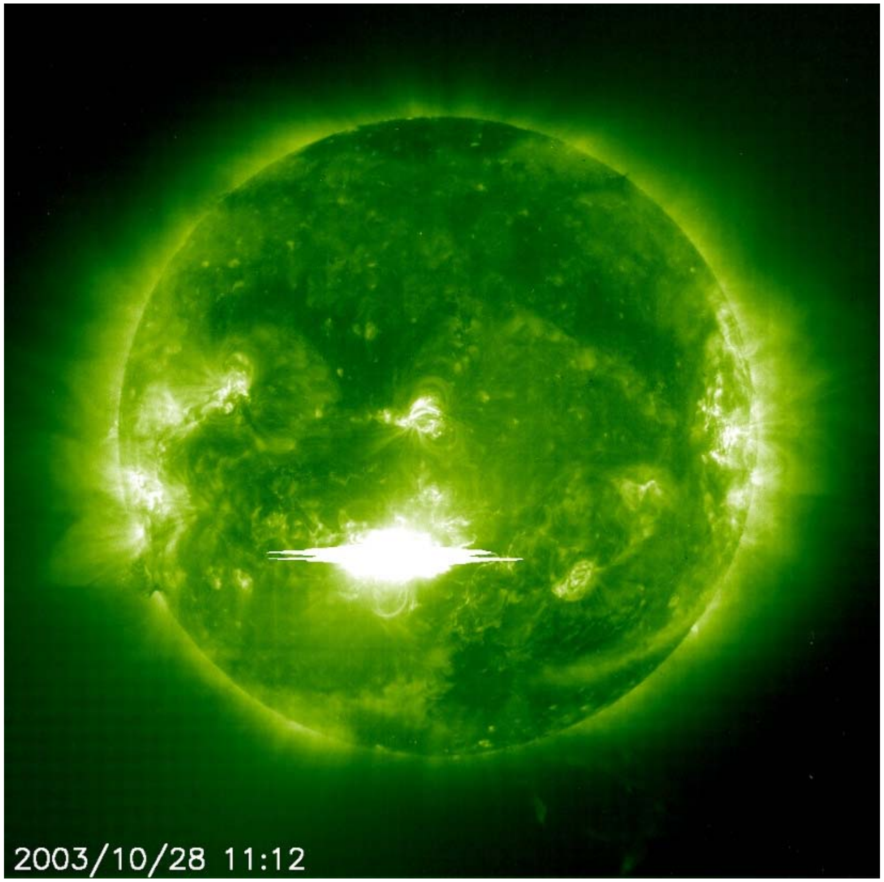
The frequency of emergence of the magnetic active regions affects the Sun's x-ray and extreme ultraviolet light emissions on short (flare), medium (solar rotation) and long (solar cycle) time scales

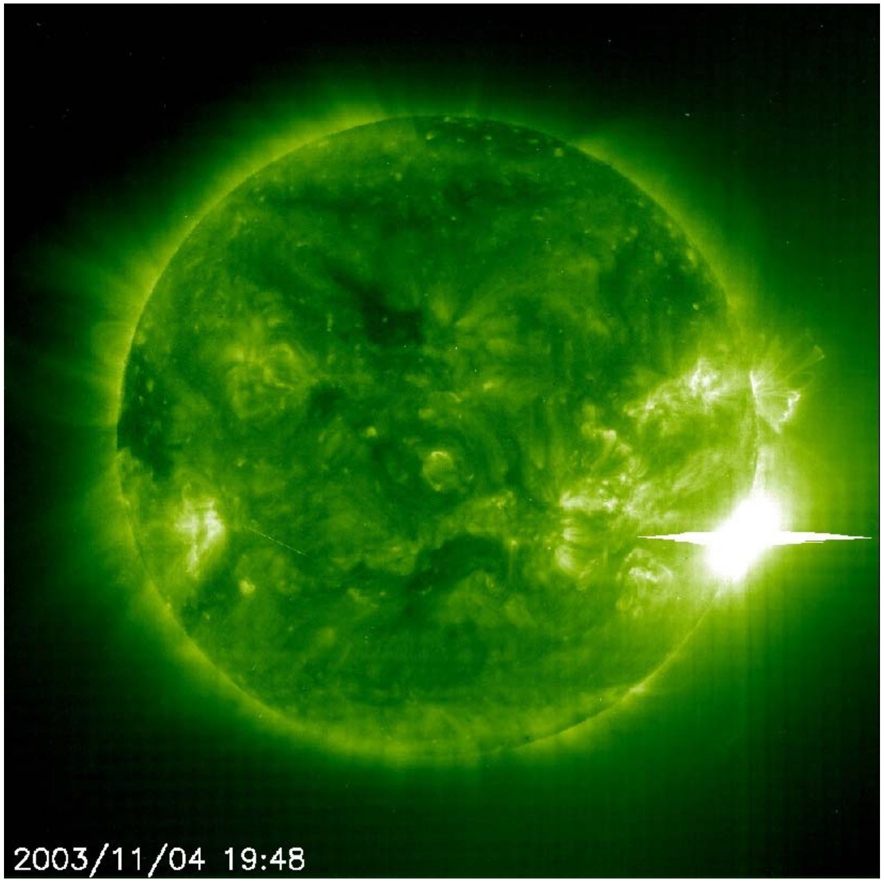




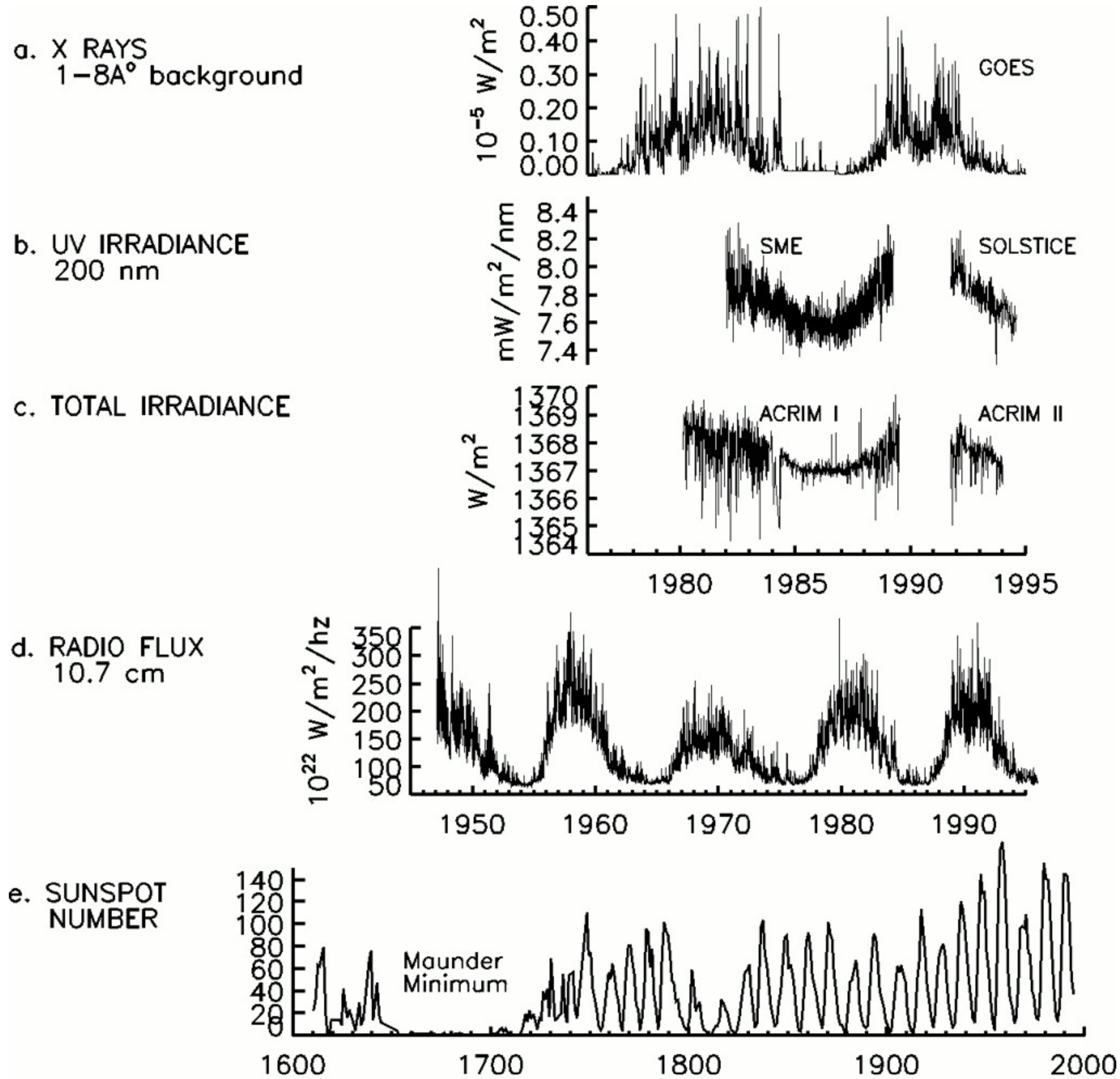
(Images from Kitt Peak Observatory magnetograph (left) and the Yohkoh Soft X-ray Telescope, SXT (right) showing x-ray bright arcades over active regions, both evolving over the course of a solar cycle)

Solar Flares produce impulsive and extreme intensifications of emissions at UV, EUV and X-ray wavelengths from localized regions on the Sun



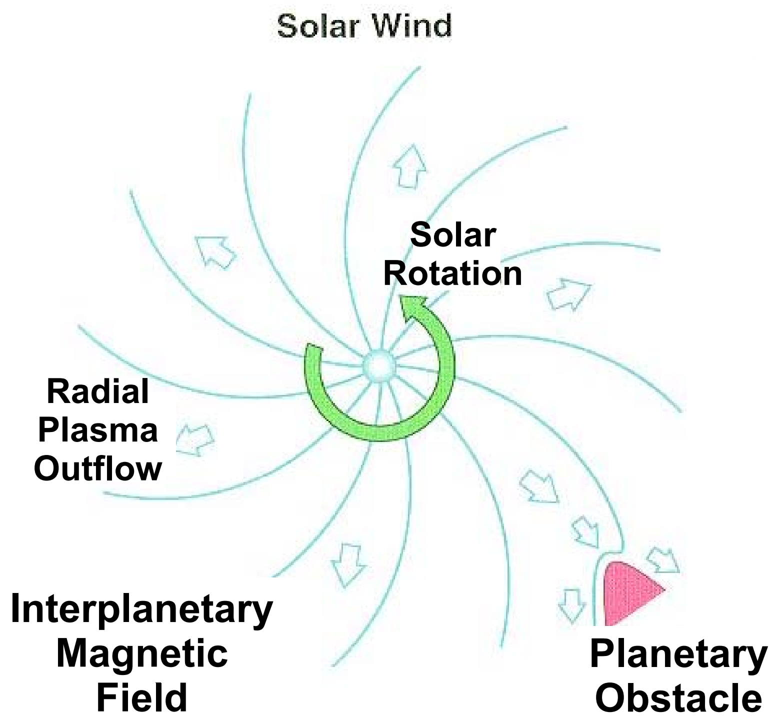


The net result-



(from an NRC report chaired by J. Lean, NRL showing the variations in Solar emissions at different wavelengths over some recent solar cycles)

External conditions in unmagnetized planet-plasma interactions are provided by the solar wind, which varies with heliocentric distance, heliolongitude, and time



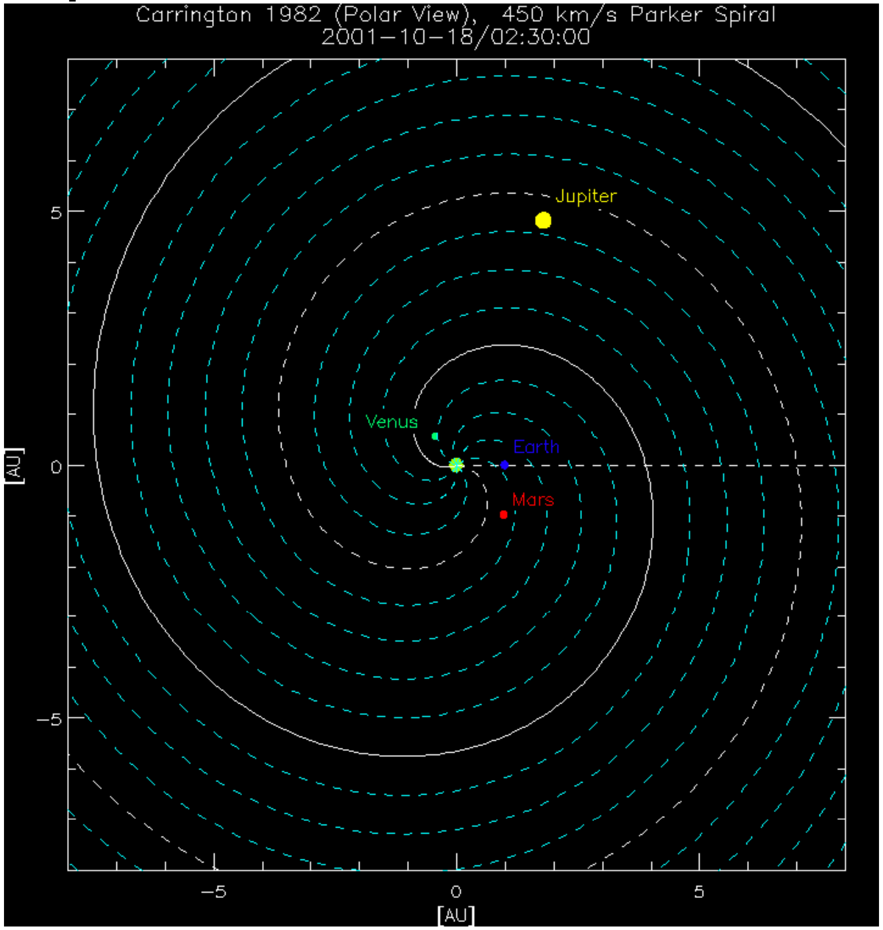
Some typical values:

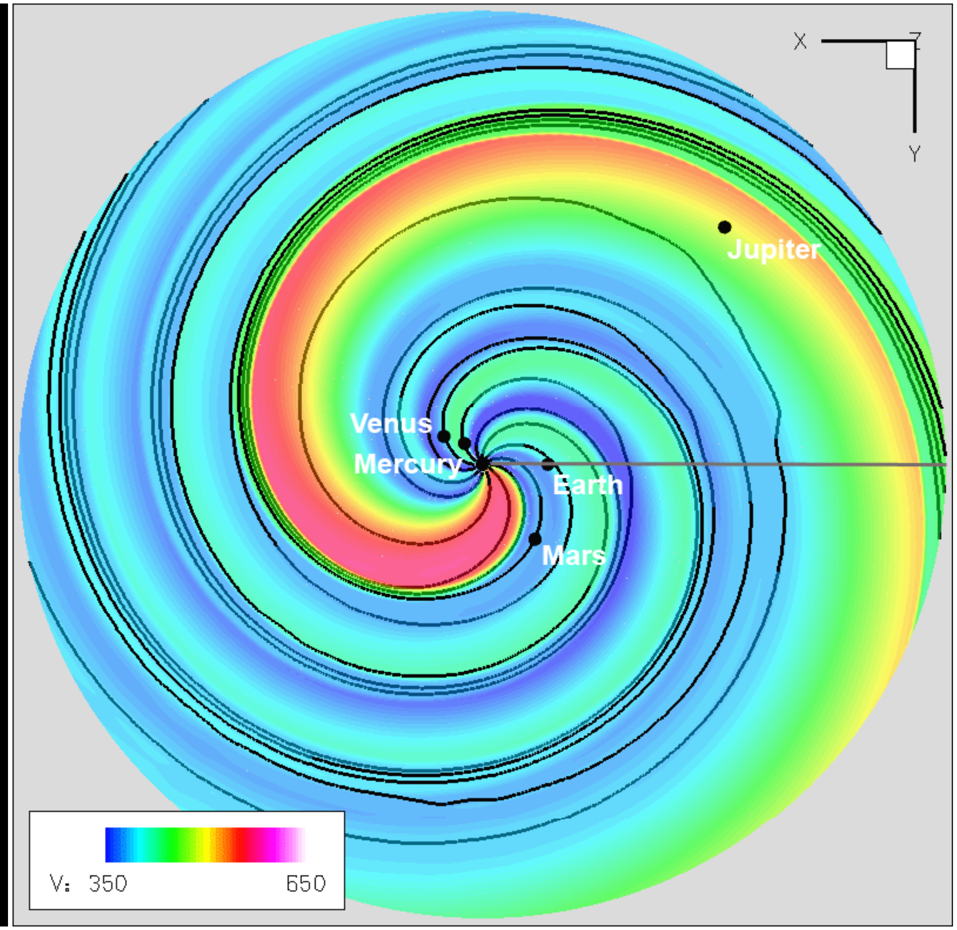
- n ≈ 6,3,12 cm^{-3}
- $|B_{IMF}|$ ≈ 6,2-3,12 nT
- v_{sw} ≈ 300-600 km/s
- Spiral ~45, 50, 35deg

} 1 AU, 1.5 AU 0.7 AU

However, even quiet conditions are not uniform or constant.

e.g. Solar Wind nonuniform stream structure provides external variations that evolve with distance

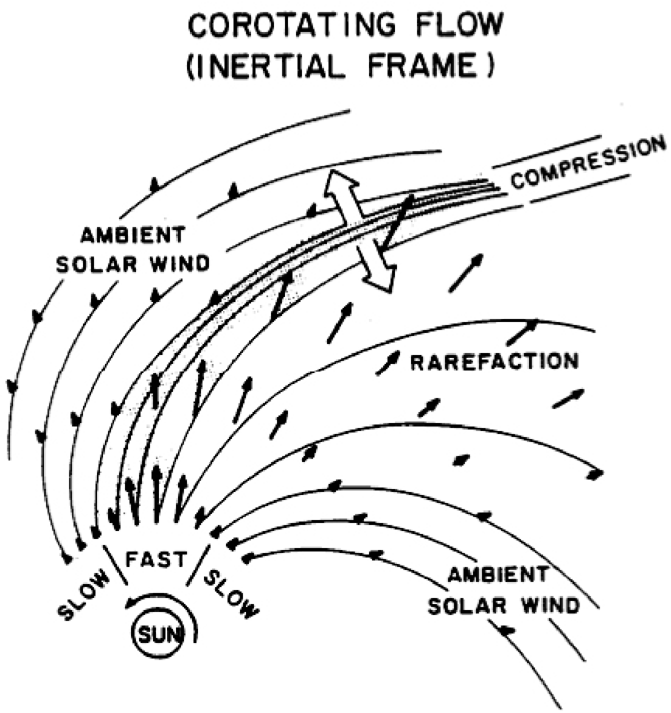


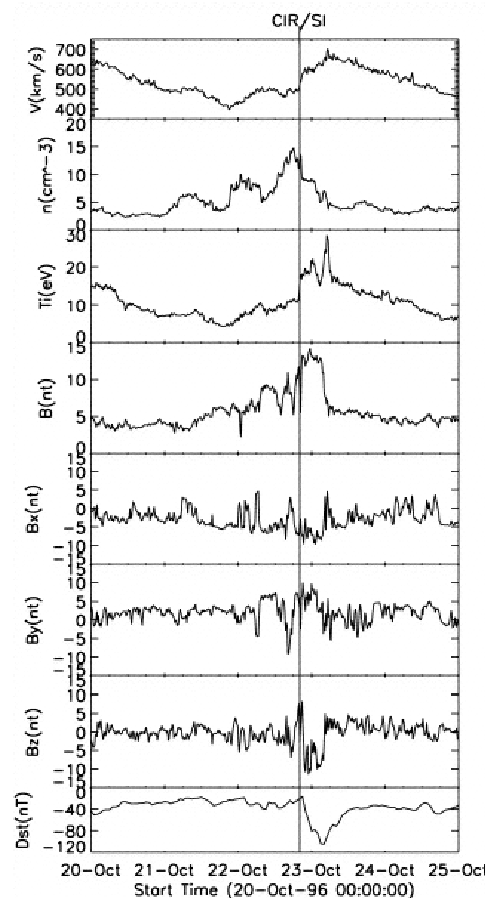


(left) Parker spiral magnetic field structure and planet locations, assuming constant solar wind speed of 450 km/sec, Earth fixed and Sun-Earth line (0 degree CR longitude, straight dashed line)-(from C. Lee UCB)

(right) Realistically modeled solar wind velocity distribution and field out to 8 AU using ENLIL MHD model (from D. Odstrcil, U of Colorado)

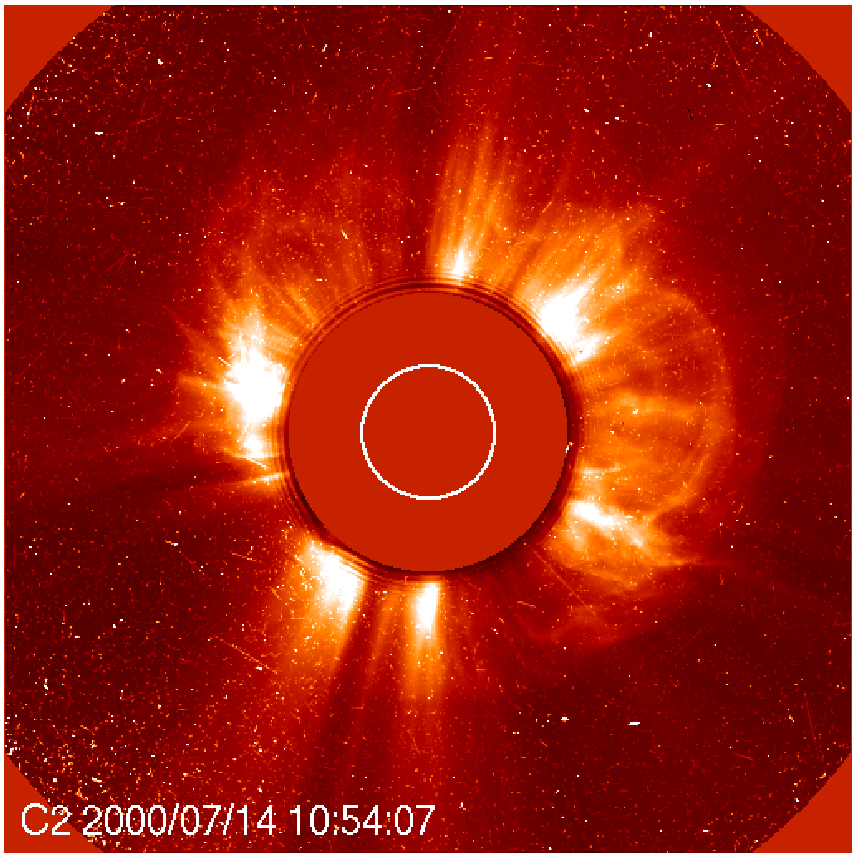
Solar Wind stream interaction regions (SIRs-or CIRs if corotating) can make interplanetary field and flow deflections and pressure ridges



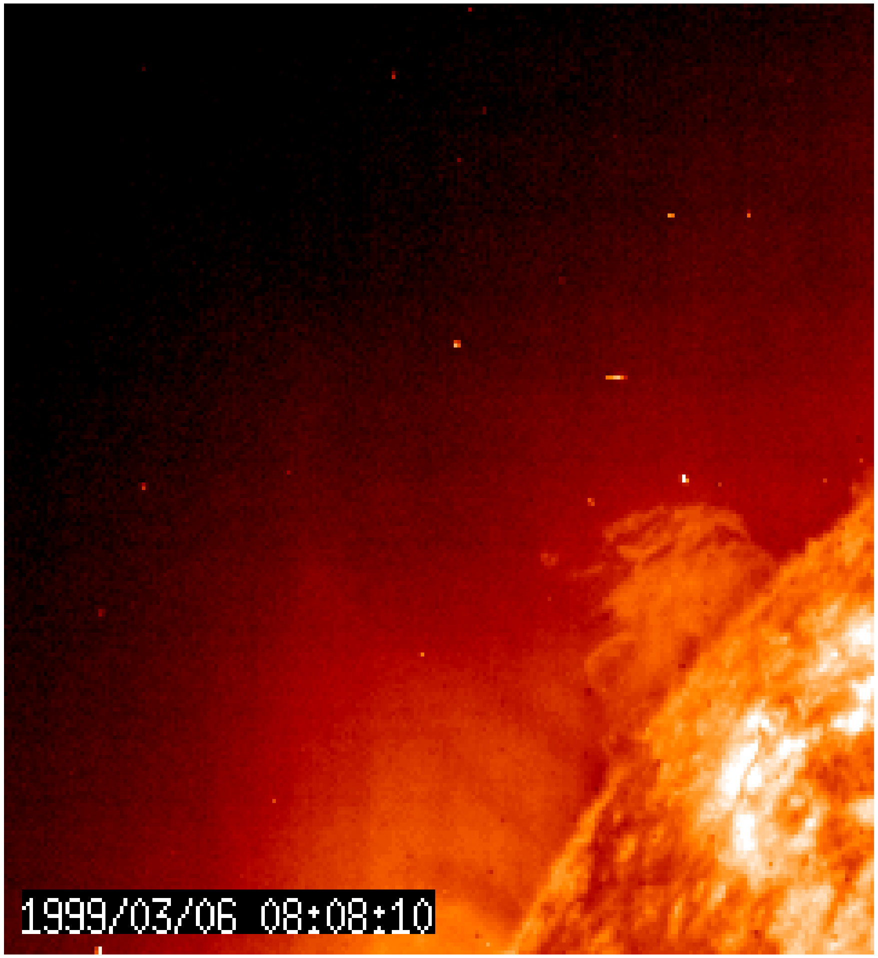


SIR “Geoeffectiveness” depends on whether high Vsw and Bz reinforce (figures from V. Pizzo, JGR 1991 (left), and J. Zhang, ApJ, 2006 (right))

The most extreme interplanetary plasma and field conditions result from Coronal Mass Ejections-CMEs

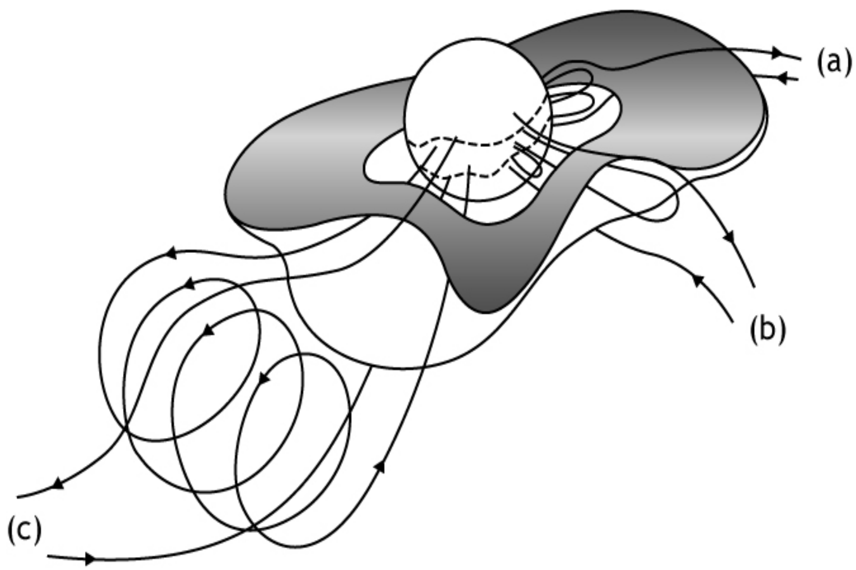


(Soho LASCO white light (above)
And EIT EUV (at right) images)

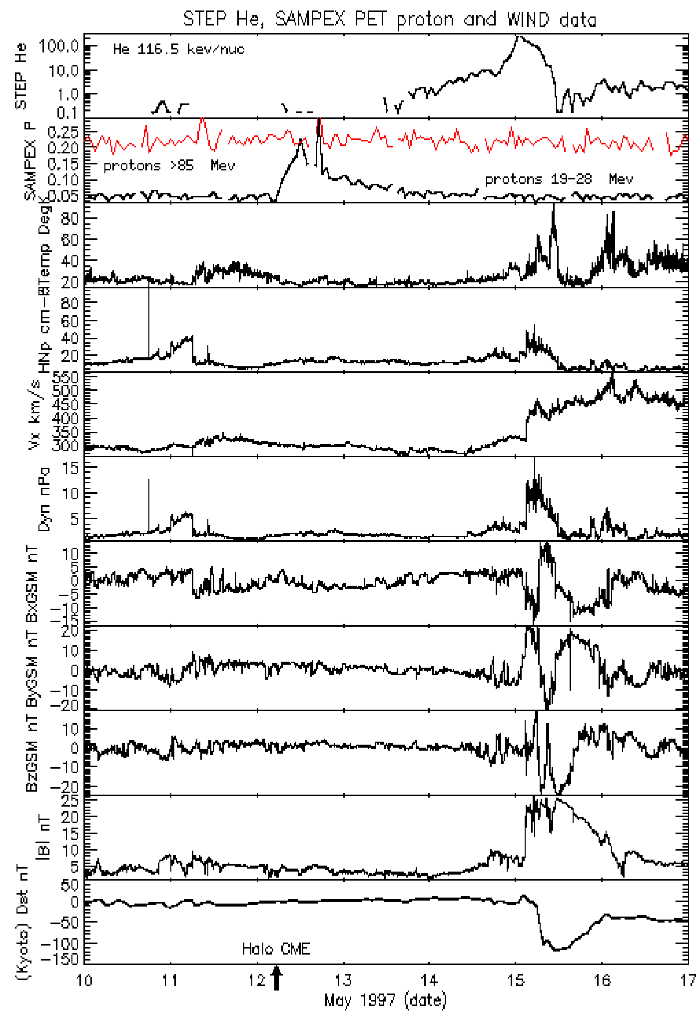


(erupting filament associated with a CME)

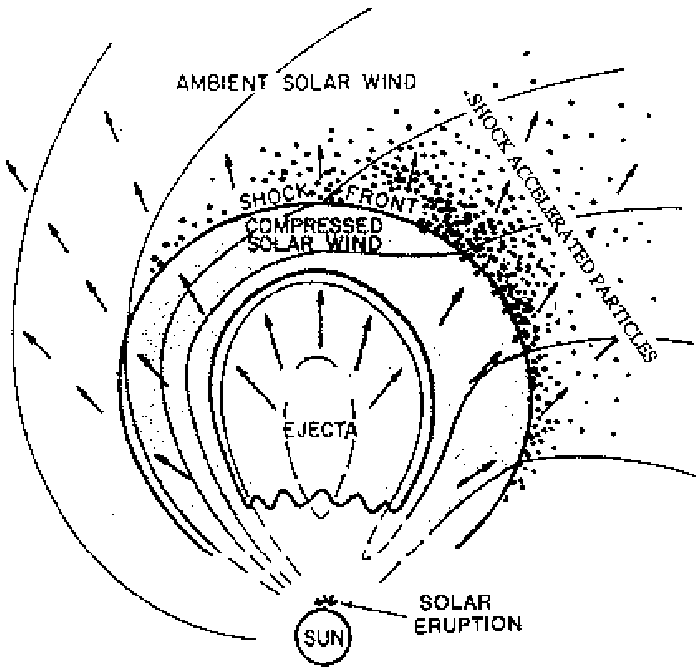
Heliospheric in-situ observations suggest that fast-moving coronal “flux ropes” may be ejected when CMEs occur

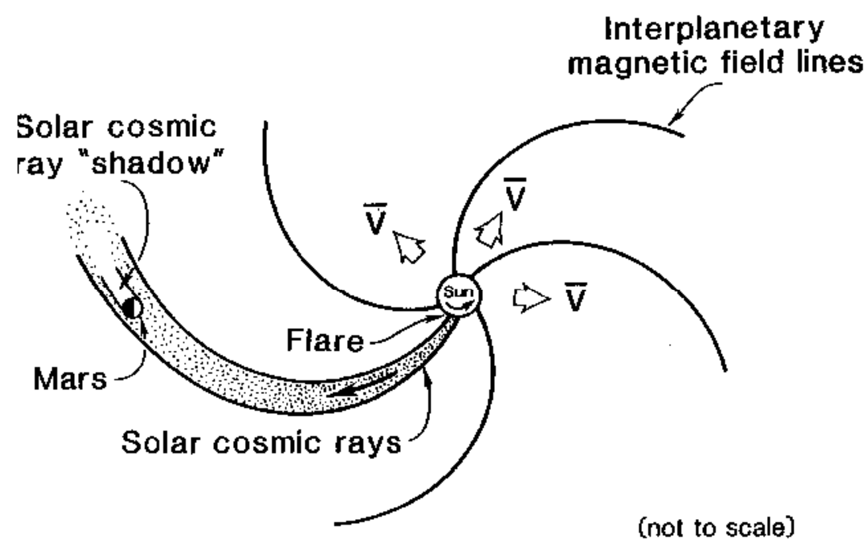


(from Crooker, 1993)



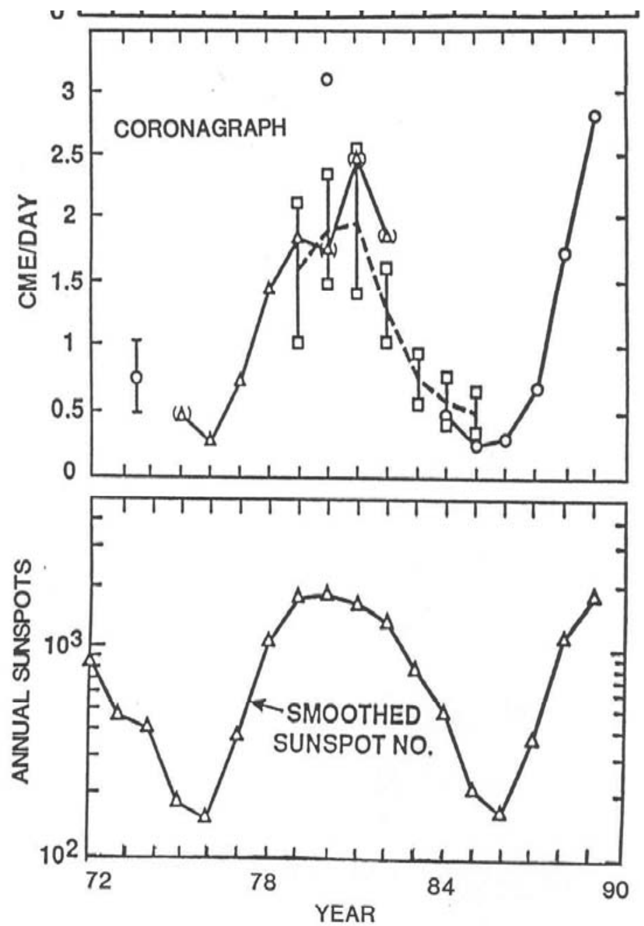
CMEs disturb the ambient solar wind, and if moving fast enough, generate a shock. Both flares and CME shocks accelerate particles. Sometimes these are mixed together.



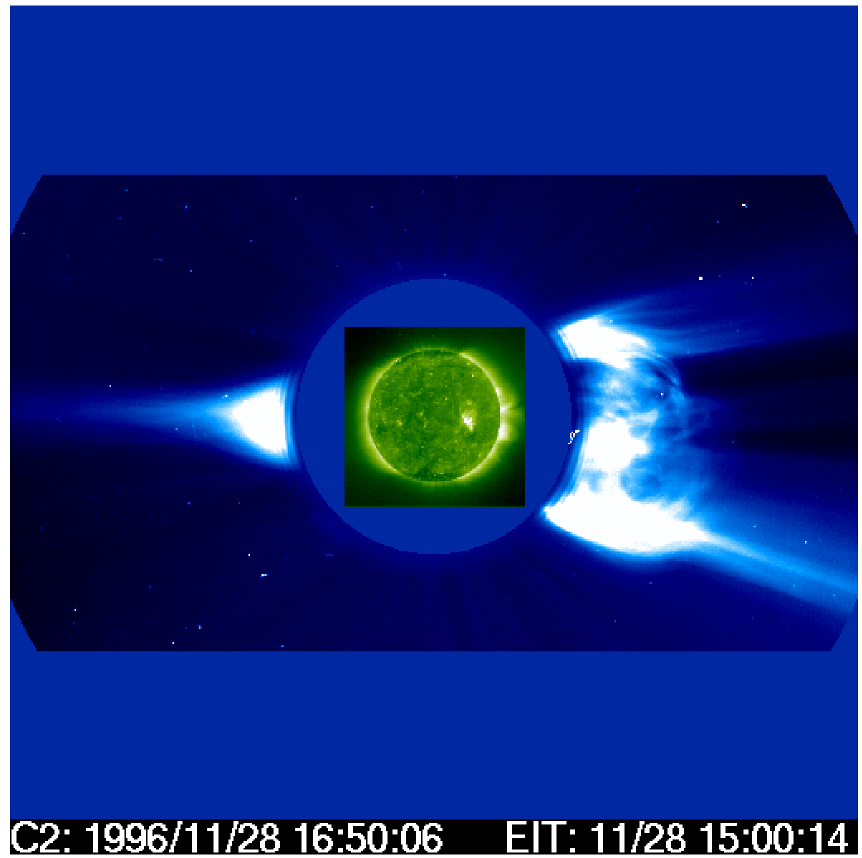


What a planet experiences depends on where it is located in its orbit in relation to the flare or eruption.

Along with XUV emissions, CME and flare occurrence rates vary with Solar Cycle phase
Thus ‘solar cycle’ effects are not only photo-effects.



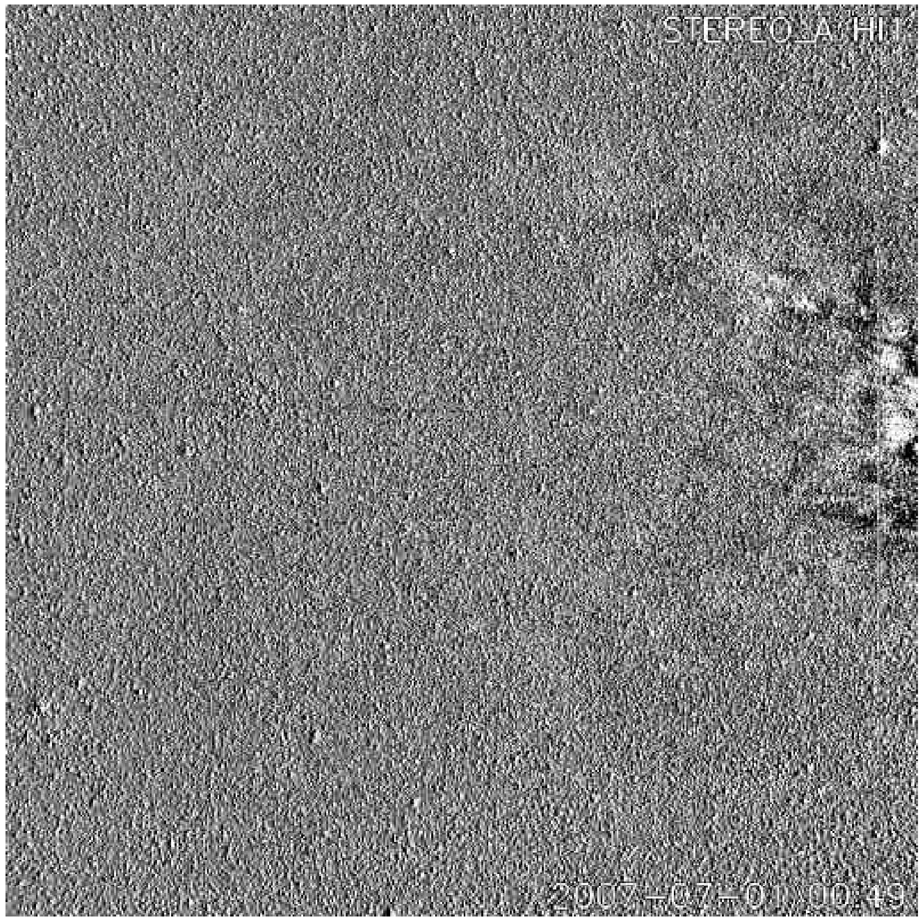
Webb et al., JGR 1991

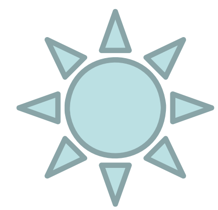


CDAW CME catalog SOHO image

But even the quiet solar wind is full of structures of various scales from evolving coronal and interplanetary conditions

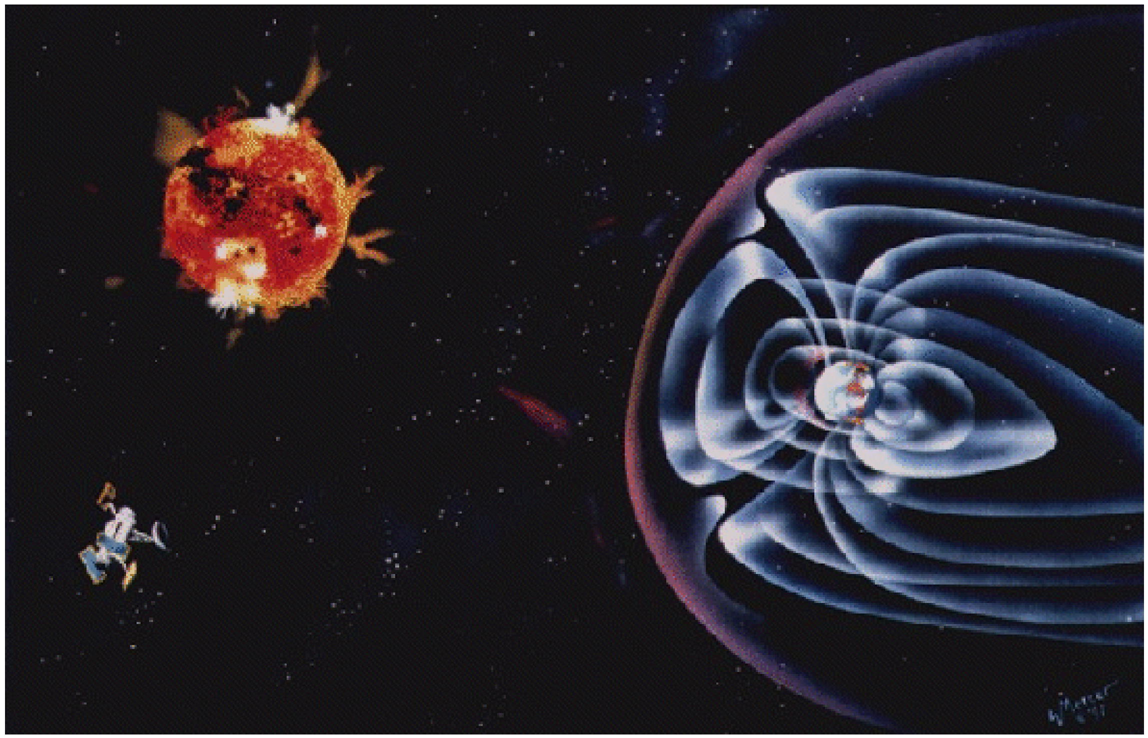
(SECCHI-HI website Image)





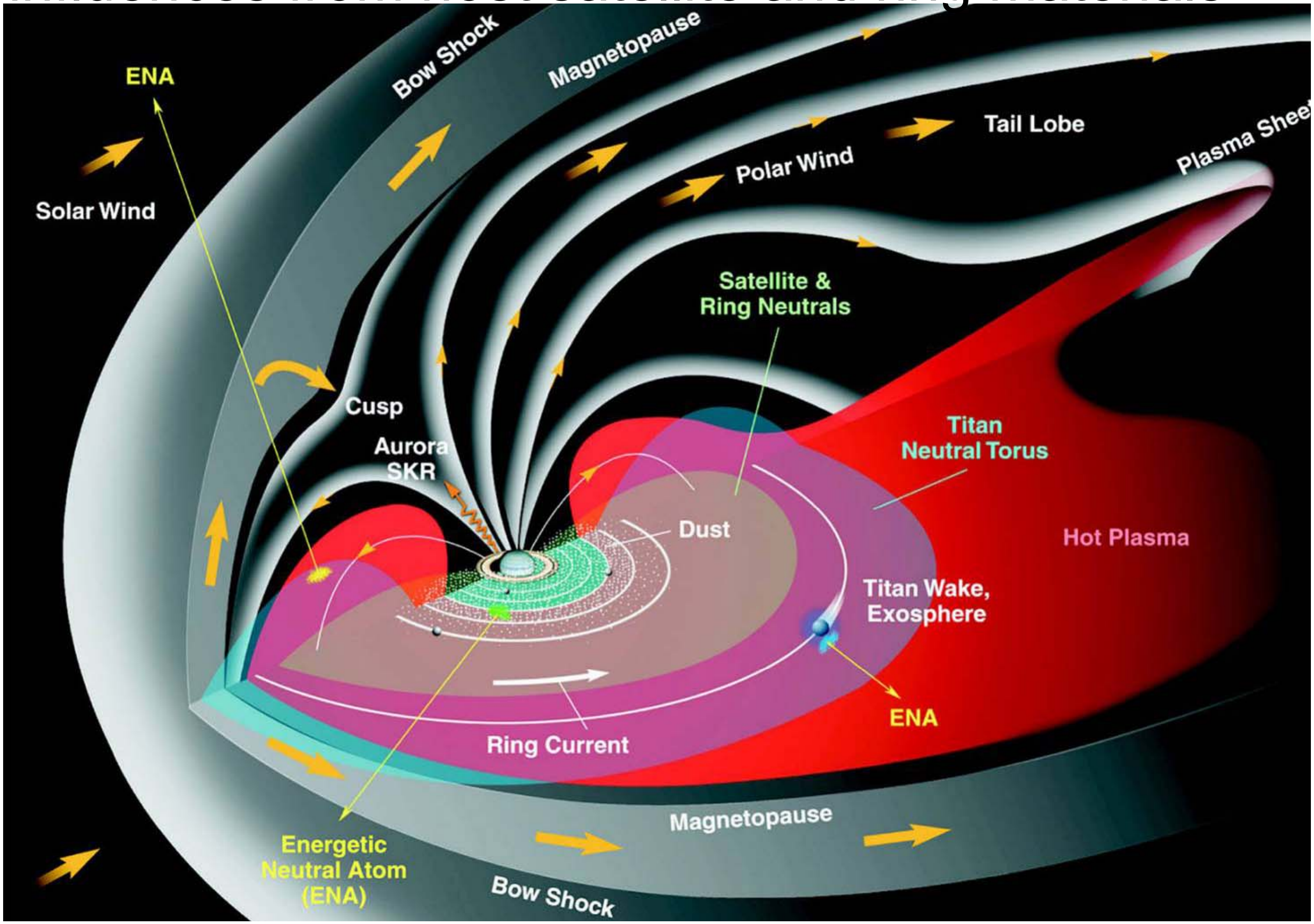
SECCHI HI observes structures on many scales moving out, while in-situ field and plasma data show many fluctuations

Another type of external environment is provided by planetary magnetospheres, spaces dominated by the host's internal field but subject to the Sun



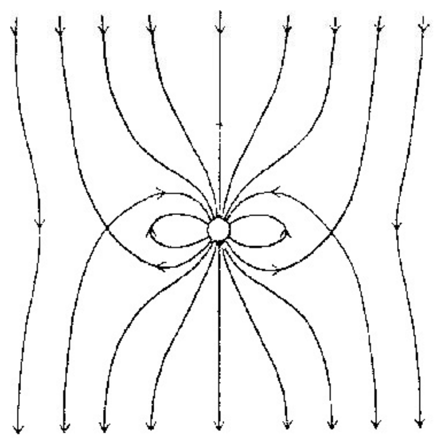
This introduces new features such as trapped radiation belt particles, and plasma densities and flows dictated by the solar wind interaction with the host's magnetic field. Host planet gravity can also be a factor.

Saturn's Magnetosphere exemplifies additional influences from host satellite and ring materials

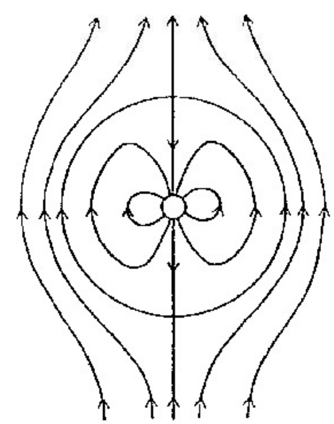


From a presentation by J-E Wahlund

Magnetospheric environments are affected by their relationship with the interplanetary environment e.g. through reconnection with the IMF (illustrated) or responses to solar wind pressure, velocity, density



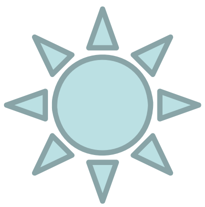
a uniform southward magnetic field added to a dipole.

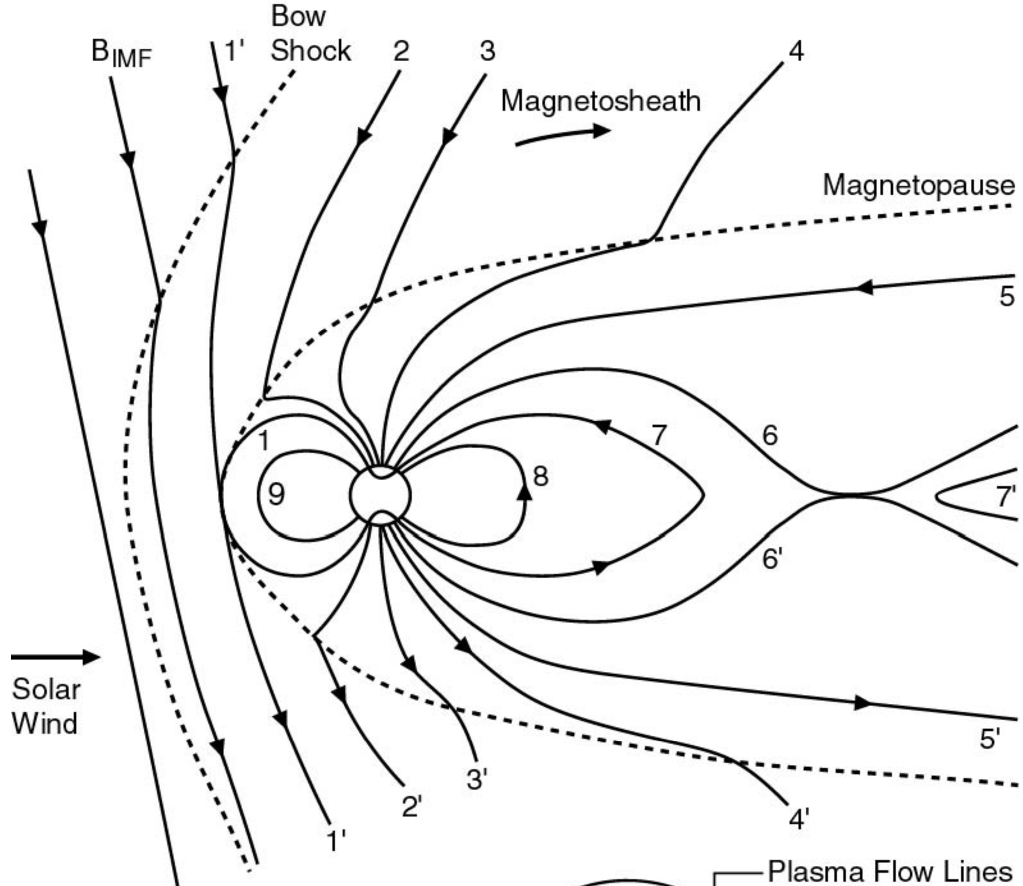


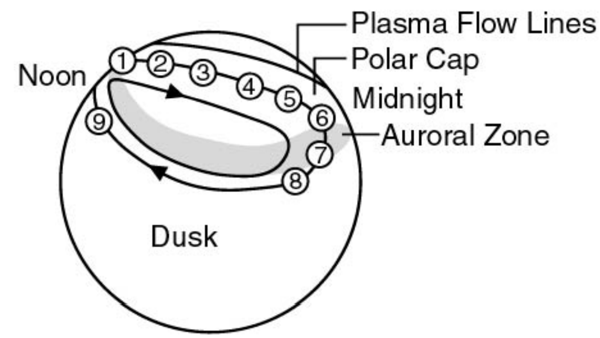
a uniform northward magnetic field added to a dipole.

External field and dipole antiparallel at equator

External field and Dipole parallel at equator

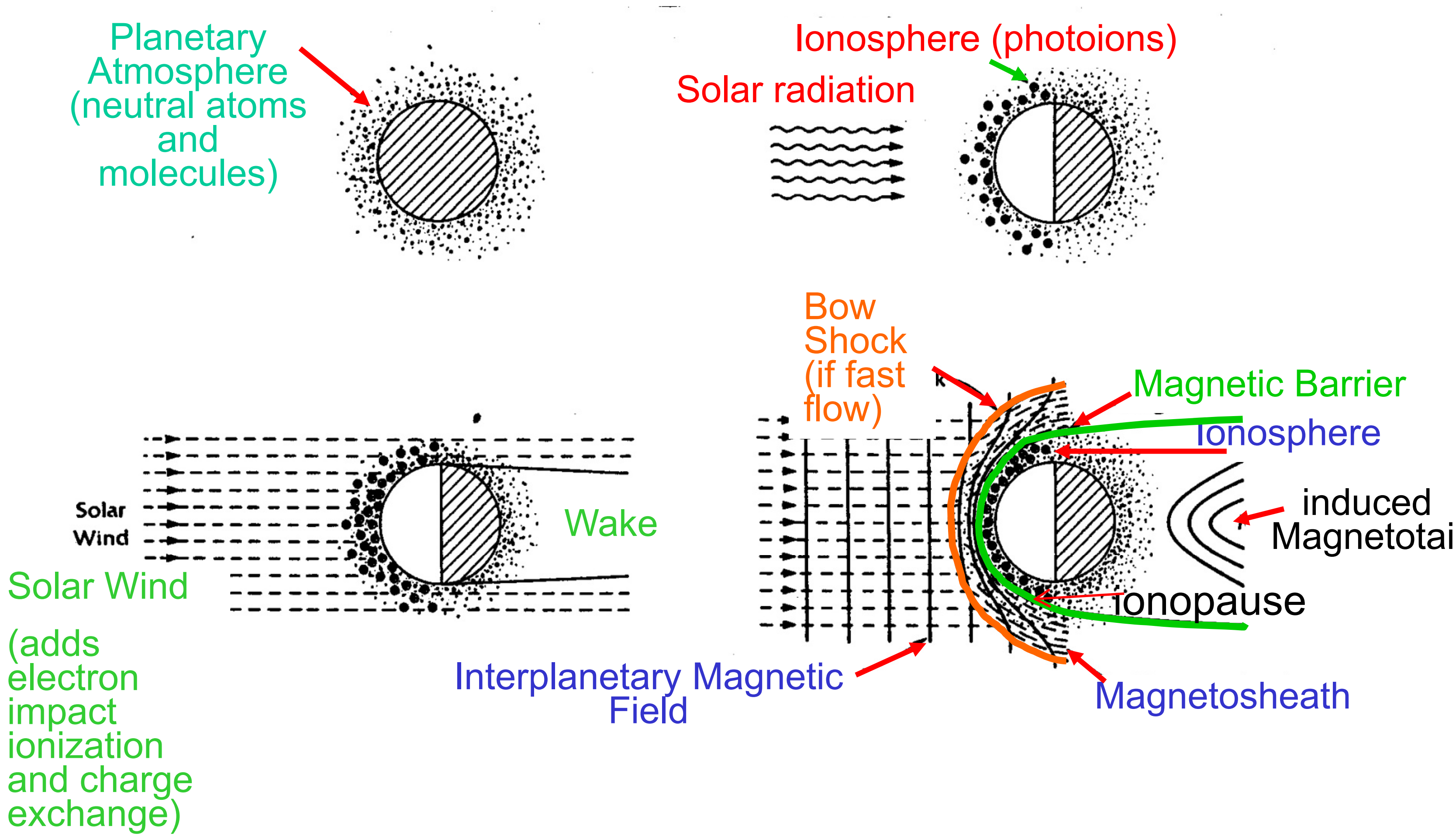






e.g. At Earth, Southward fields make the strongest response: The Magnetic Storms/substorms. Other magnetospheres have their own sensitivities and responses. The main point is that magnetospheres present variable plasma and field environments too.

Prototypical field-free ‘planet with an atmosphere’-solar wind interaction



Pressure Balance Concept for an Atmospheric/Ionospheric 'Obstacle'

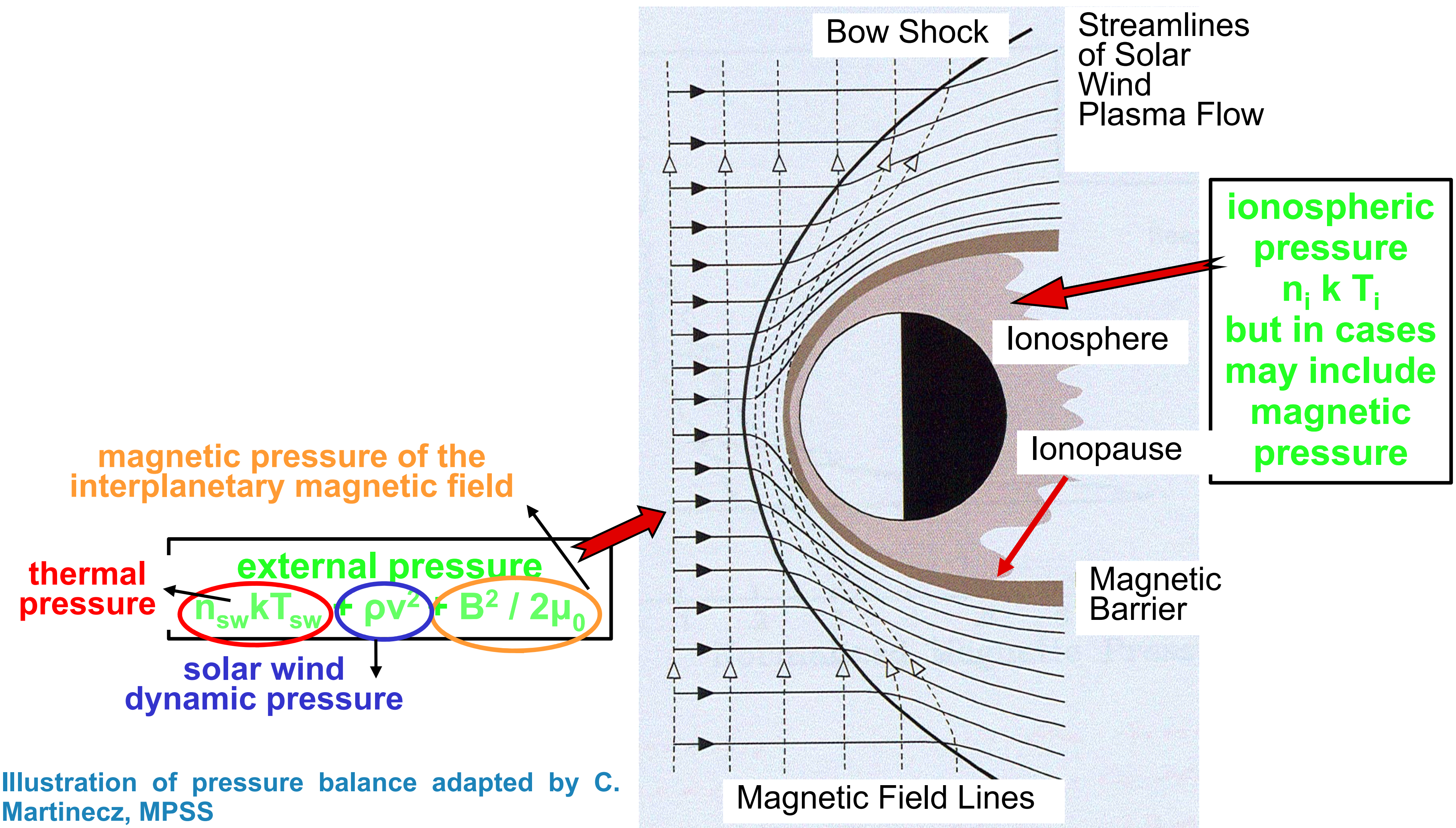
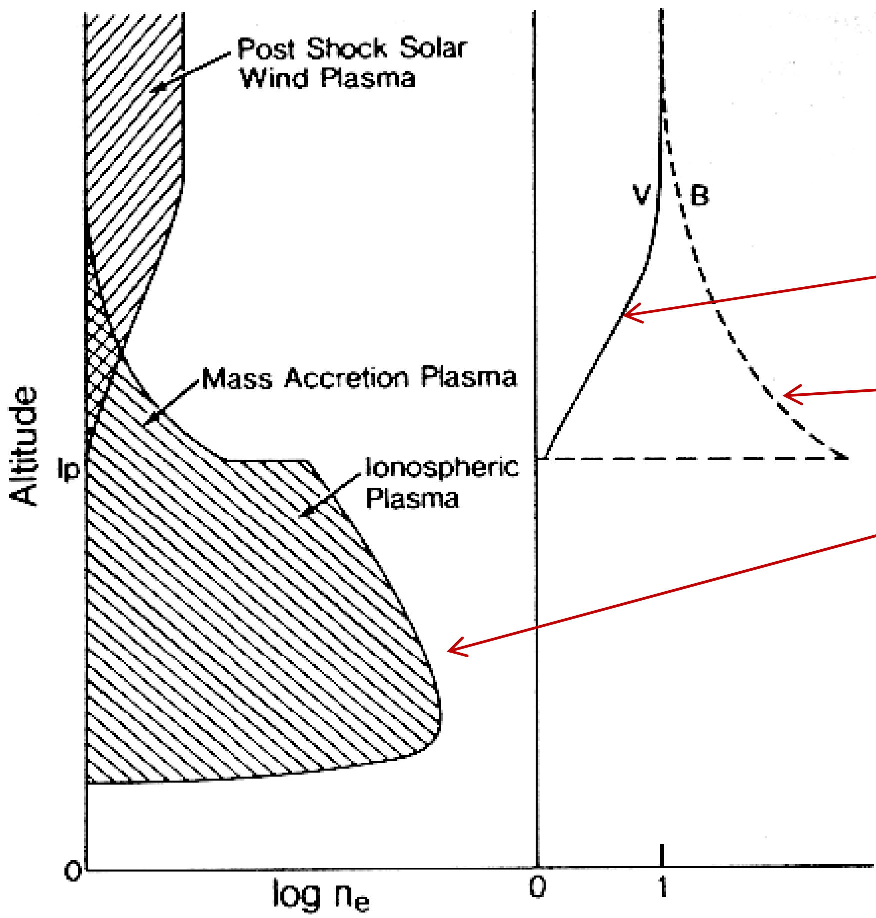


Illustration of pressure balance adapted by C. Martinecz, MPSS

Stagnation line pressure balance



Dynamic pressure
goes to
Magnetic pressure
goes to
Ionospheric thermal
Pressure (magnetic
contributions can
remain)

(from Russell and Vaisberg in VENUS, Univ of Arizona Press, 1982)

Comparison of atmospheric obstacle, sheath, and bow shock scales

Earth radius = 6371 km

Venus radius = 6051.8 km

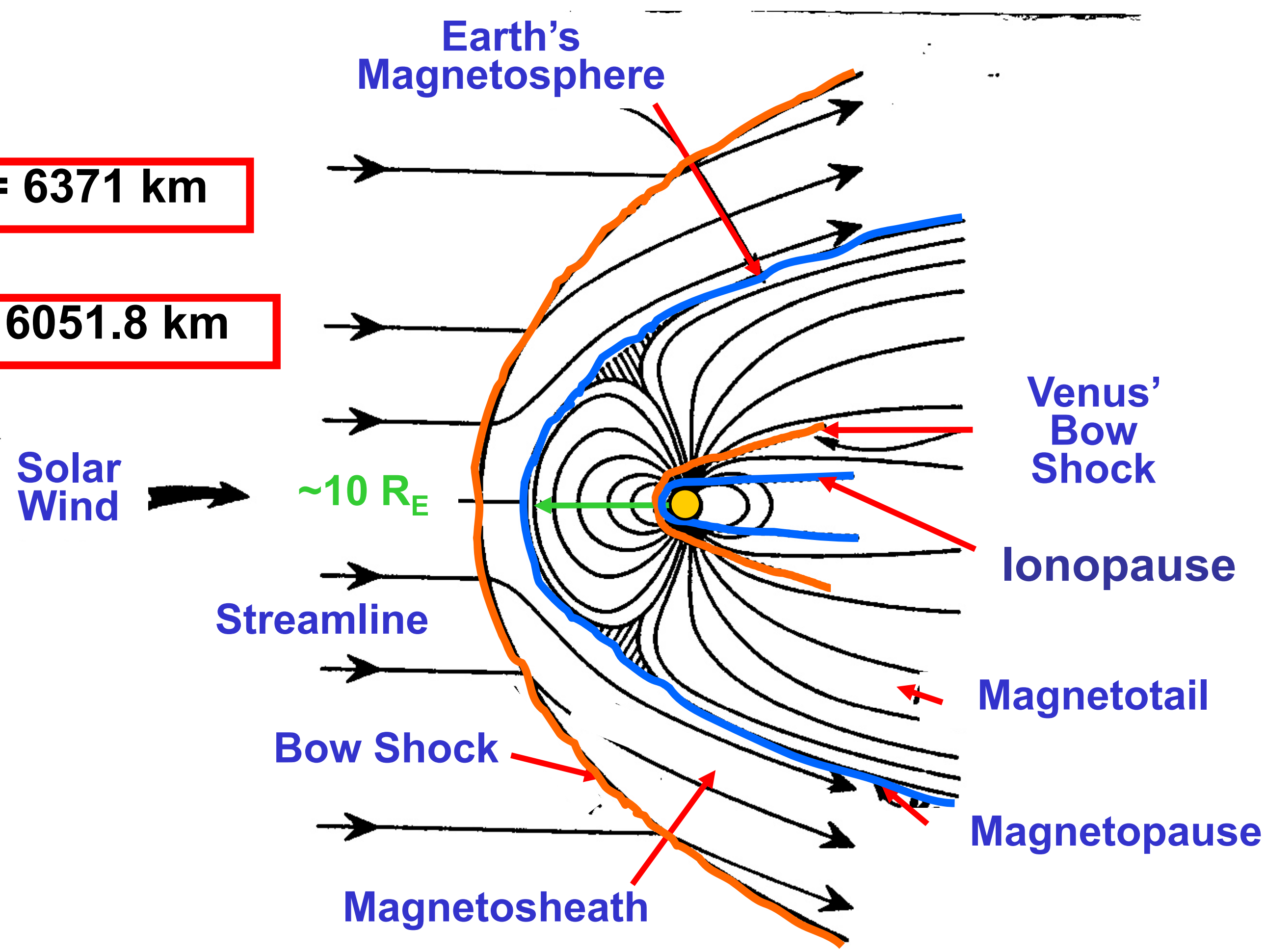
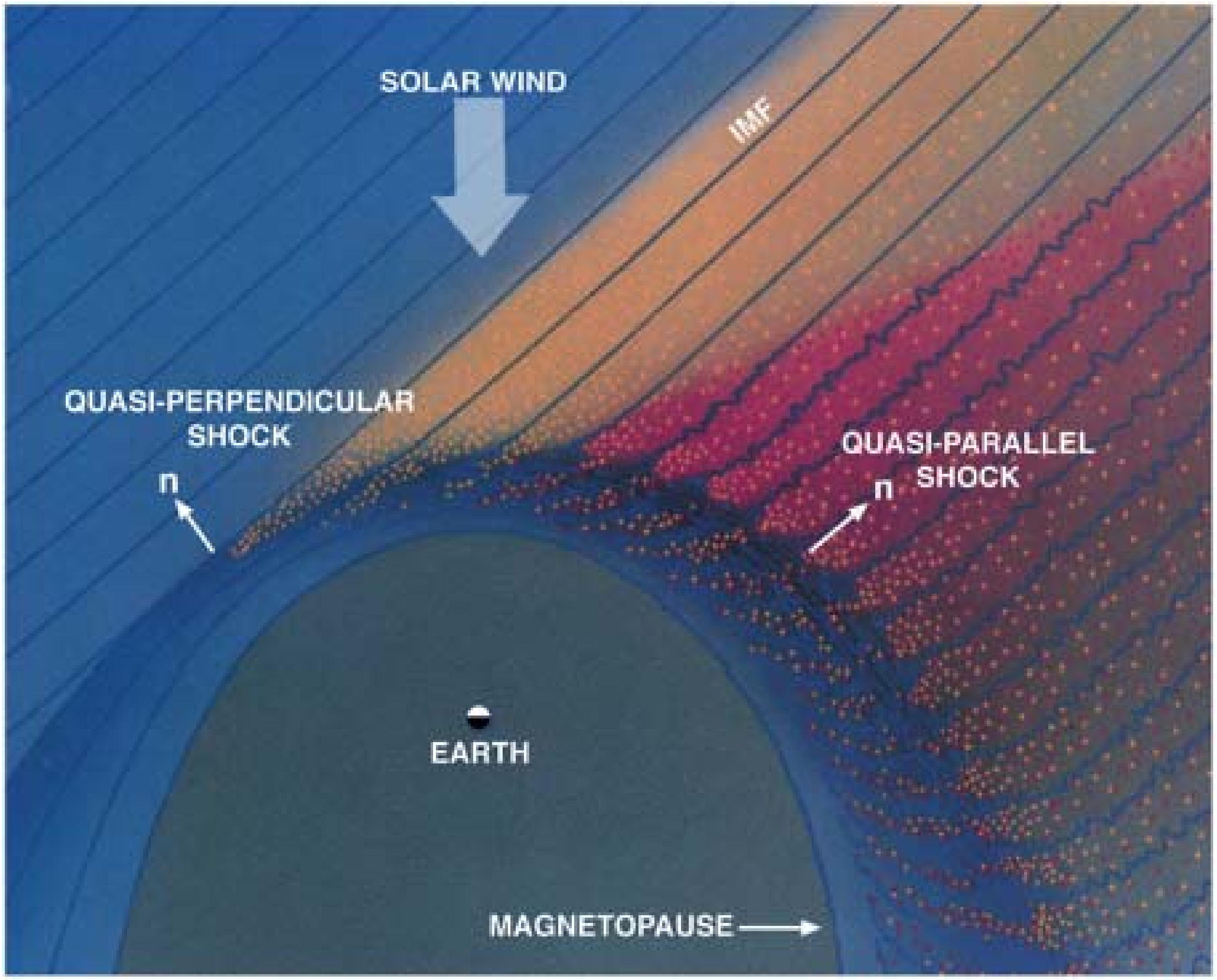


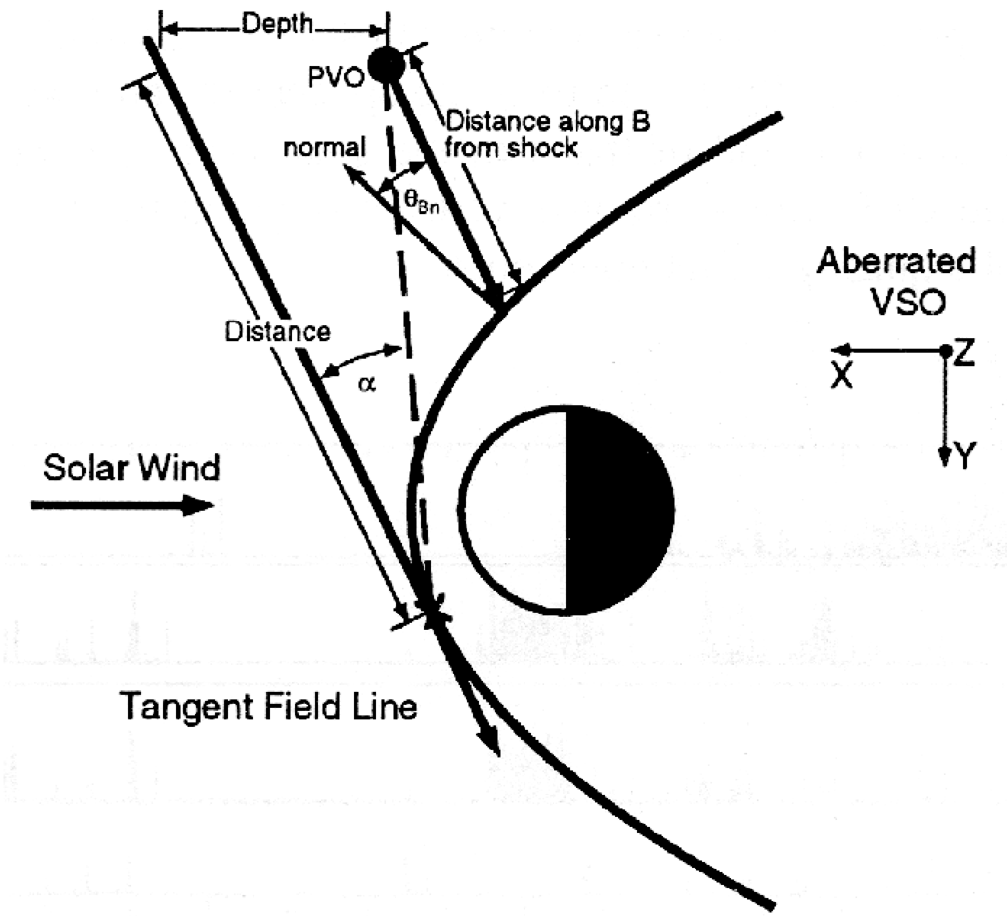
Illustration Adapted by C. Martinecz, MPSS

Added incident fluctuations come from foreshock waves generated by ions energized or reflected at the bow shock that are convected into the sheath



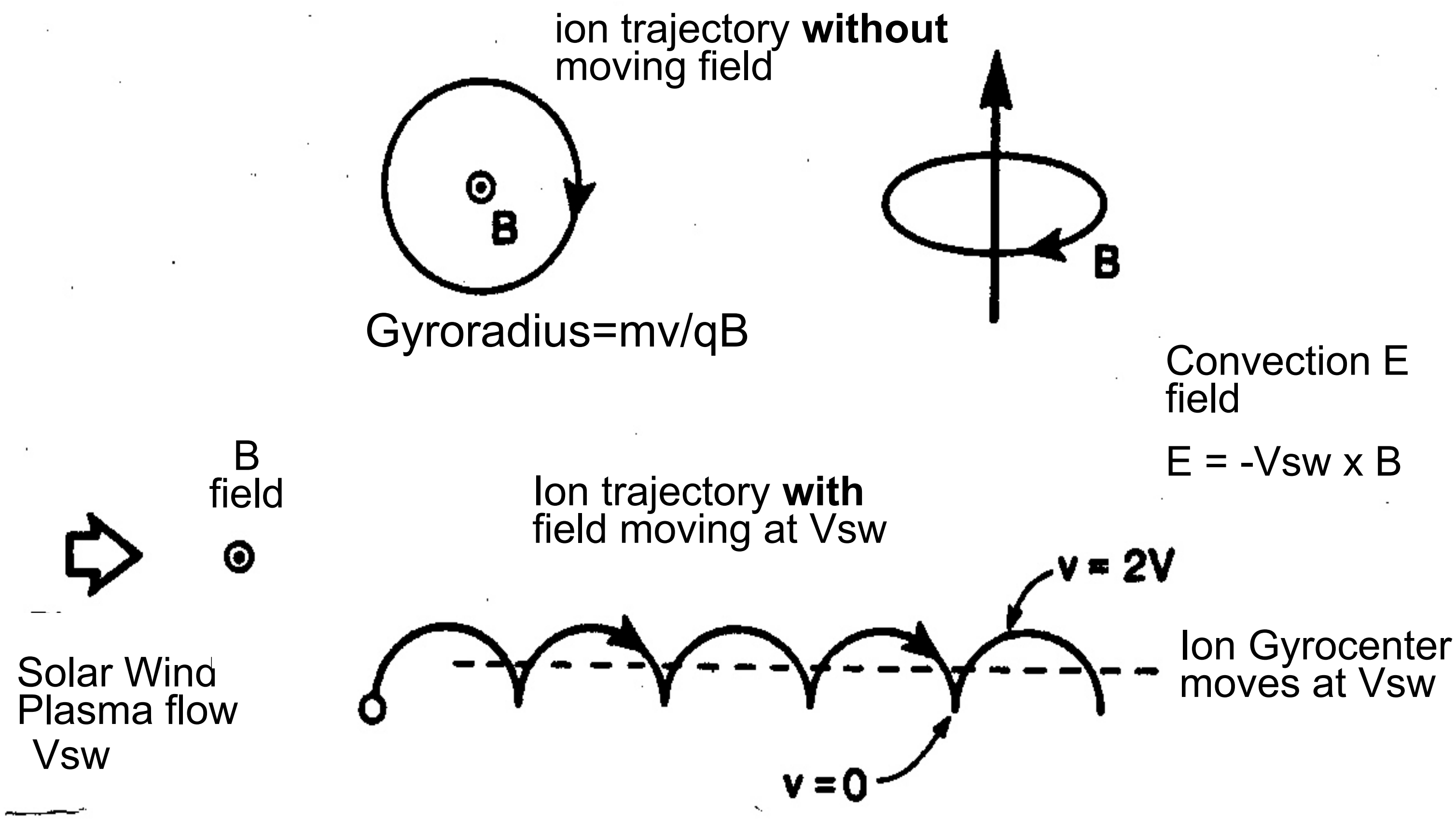
(Figure From Tsurutani et al., 1995)

These can be especially effective when the shock/sheath is small relative to the obstacle, adding to already existing sheath turbulence



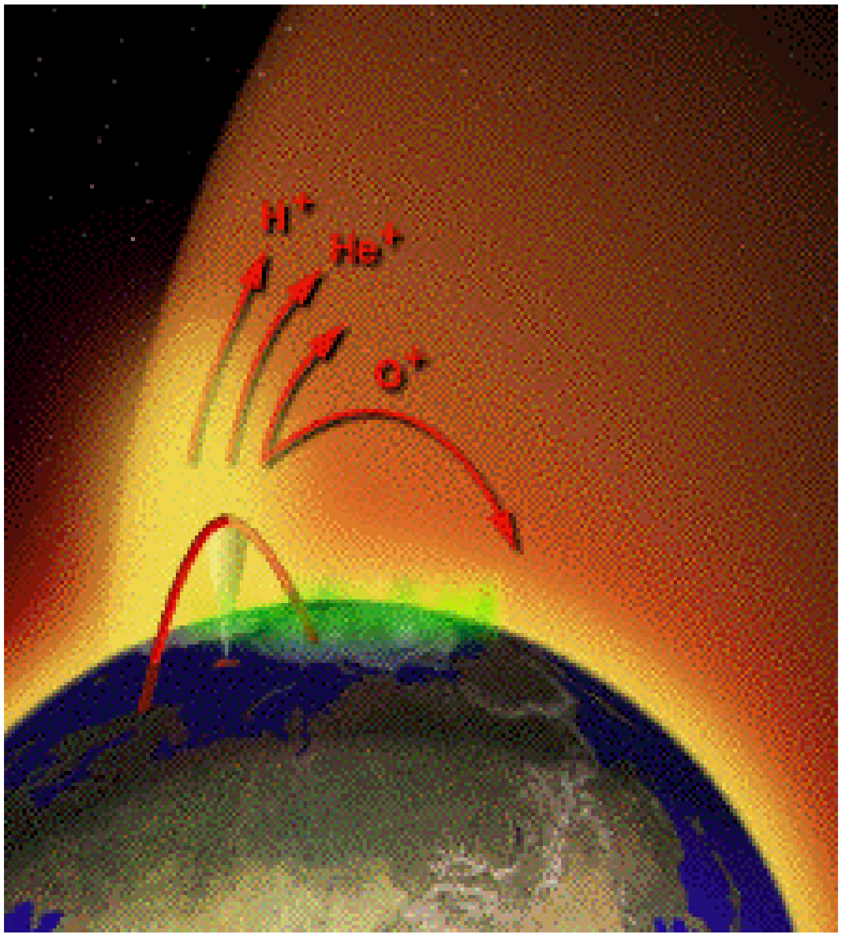
(figure from Strangeway et al., GRL)

Ion kinetic effects are important in the plasma-atmosphere interactions, especially for pickup ions



*but note ion kinetic effects may *also* matter for incident flow ions. Pickup ions *mass load* the flow and also affect the atmosphere through energy deposition by *impact*, or *via escape*.

A possible additional escape process may be like Earth's polar region atmospheric ion outflow



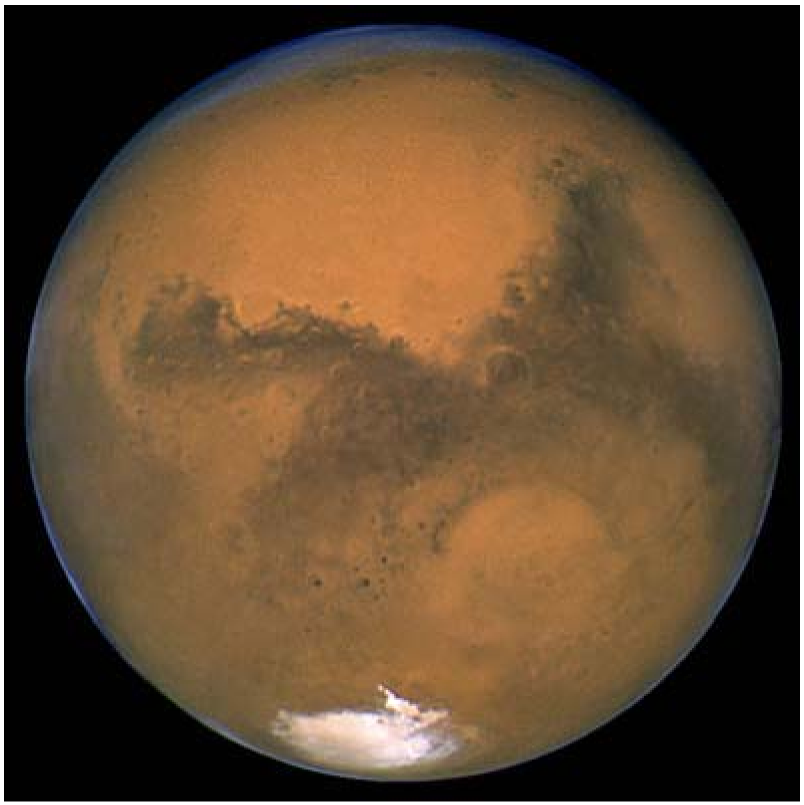
(Horwitz et al. illustration)

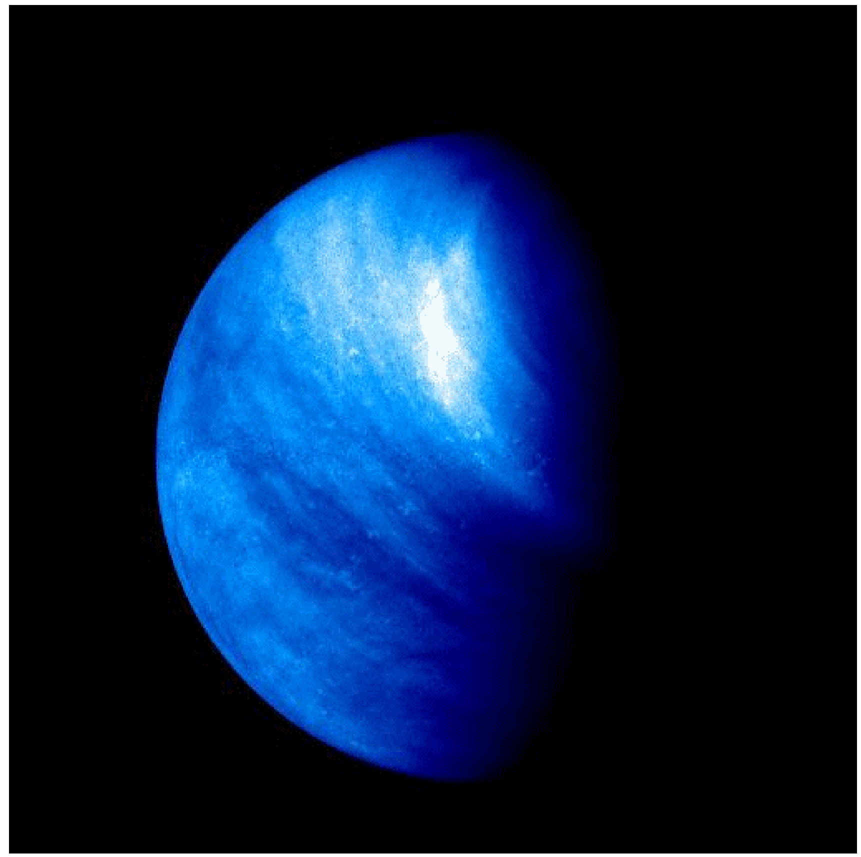
Includes:

- Classical light ion 'polar wind' (H+ and He+)
- Cusp 'ion fountain'
- Highly variable but sometimes intense 'Auroral outflows' include heavy ions like O+

>>***This is one of the only ways Earth can lose important heavy elements to space. Does this happen on Mars in the cusps? At Venus on draped tail fields?***

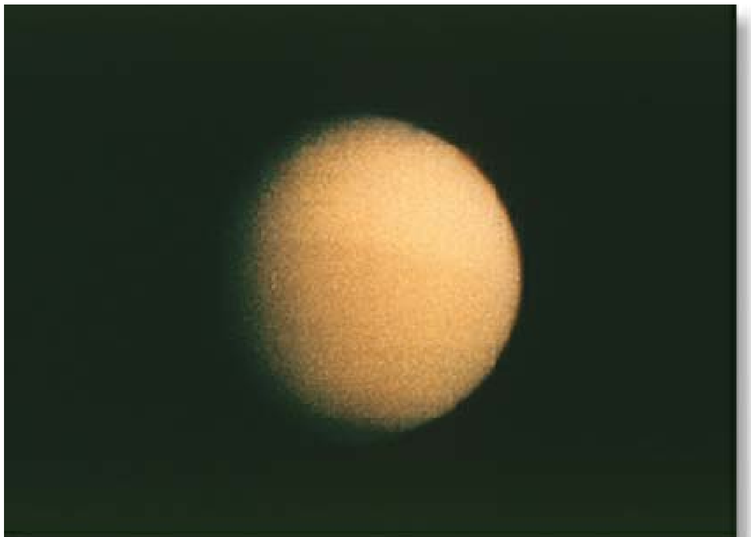
Mars and Venus in the Solar Wind





NASA Mars image, VEX Venus movie

Titan in Saturn’s Magnetosphere

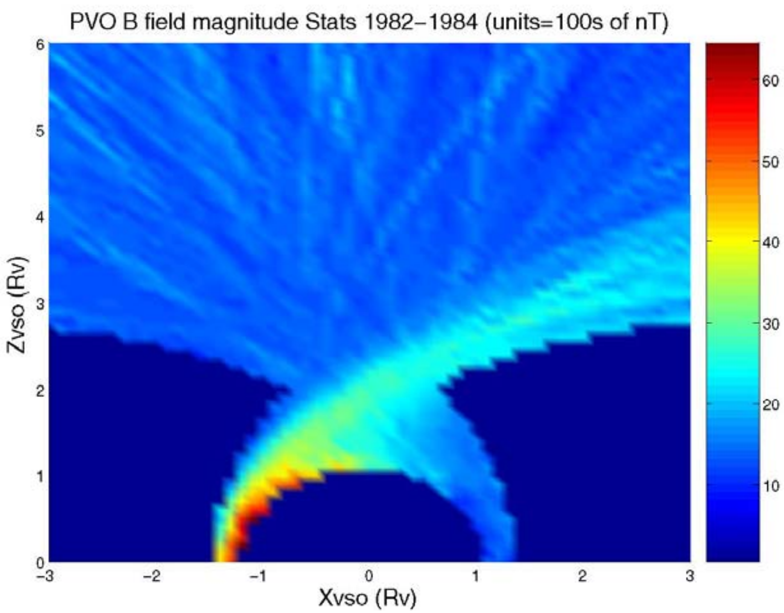


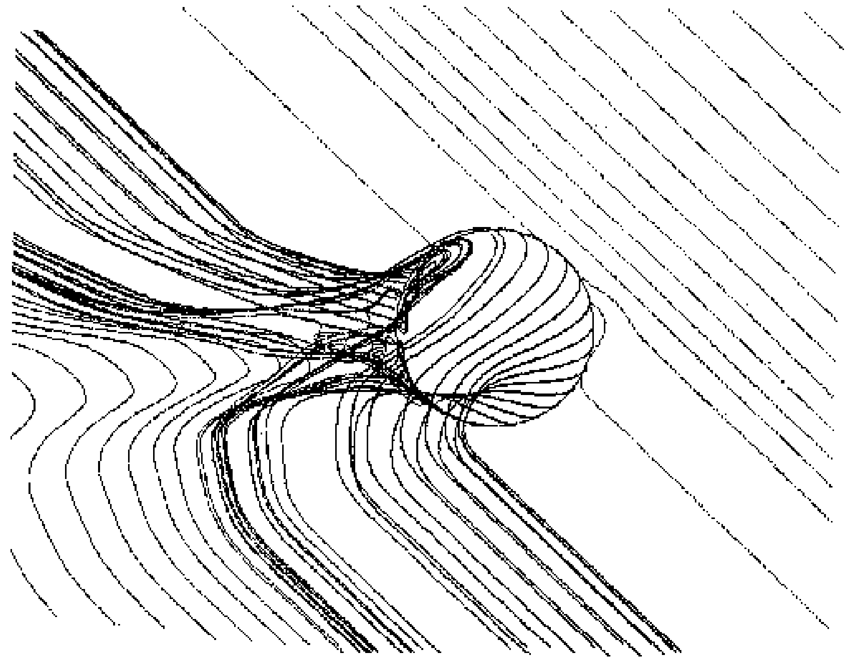
Cassini Image, NASA (C. Porco, PI)

Some Key Scales

		VENUS	MARS	TITAN
Planetary Radius:		~6053 km /Rv	~ 3395 km/Rm	~ 2575 km/Rt
Exobase alts:		~200 km	~200 km	~1450 km (thick atmos!)
Escape velocity		~11 km/s	~5 km/s	~1.5 km/s
Subsolar ' Ionopause'*		~250-350 km (typ. Solar max)	~350-450 km (lumpy magneto/ionopause)	(variable?)
Ion gyroradii	H+	~0.1 Rv	~0.3 Rm	~0.4 Rt
	O+	~1.0 Rv	~3.0 Rm	~4.0 Rt
External flow		~350-750 km/s	same as Venus	~80-120 km/s
bow shock nose		~1.5 Rv	~1.5 Rm	(none in magnetosphere)

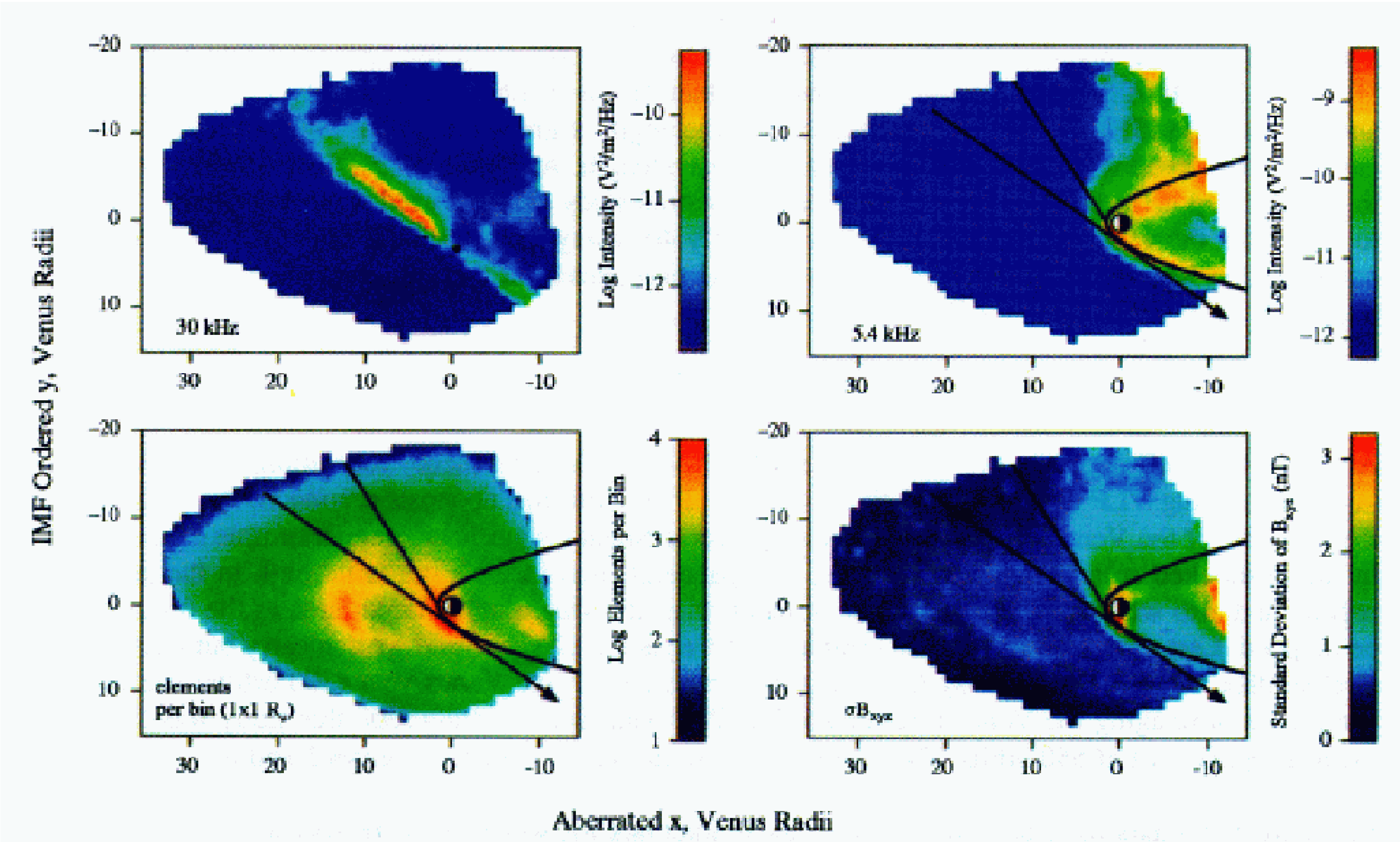
The Venus interaction to first order looks like MHD flow around a conducting sphere



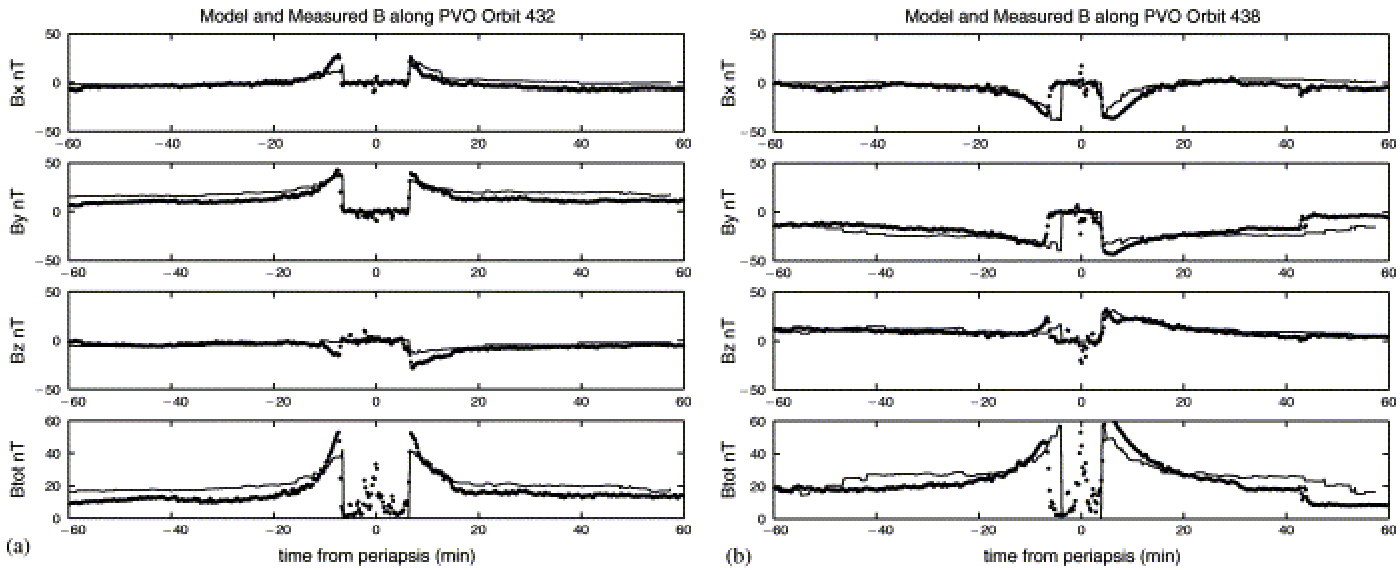


The shock location and the magnetosheath field pileup show up clearly in the field statistics from PVO (left). MHD model fields (e.g. Tanaka's (1996) at right) are a good representation.

Venus Plasma Wave foreshock observation statistics show the sheath can be full of convected upstream fluctuations (also seen in B fields)



(Strangeway et al., GRL, results from PVO)



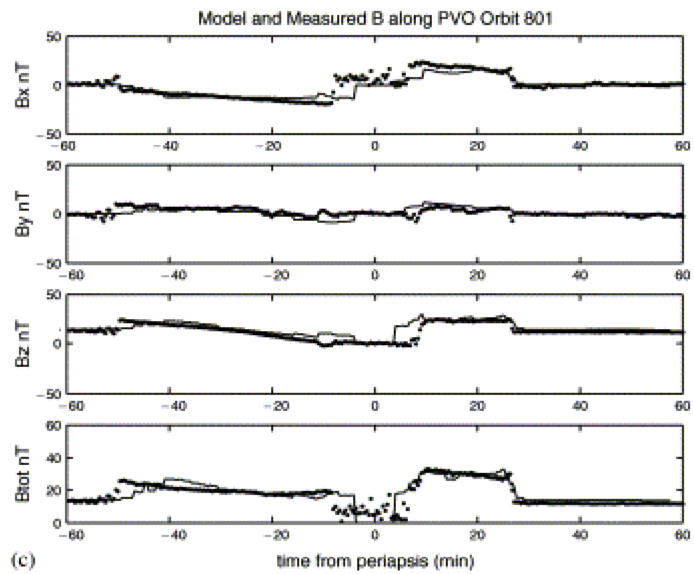
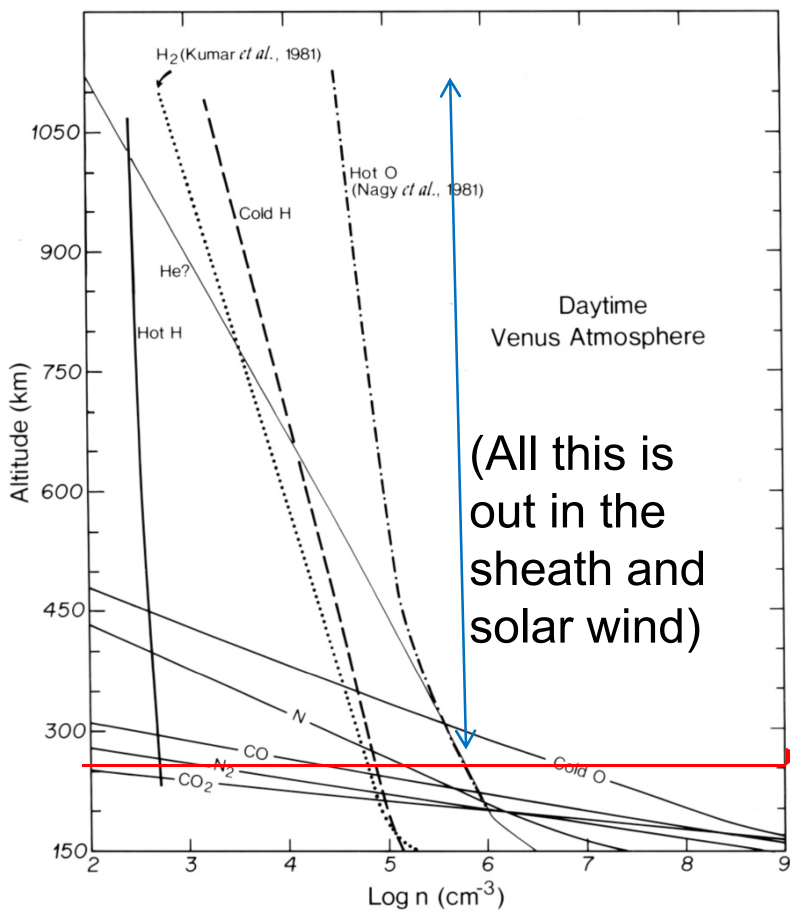
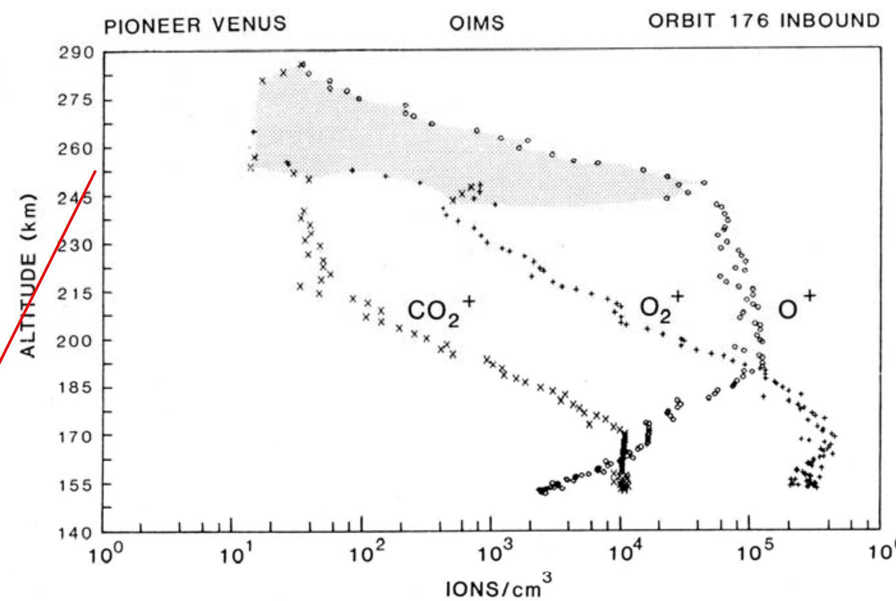


Illustration of how well an MHD sheath field model describes the Venus data at Solar maximum, with the ionopause used as the obstacle. (Luhmann et al., PSS 2005) –(and when the foreshock is not affecting the sheath.)

Inside the Venus Obstacle: Ionospheric Composition and Altitude Profiles

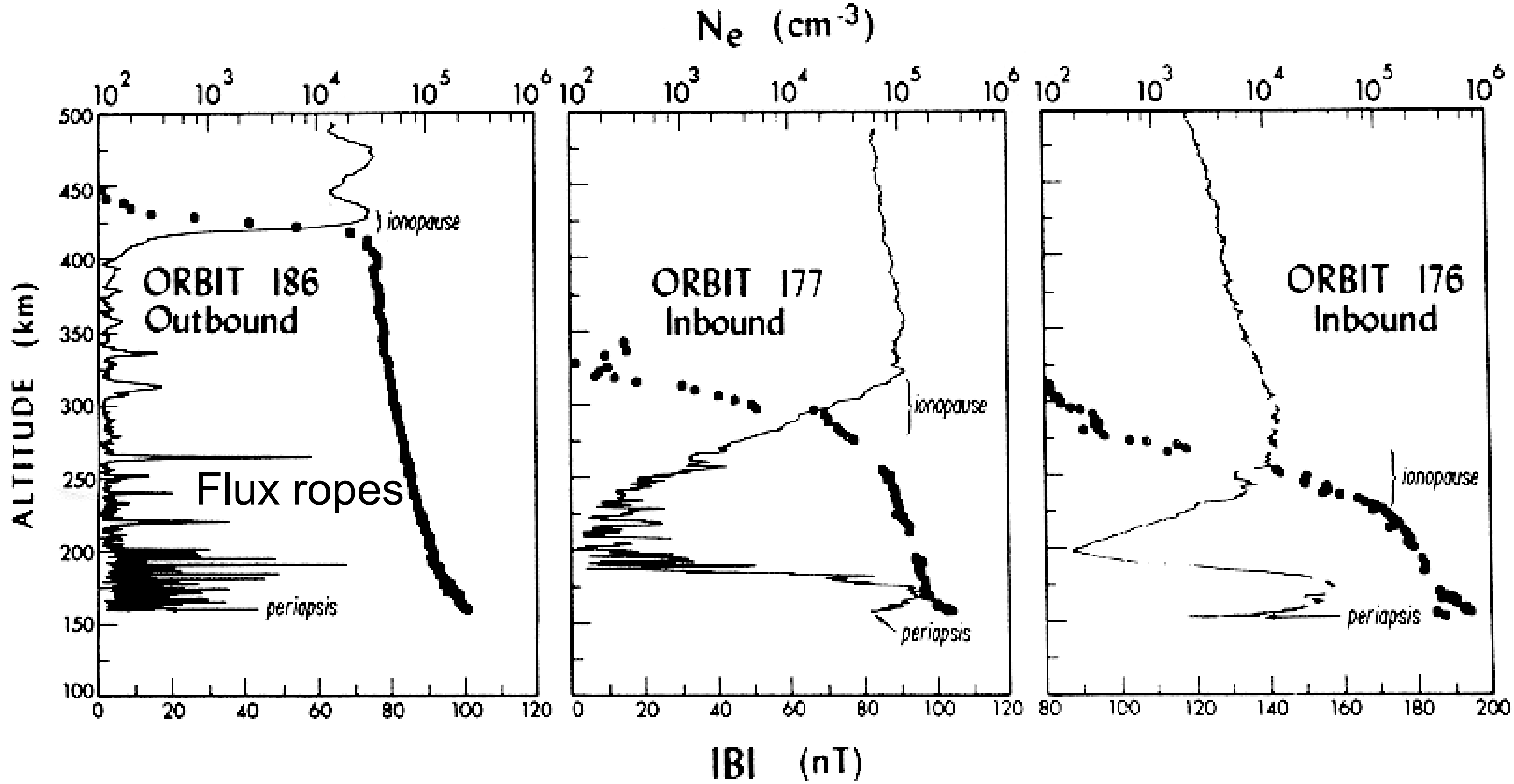


The ionosphere is mainly molecular and atomic Oxygen ions (like Mars), characteristic of a CO_2 atmosphere. Its high altitude boundary is controlled by incident Solar wind pressure and by Ion removal above the 'ionopause'.



Taylor et al., JGR, 1980

PVO observed different states of dayside ionosphere magnetization during its solar max prime mission, depending on the solar wind pressure. This ‘induced’ magnetization can be described as penetration by the overlying sheath fields due to collisional diffusion and downward convection.



*Note the ionopause is thinnest when it forms at highest altitude.

(Figure from Elphic et al., JGR, 1981-data points show Langmuir Probe electron density, Ne, lines show the B field magnitude).

Flux Rope Concept/Proposed Interpretations

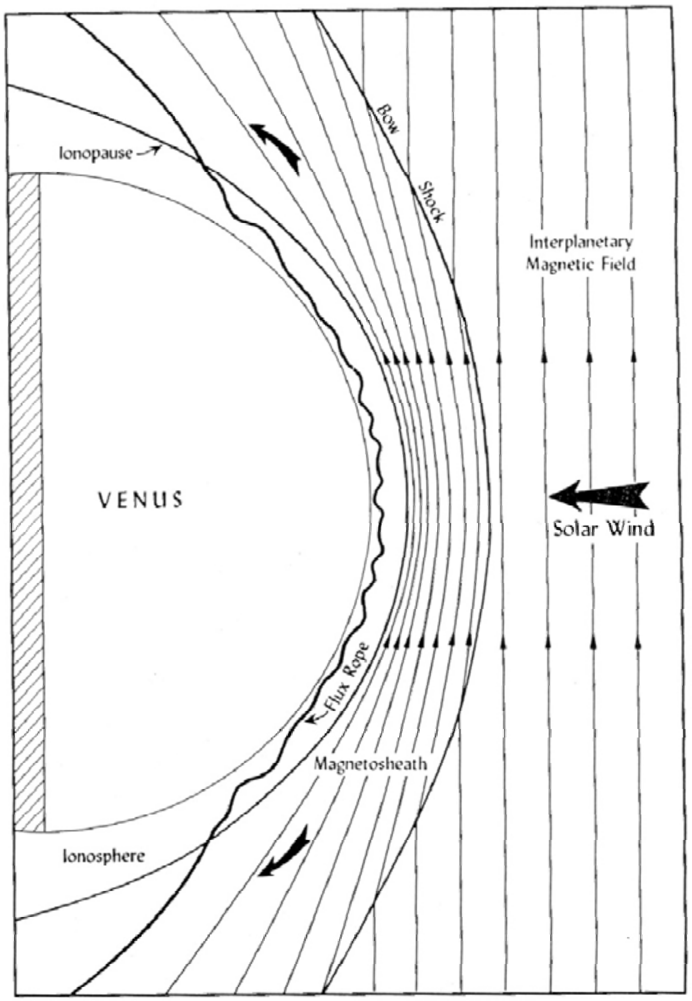
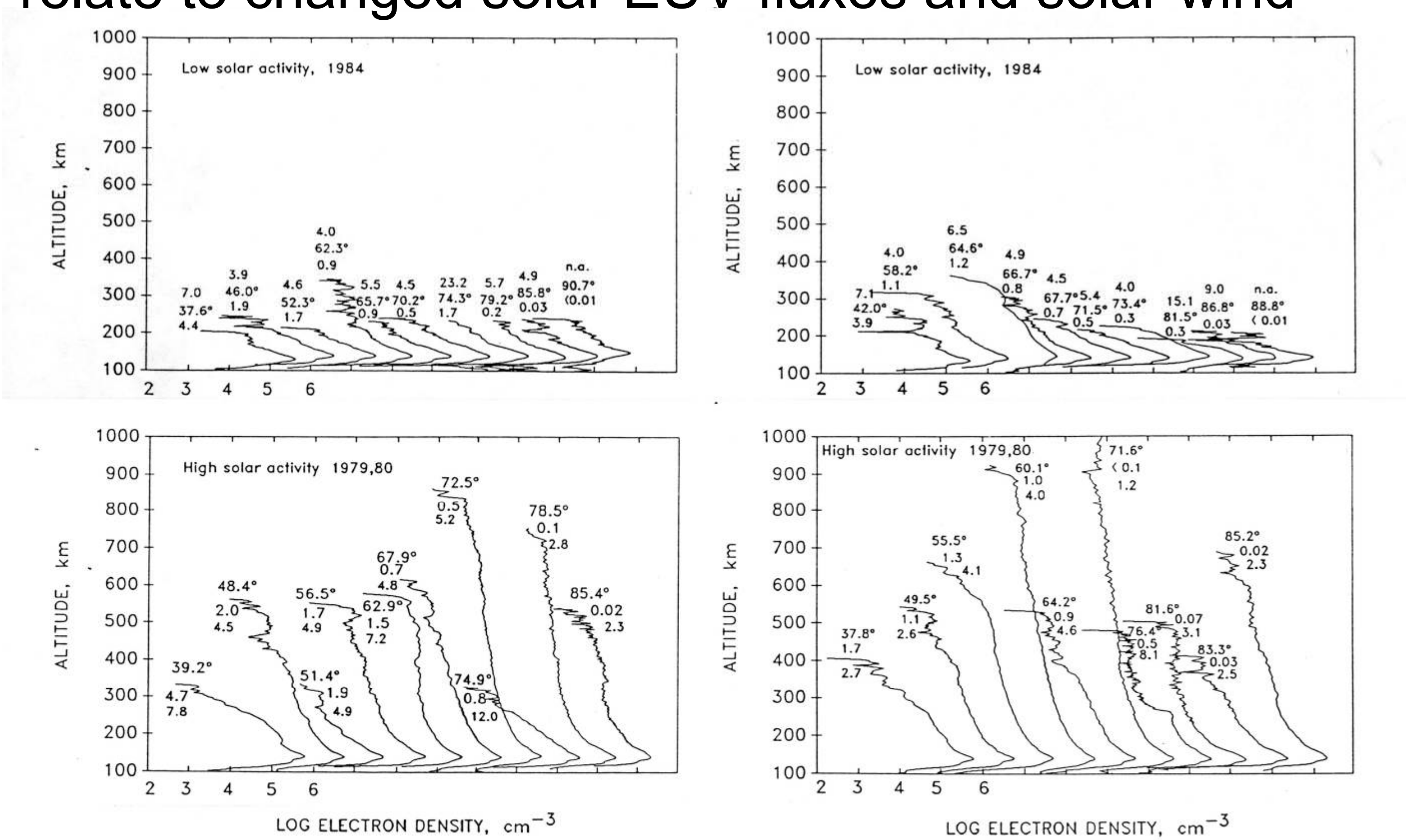


Figure 54

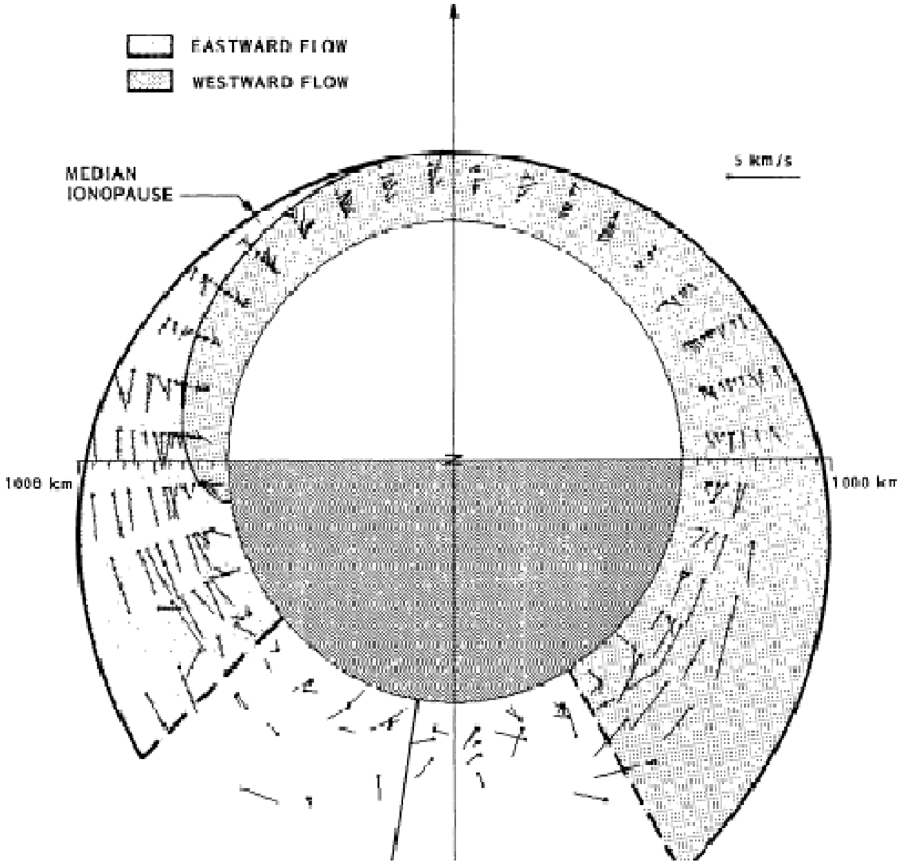
- Penetration of sheath flux tubes through ionopause shear layer
- K-H instability at the ionopause
- Action of atmospheric gravity waves on penetrated weak fields

Electron density profiles from Solar Min and Max from PVO Radio Occultations show solar cycle variations relate to changed solar EUV fluxes and solar wind



-no in-situ data exist for solar minimum. (Figure from A. Kliore et al., JGR)
The (presumably) magnetized solar min ionosphere is less ‘compressible’..

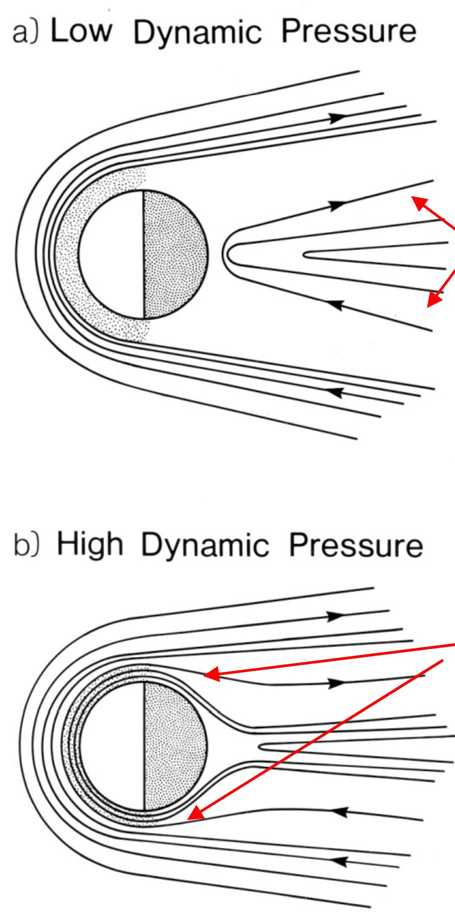
Thermal ionosphere pressure-gradient flows produce a nightside ionosphere at Venus, which seems to vanish for high solar wind pressure events



PVO RPA (Retarding Potential Analyzer) measurements of Venus ionospheric ion flows from the subsolar region (top), toward the nightside. At solar maximum trans-terminator flows create the Venus nightside ionosphere. (from Miller et al., JGR)

Note that some of the high altitude flows are also likely to be affected by the solar wind interaction. The escape velocity is ~11 km/s/

Possible Interpretation of magnetic field observations and nightside ionospheres

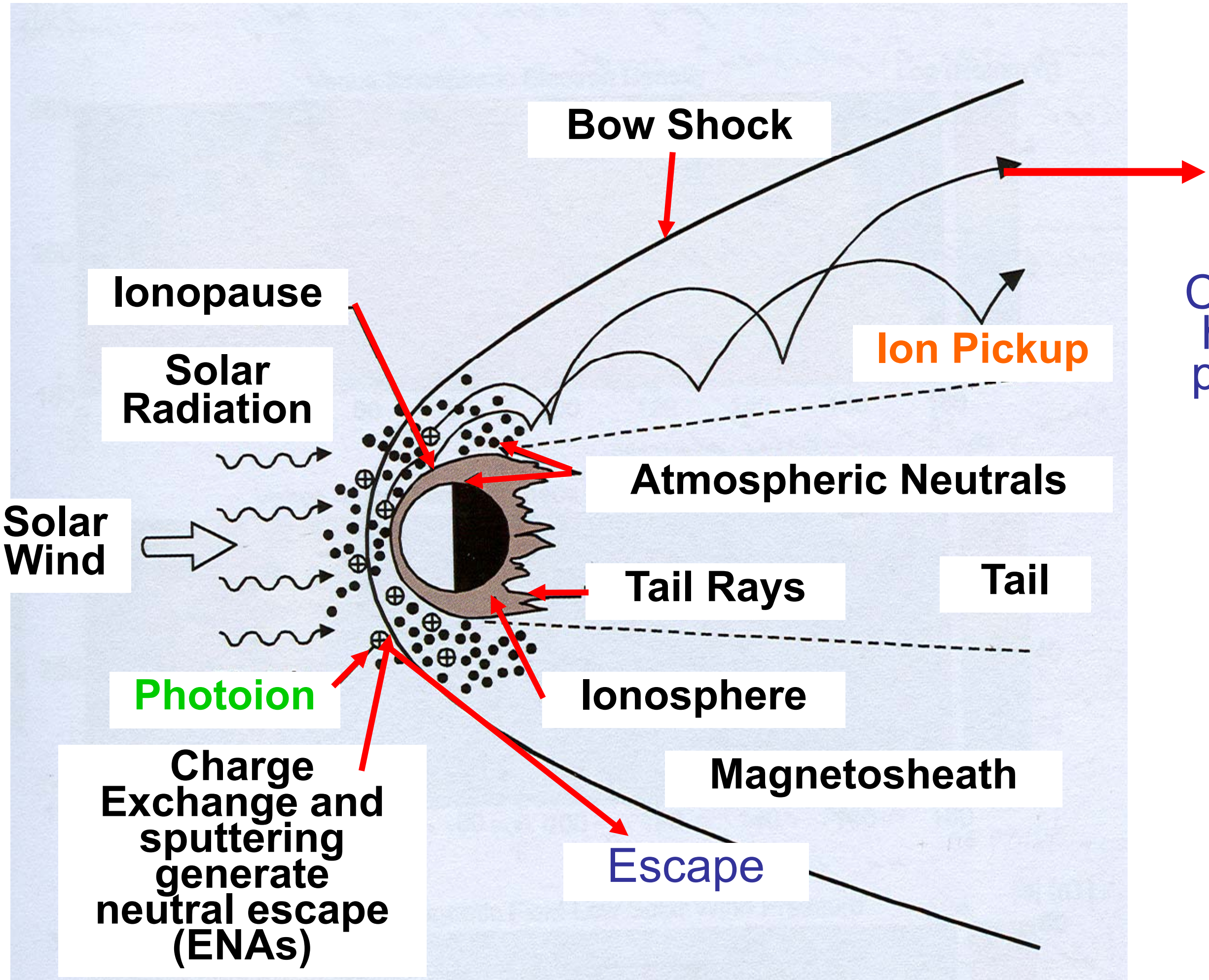


Fields of ionospheric “holes”?

Suppressed nightward flow and horizontal nightside ionospheric fields during ‘disappearing’ episodes

3D Modeling still needed to sort this out, with some relevant new observations expected from VEX

What happens to the upper atmosphere: Pick up and escape processes



Escape:

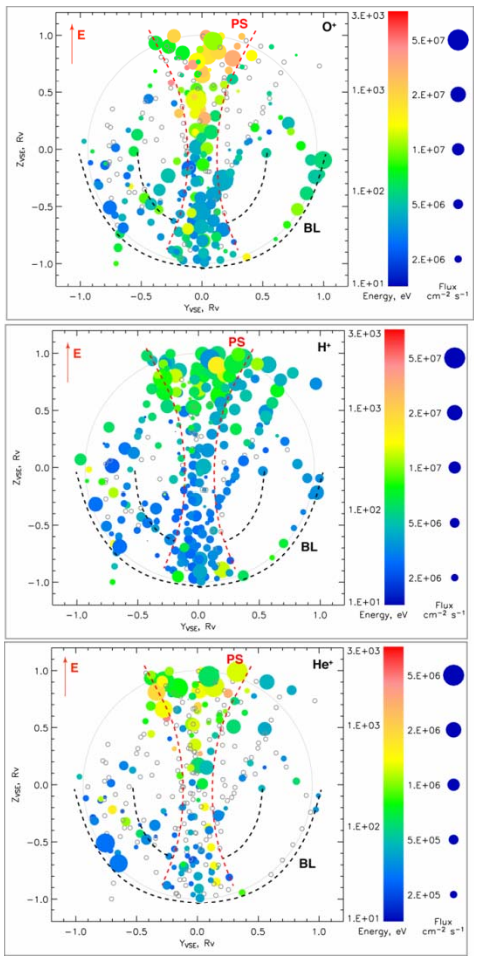
Characteristic hemispheric preference in direction of

E=-VxB

Note that this process can be affected by turbulent sheath fields

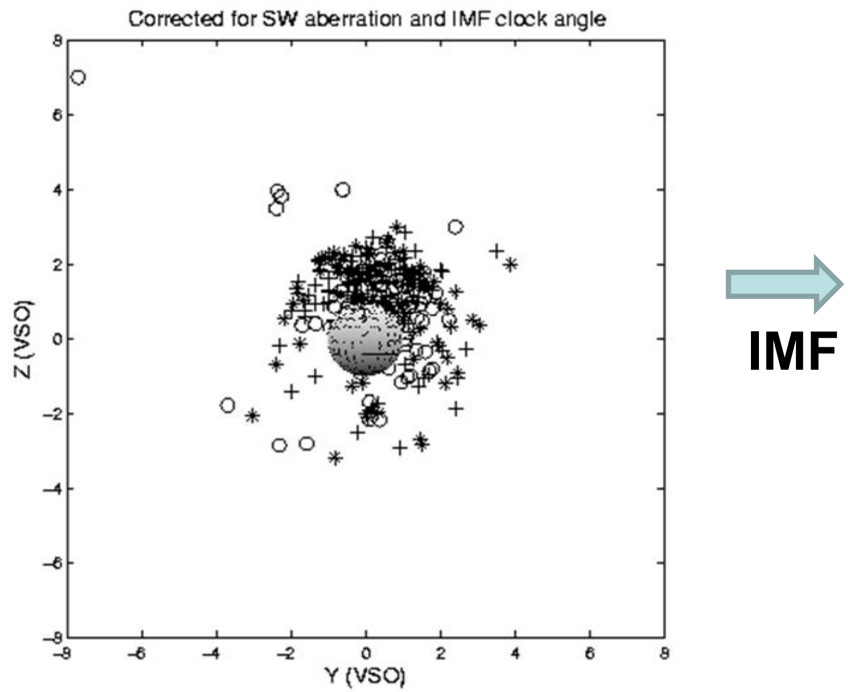
(adapted by C. Martinecz, MPSS)

Statistical O+ escape observations in the Venus wake from VEX (left) and PVO (right), organized by IMF



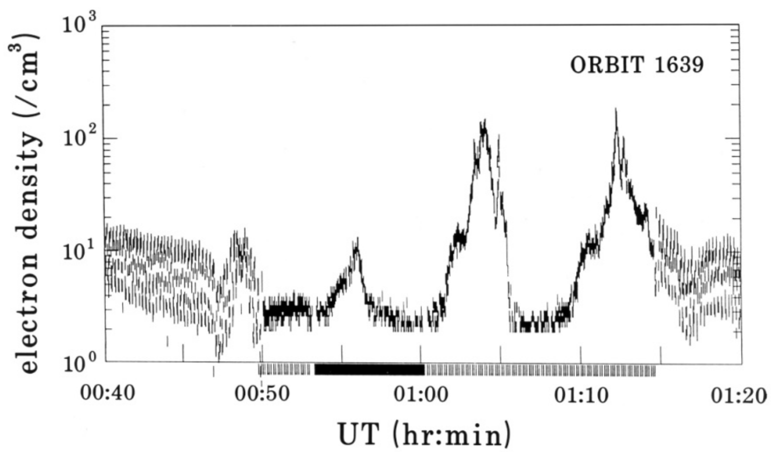
(from Barabash et al., Nature, 2007)

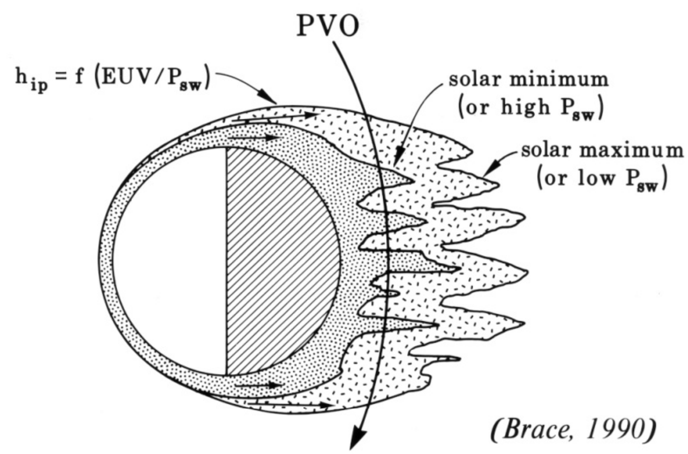
Asymmetries consistent with pickup



(from Luhmann et al., PSS, 2006)

“Tail rays” seen by the PVO Langmuir Probe

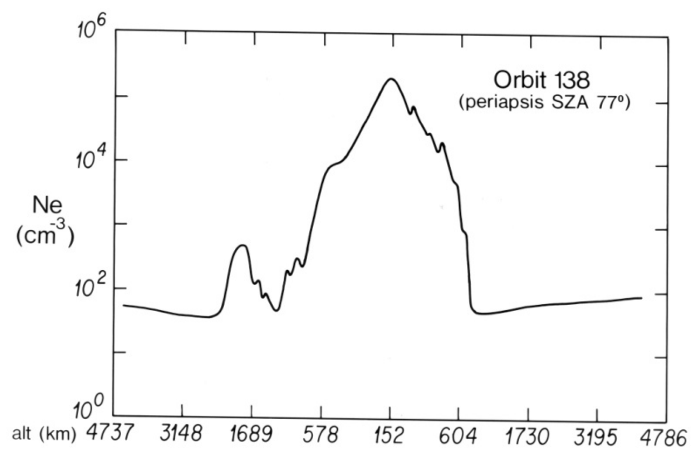


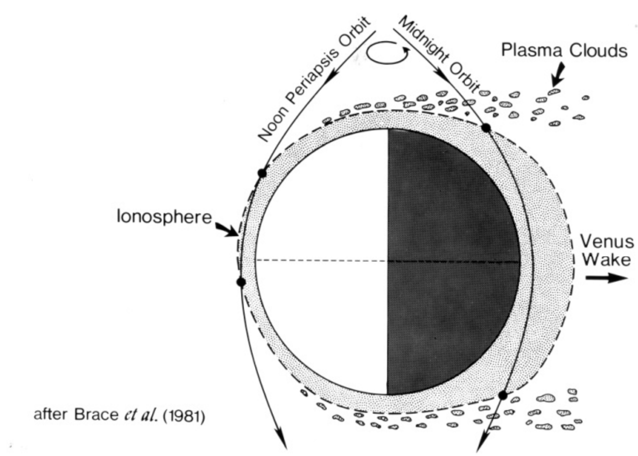


(Brace, 1990)

Another escape process? Or merely the near-Wake signature of low Energy escaping Pickup ions?

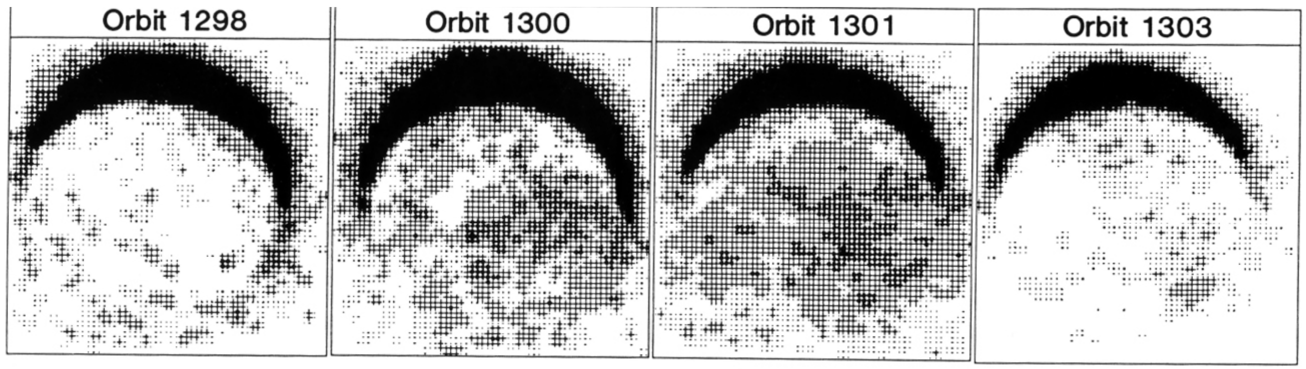
Ionopause “clouds” seen by the Langmuir Probe





Another escape process??-possibly not.(Ong et al., JGR)- although comet-like tail Disconnections may occur when a current sheet (or large rotation) in the interplanetary field passes.

Venus also has a UV Aurora

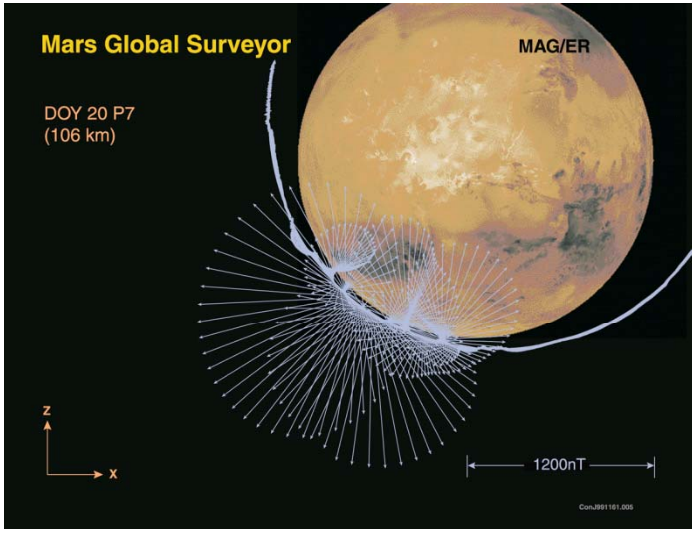


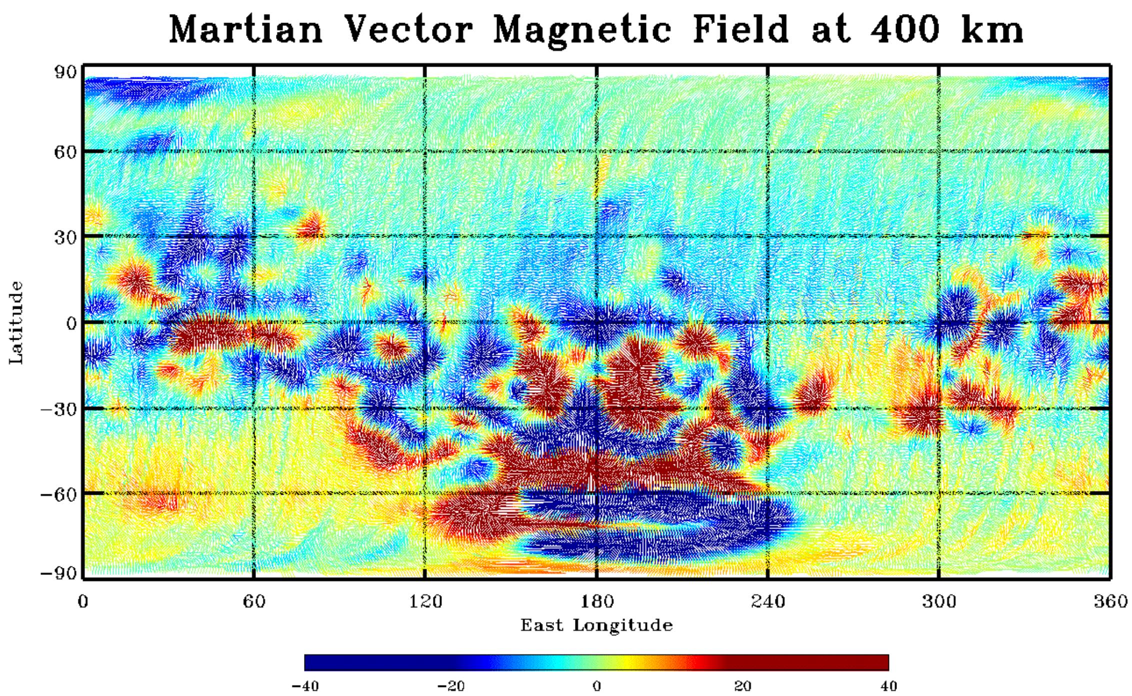
Nightside views of the Venus 130.4 nm aurora observed by the PVO UVS –showing the brightness response to a high solar wind pressure event. Particle precipitation must therefore contribute to the production of the Nightside ionosphere- with its contribution depending on external conditions.. Other implications still TBD.

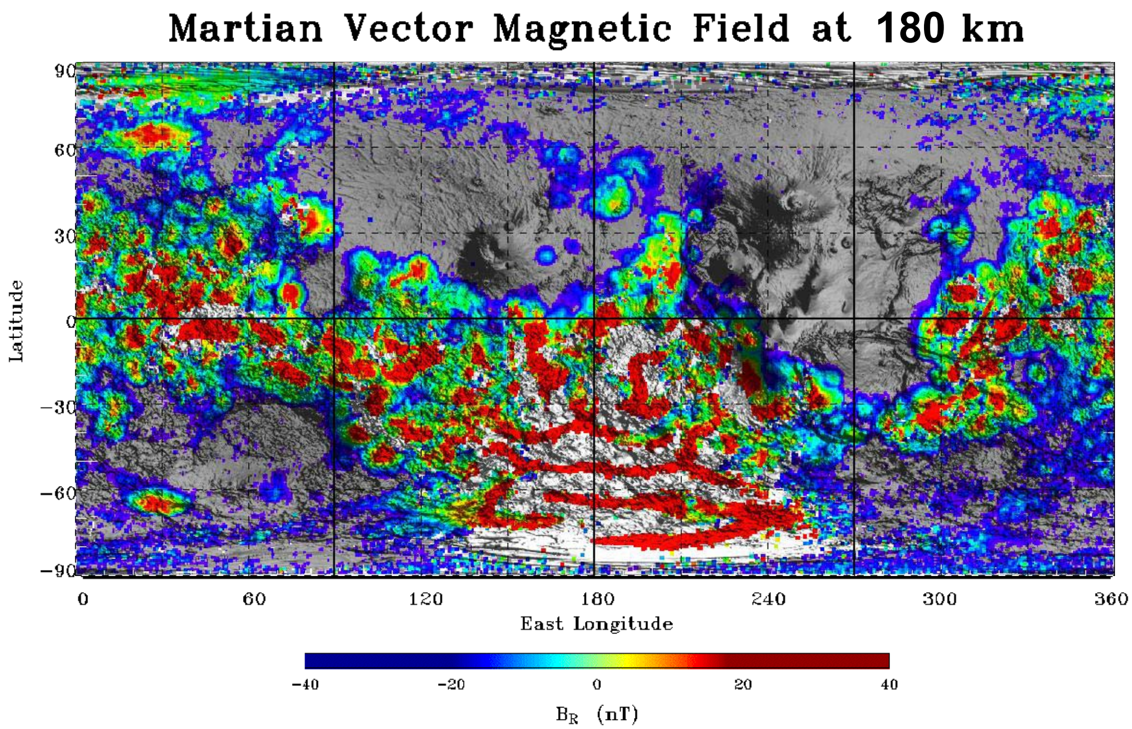
(from Phillips et al., JGR-darker means brighter. Dayside seen as the dark crescent in these images) Fox and Stewart deduced these UV auroras were produced by soft electron precipitation.

Mars presents a more complicated story

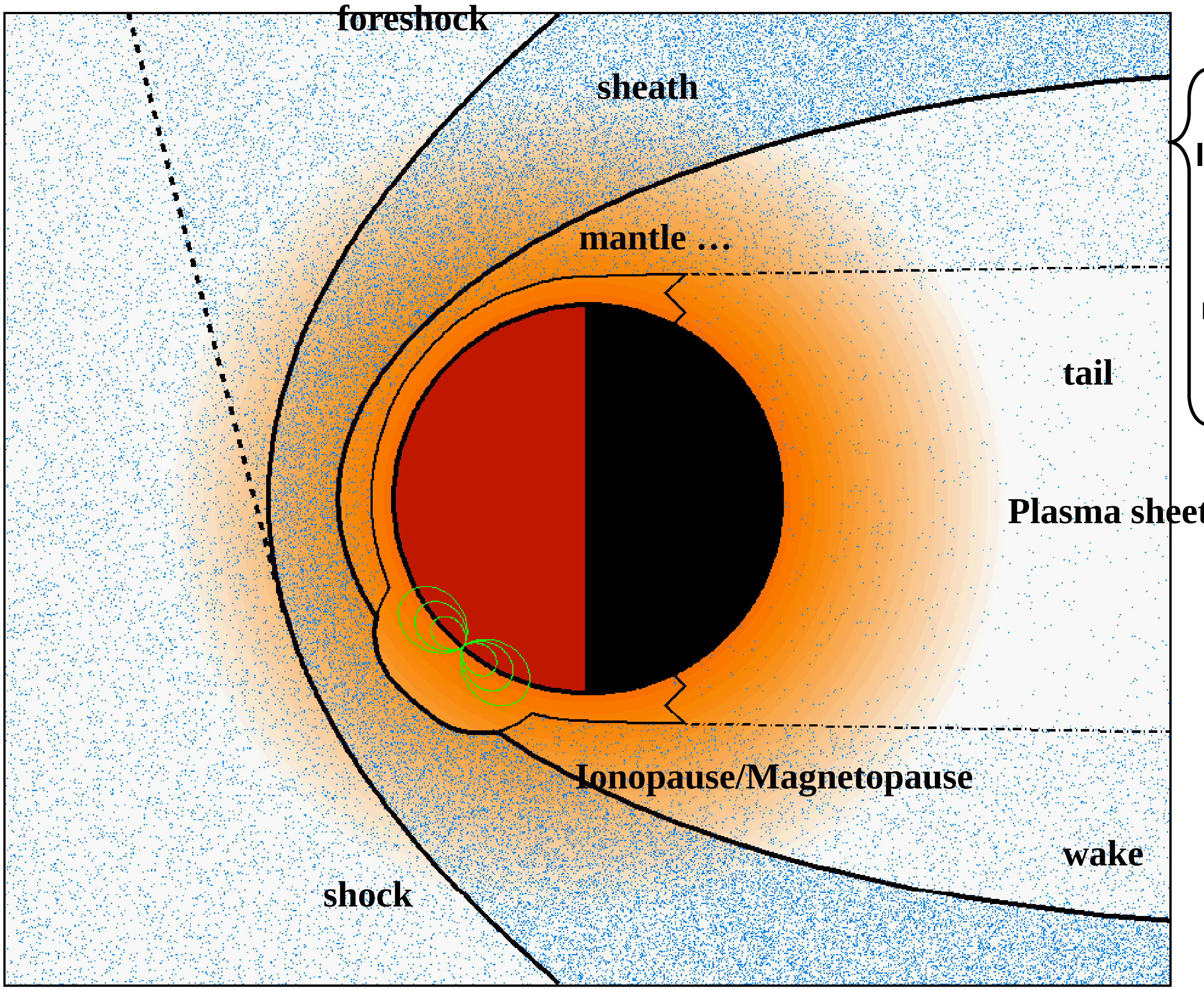
(slide from D. Brain)





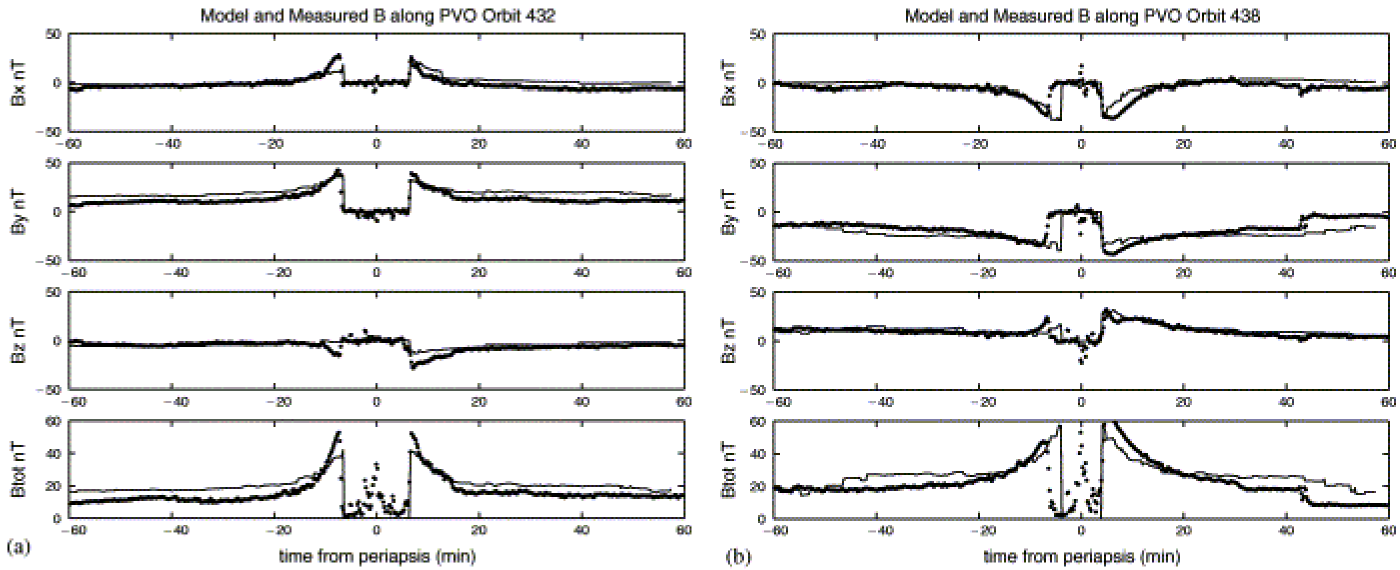


Mars-solar wind interaction: Complications of a Crustal Field

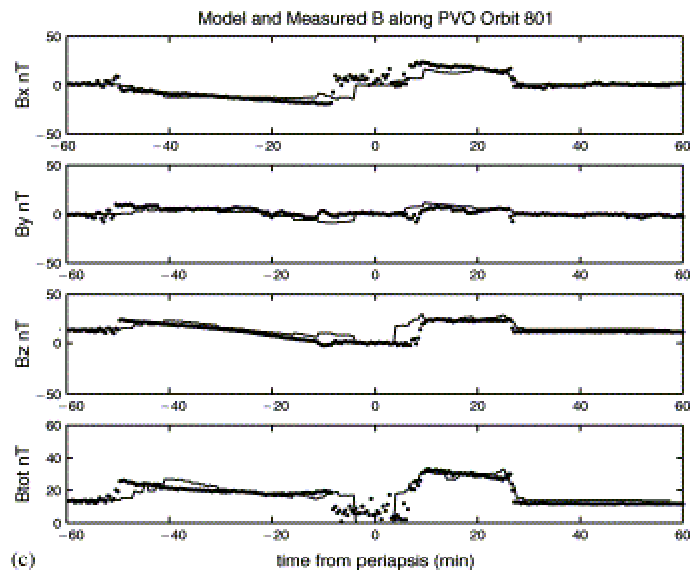


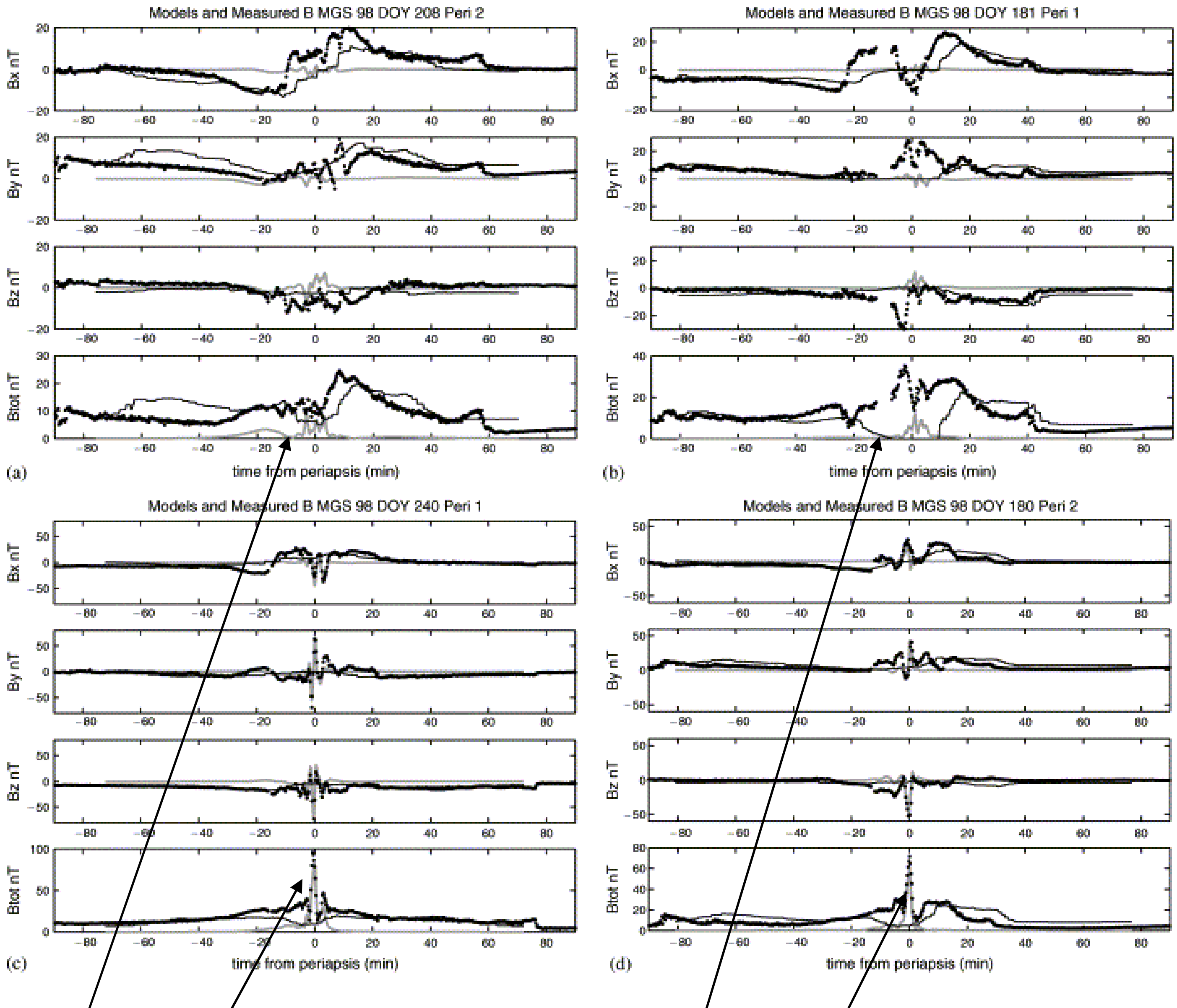
A complex boundary layer involving external field pileup, ion composition changes, mass loading, and magnetic reconnection between external and crustal fields

(Adapted from D. Brain, 2005)



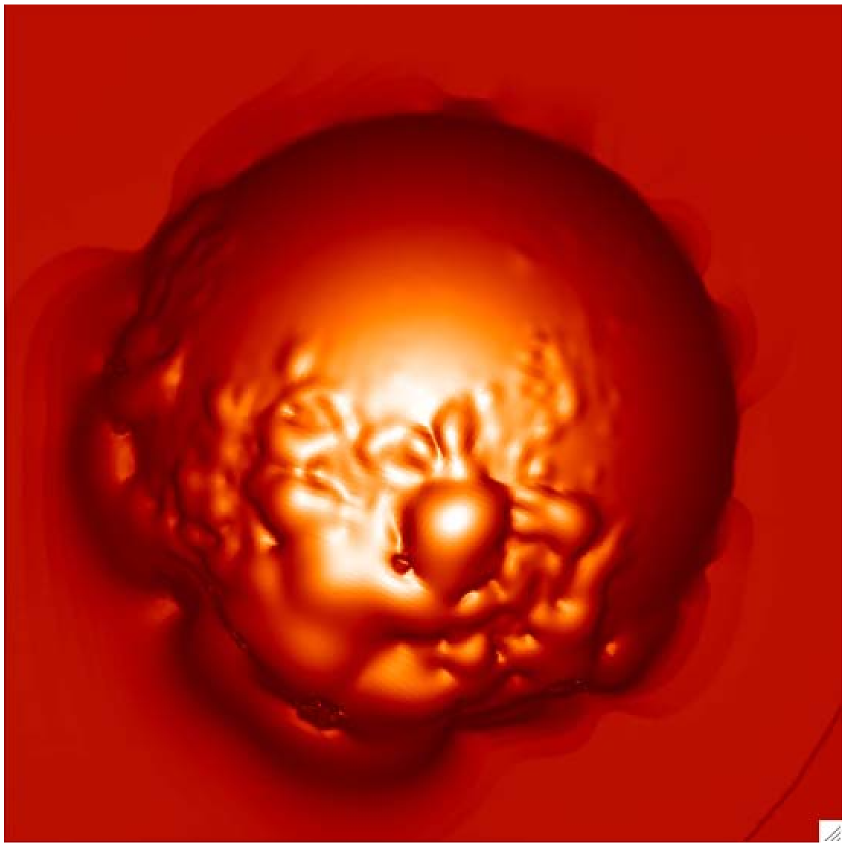
Remember how well Venus fit the conducting Obstacle model…..

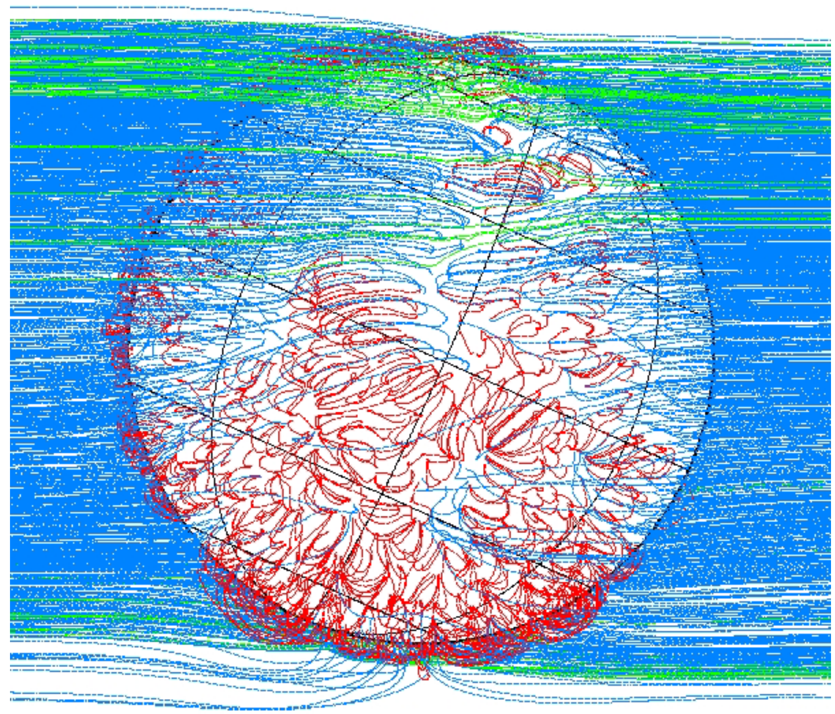




Crustal field intrusions in MGS Mag data and their apparent effects on field draping show the need for more complicated models for Mars

Crustal Fields make a lumpy Mars obstacle with some planetary field lines 'closed' and others connected (open) to interplanetary fields –making Mars full of 'cusps'



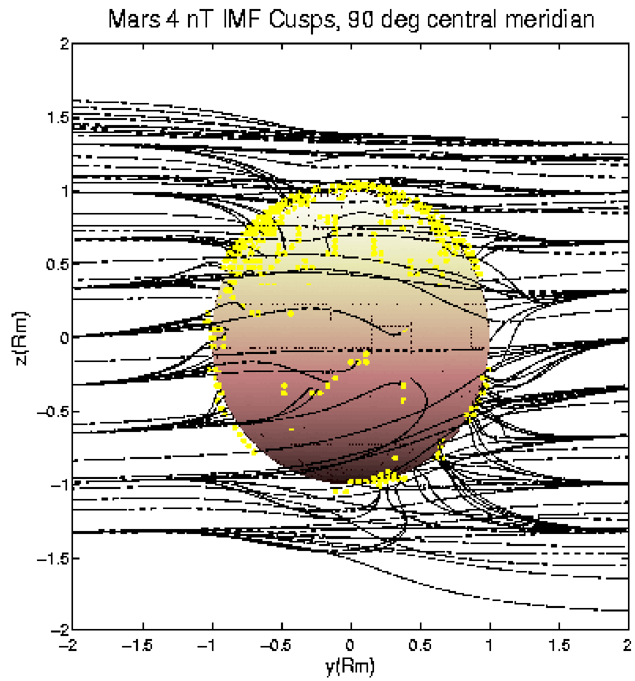


closed **open** **draped**

(D. Brain illustrations)

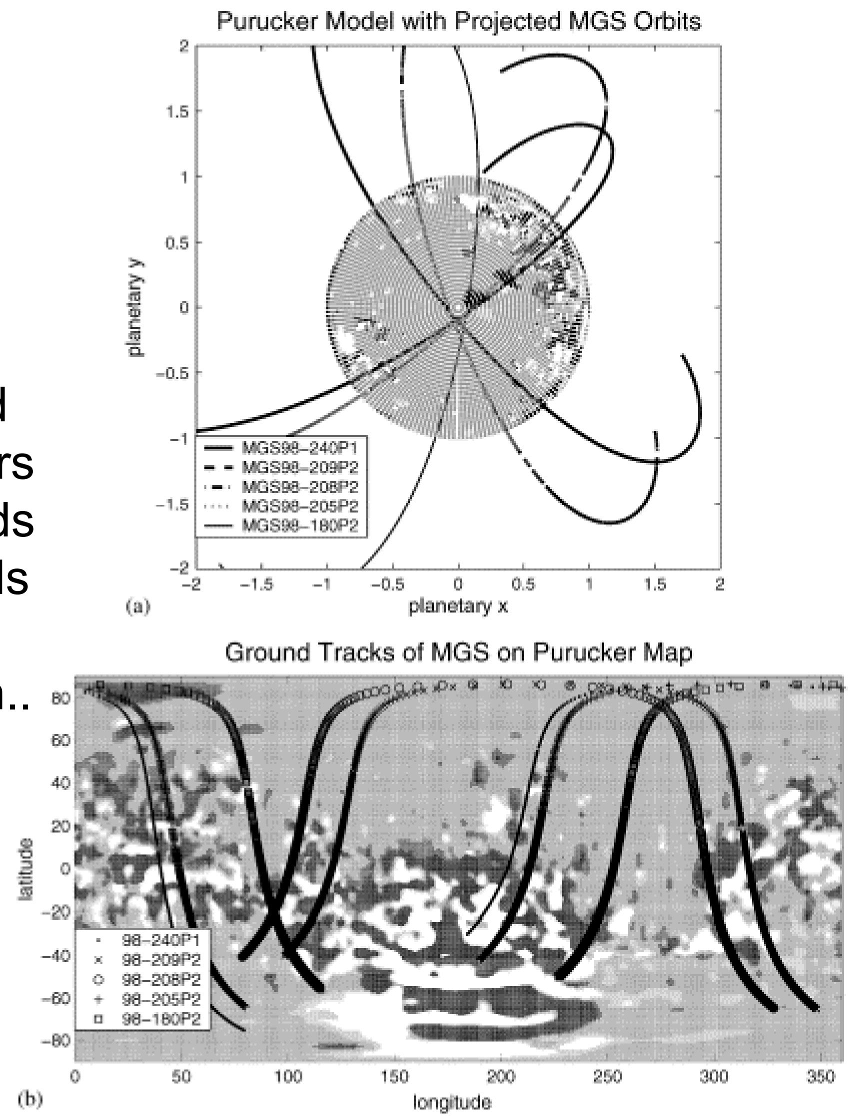
Open-closed field regions at Mars vary with the interplanetary Field direction (suggested by this simplified model), and with the Orientation of the crustal fields with respect to the solar direction

Yellow dots show 'footpoints' of open magnetic fields as they change in response to the interplanetary field reorientation- (simplified uniform IMF superposition 'model')



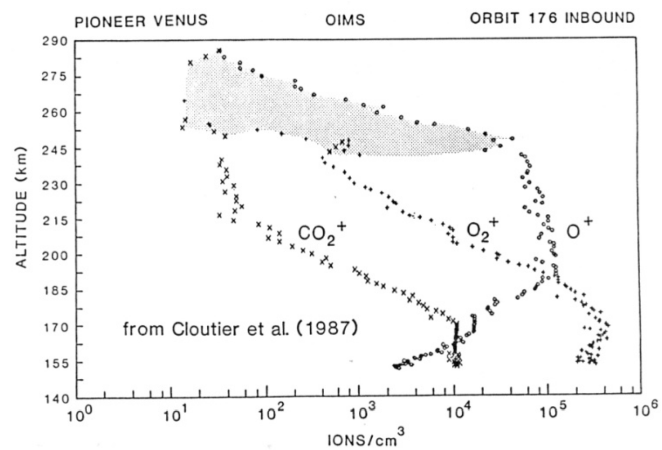
Contrast this to the Earth case where the open fields are always in the polar regions.

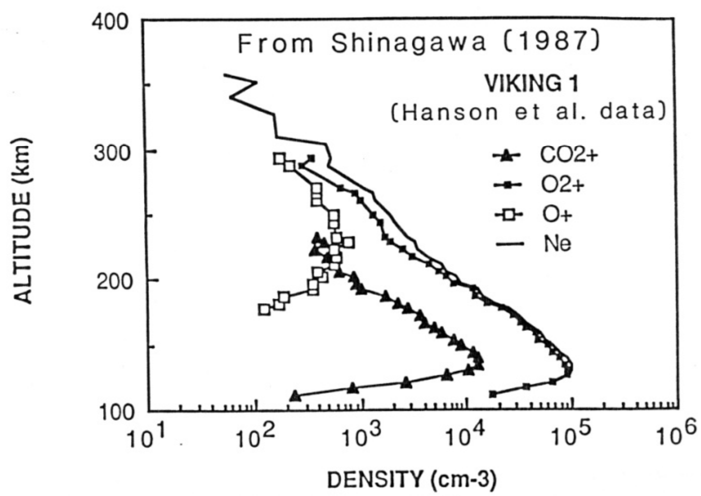
In addition to
Solar wind and
interplanetary field
variations, the Mars
interaction depends
on the crustal fields
orientation with
respect to the Sun..



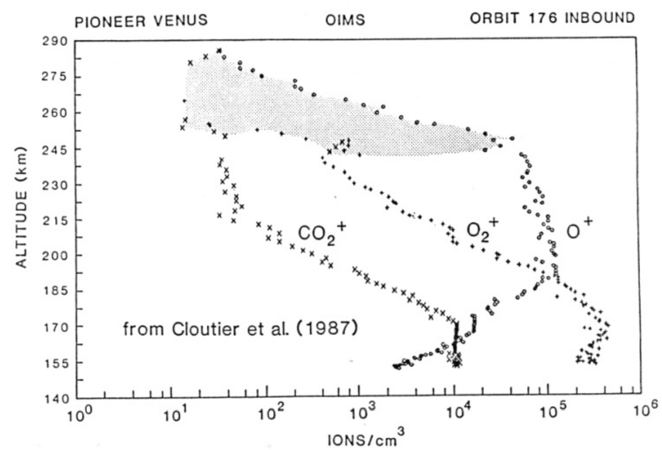
(from Luhmann et al., PSS 2004)

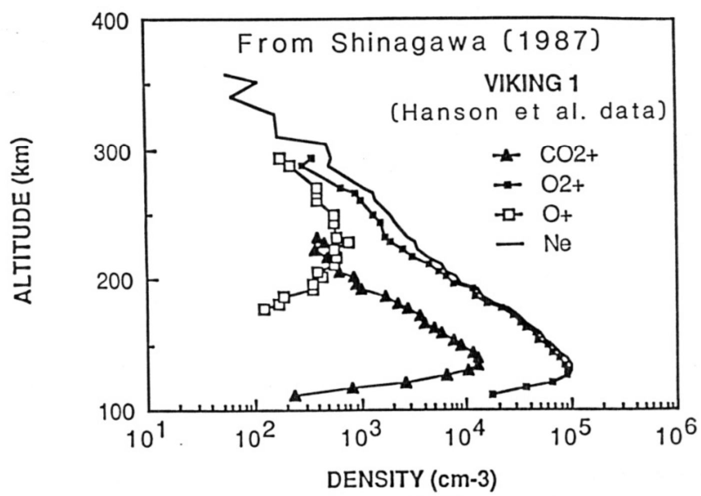
Because Venus and Mars have similar upper atmosphere composition, they have similar ionospheric composition-dominated by O_2^+ at the peak and O^+ at high altitudes.

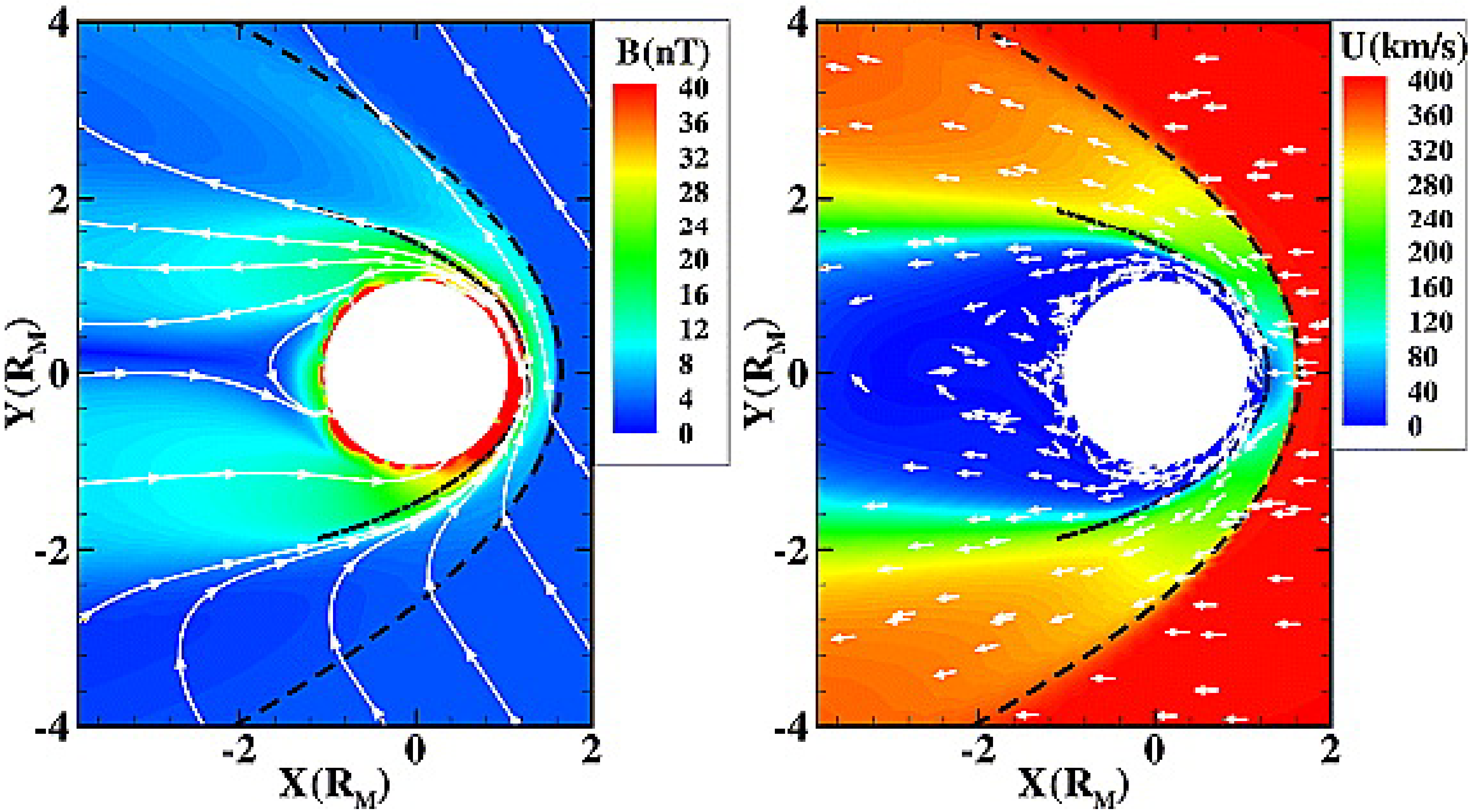




Loss from the top is required to produce both of these ionosphere profiles, although Mars is more often in a solar wind ‘overpressure’ situation due to its weaker ionospheric pressure relative to the typical incident solar wind pressure

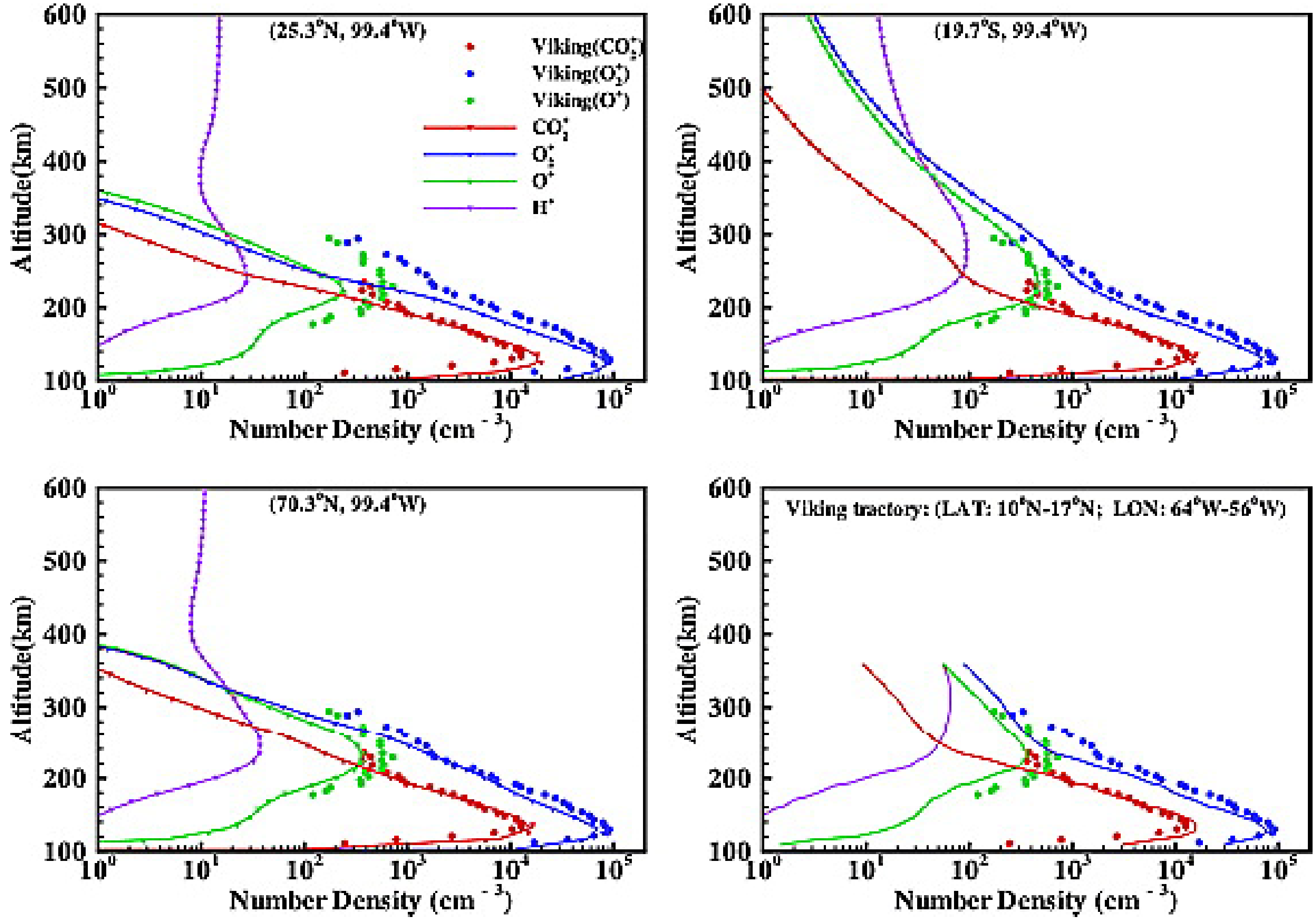






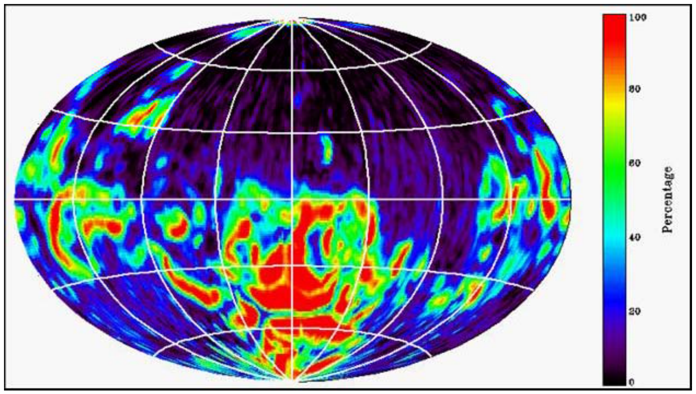
Sophisticated numerical models (this due to Yingjuan Ma et al.) are necessary to understand the complicated geometry of the Mars solar wind interaction- and to interpret the various phenomena observed in these plasma interactions. This model has both crustal fields and a realistic ionosphere.

Ma et al. model ionosphere at various locations vs. Viking data

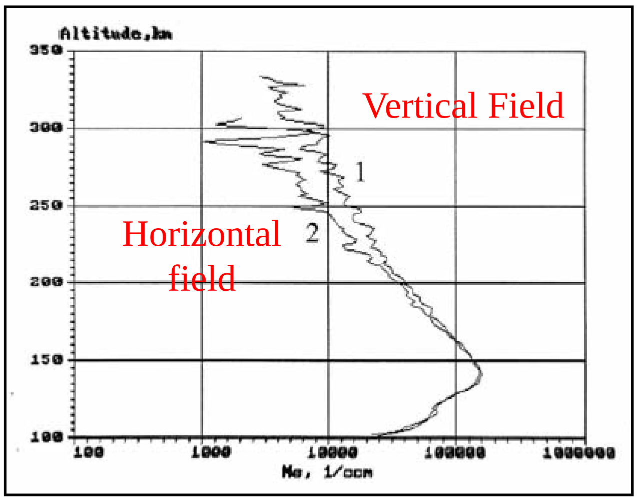


Their self-consistent ionosphere model reproduces Viking Lander profiles.

Mars Ionosphere Observational Results



Brain et al., 2005-durably closed field regions



Krymskii et al., 2002-RO profiles

- Studies by Mitchell et al. , Brain et al. and Krymskii et al. show the lumpiness of the Mars ionosphere that results from the crustal fields

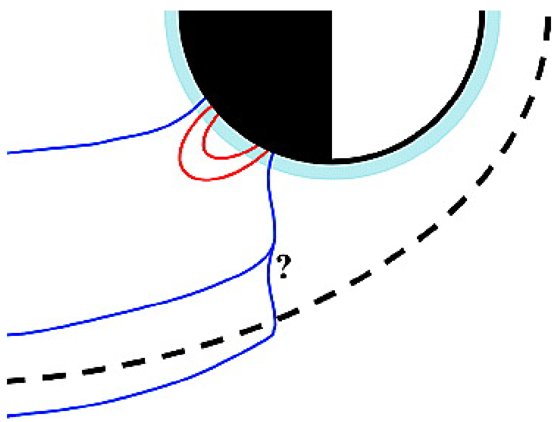
- Features attributed to the crustal fields have also shown up in radio occultation profile studies and ionospheric sounding studies.

- Are there other consequences of the crustal field?

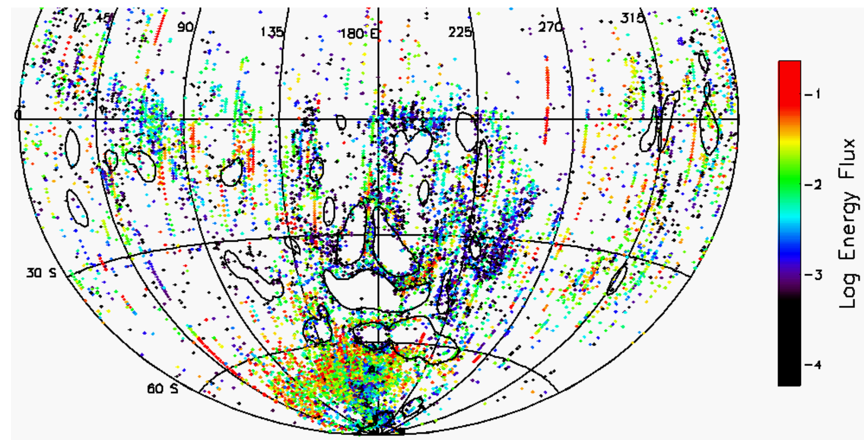
(Slide from D Brain)

Mars Aurora- Inferred particle precipitation suggests auroral energy deposition may affect the cusp ionospheres-

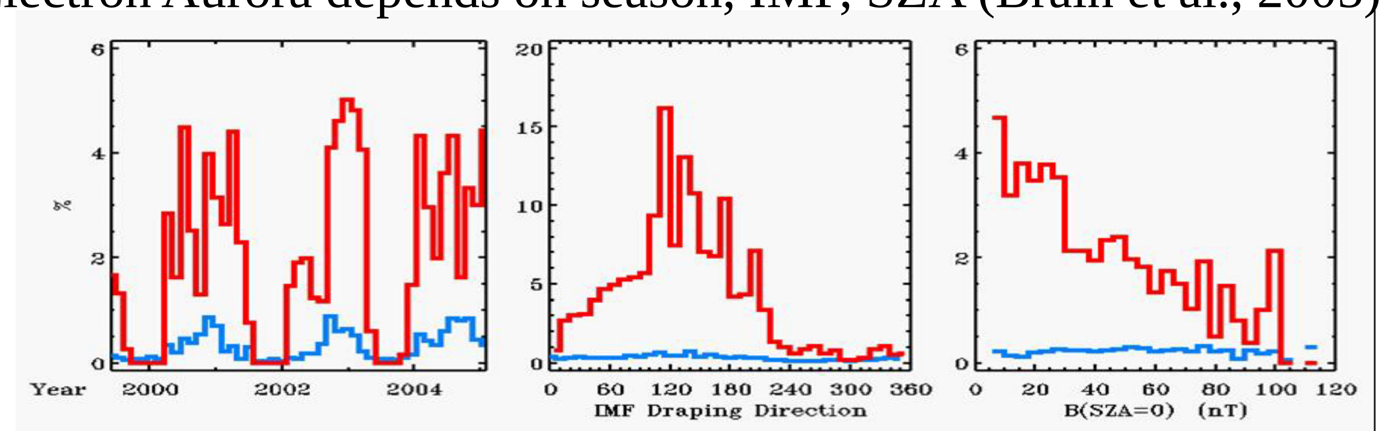
Auroral Field geometry?



Inferred Energy fluxes from MGS-ER electrons near "cusps"

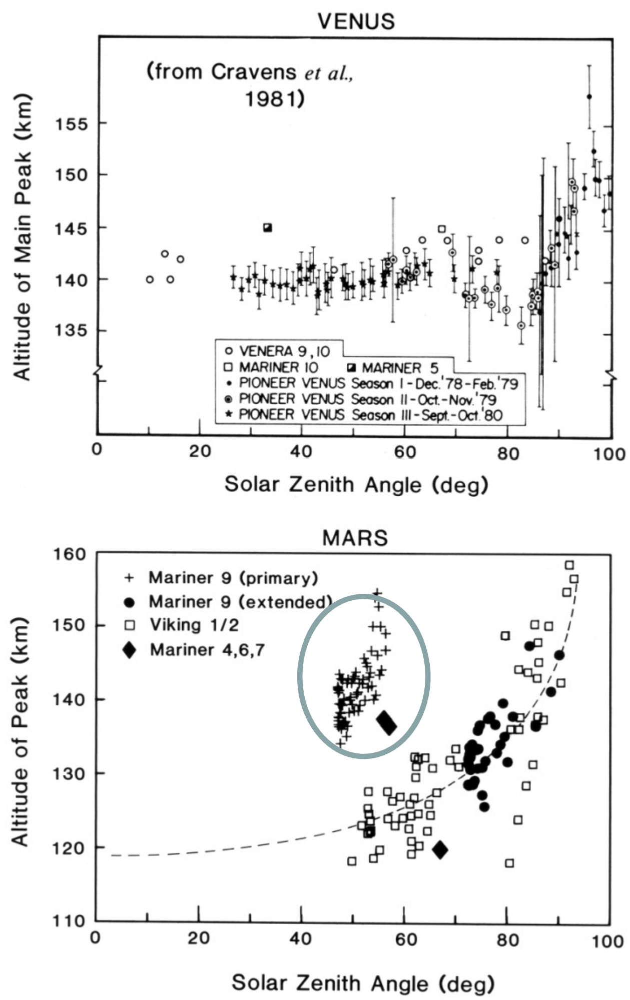


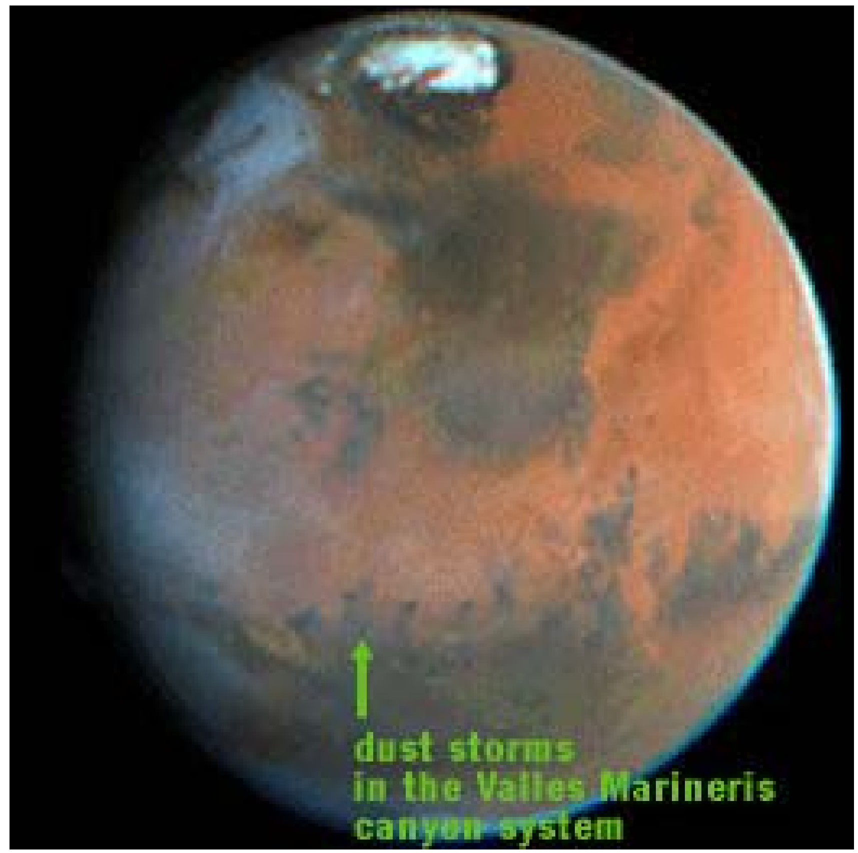
Electron Aurora depends on season, IMF, SZA (Brain et al., 2005)



(D. Brain Slide)

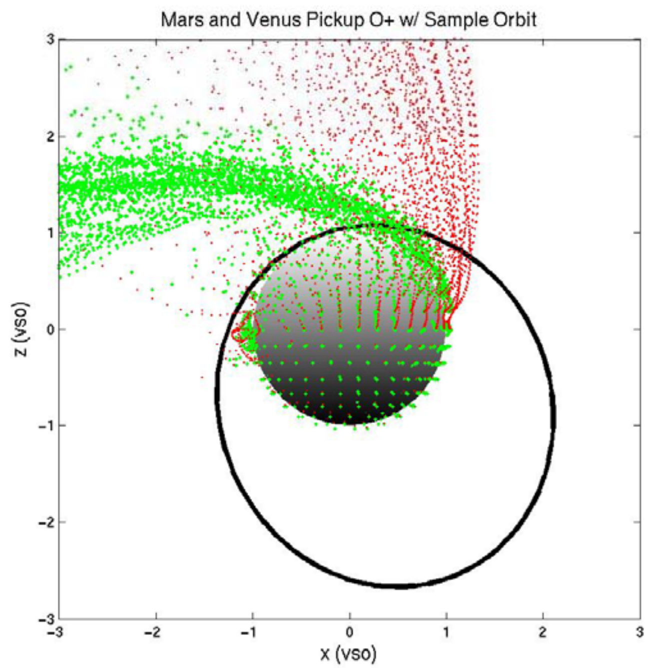
Dust storm effects on ion density profiles are also observed at Mars-but it is unclear how dust storms affect the big picture of the plasma interaction

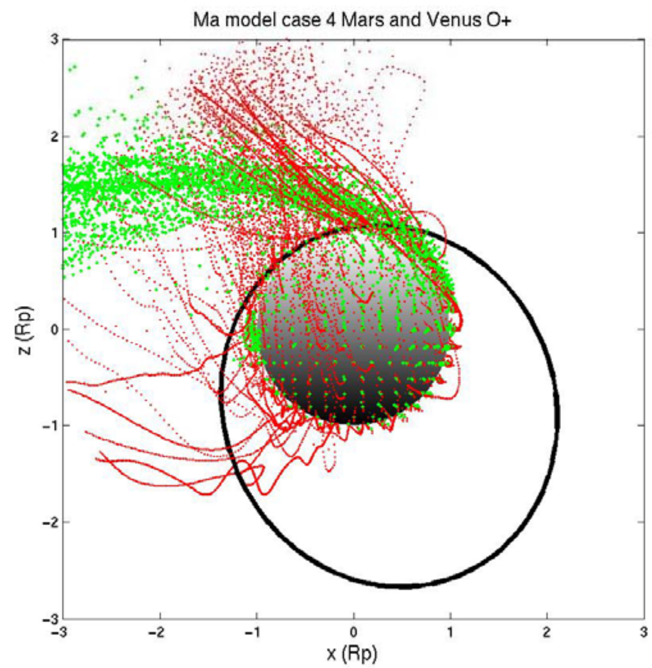




NASA image

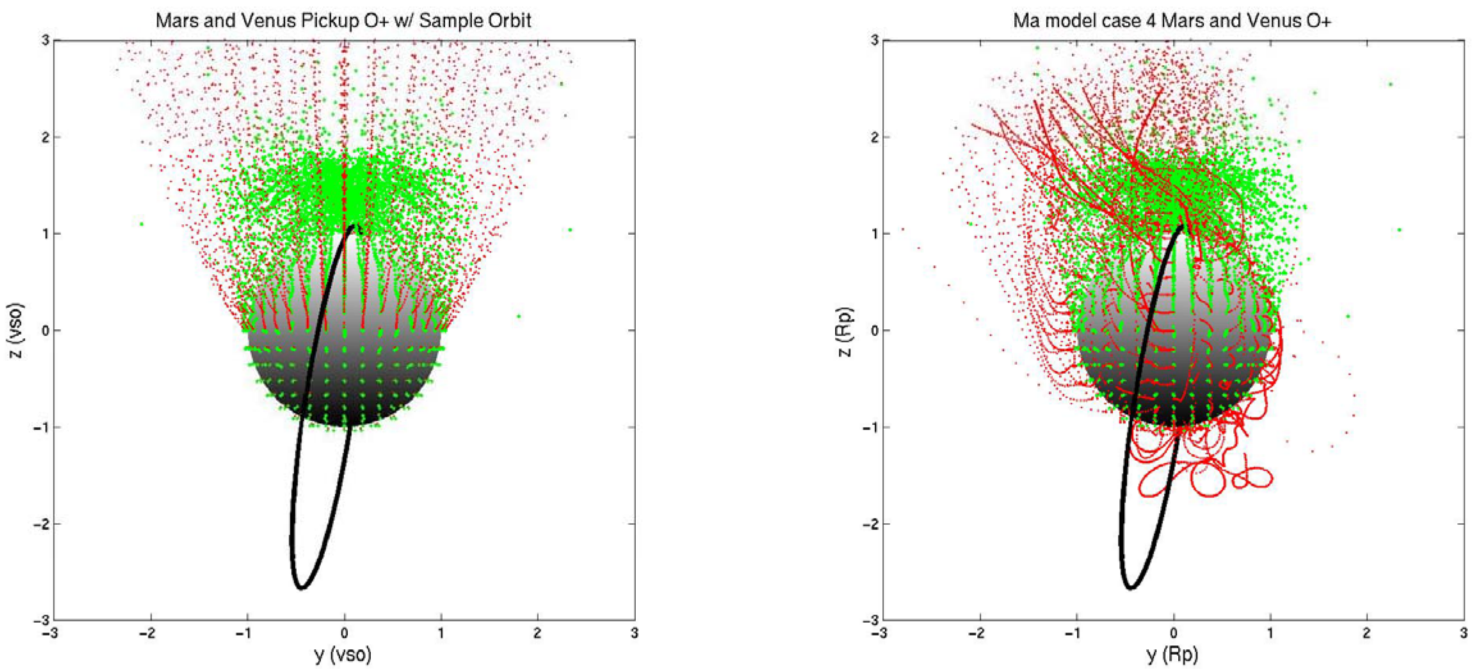
What about escape? Modeled Mars O+ Pickup Ion Trajectories (red) compared to Venus' case (green)- Noon-Midnight views. Left picture neglects crustal fields, which scatter the Mars ions (right).





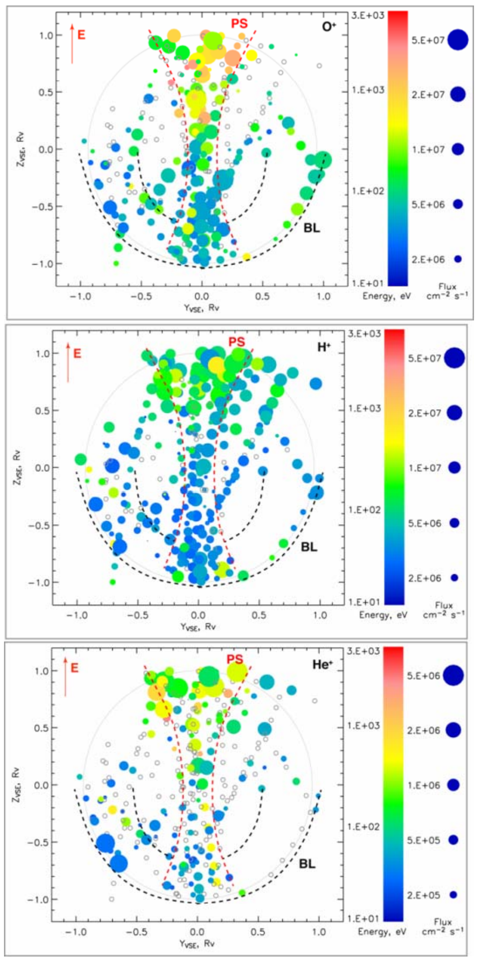
Trajectories scaled to planet size. Mars results show effects
Of both smaller planet size and weaker IMF magnitude at 1.5 AU

Views from Sun

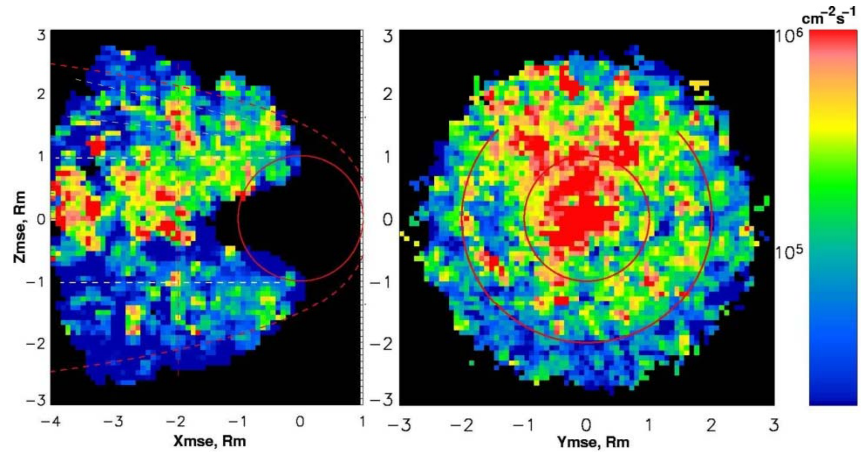


Mars crustal fields effectively scatter these test particle ions

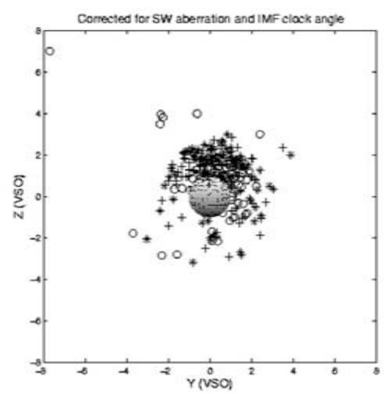
Same escape story for Mars and Venus ???



(VEX ions from Barabash et al., Nature, 2007)

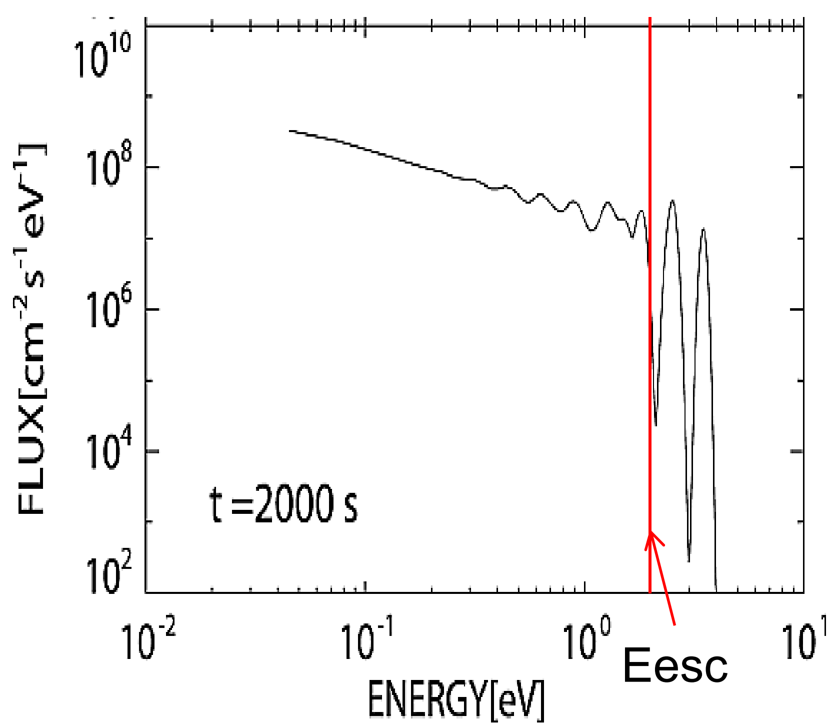


(ASPERA-4 IMA O+ statistics from Fedorov et al., PSS, 2006 (above) and PVO O+ from Luhmann et al., PSS, 2006 (below)



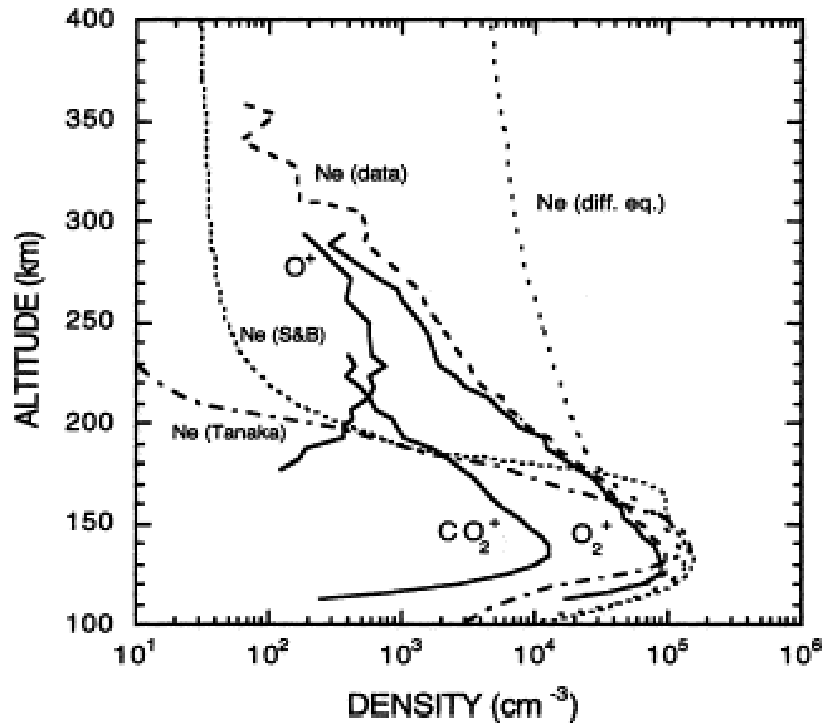
BUT Dissociative Recombination-enabled escape of O (O_2^+ + e ->2O*), which doesn't work for Venus (need 10 eV); may dominate oxygen escape from Mars today (need only 2 eV)

Example of Dissociative Recombination-produced Atomic Oxygen Spectra at The Mars exobase …



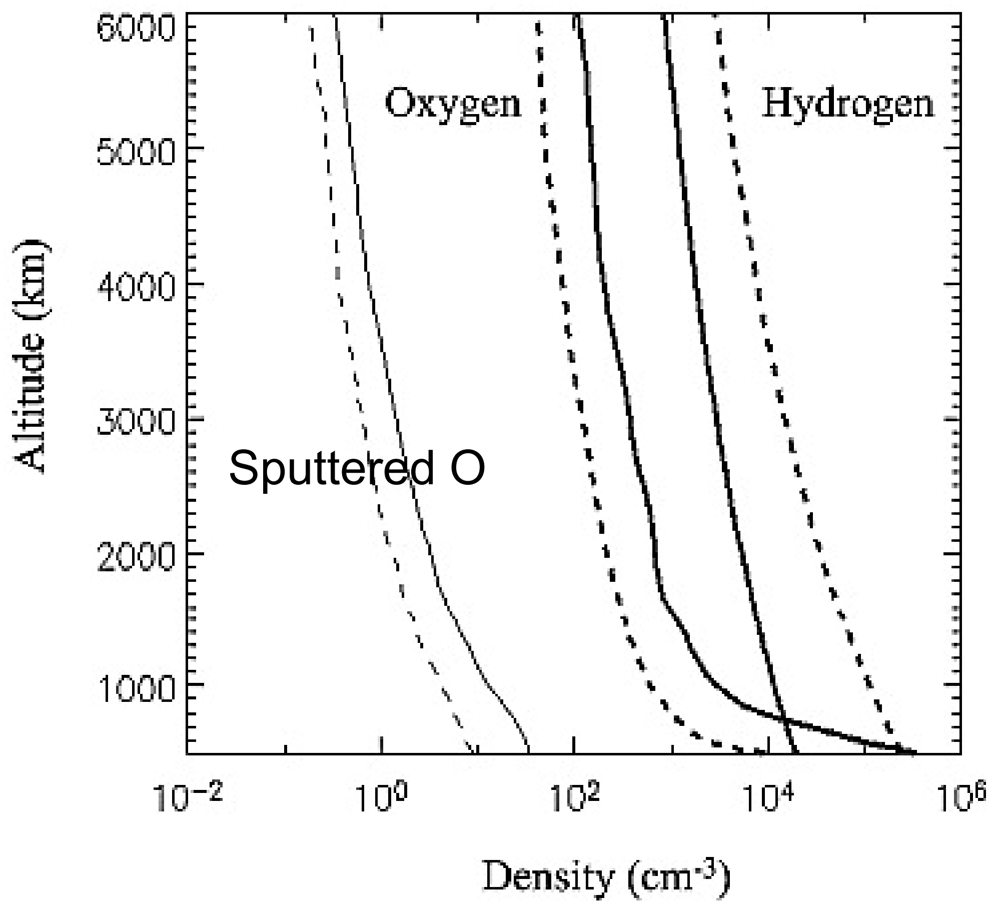
(from Terada et al., GRL 2007)

Ionospheric 'source' of hot O



From Shinagawa, JASR, 2005

Comparison of modeled sputter-produced and photochemical hot O at Mars suggest sputtering is a minor contribution today, under quiet conditions



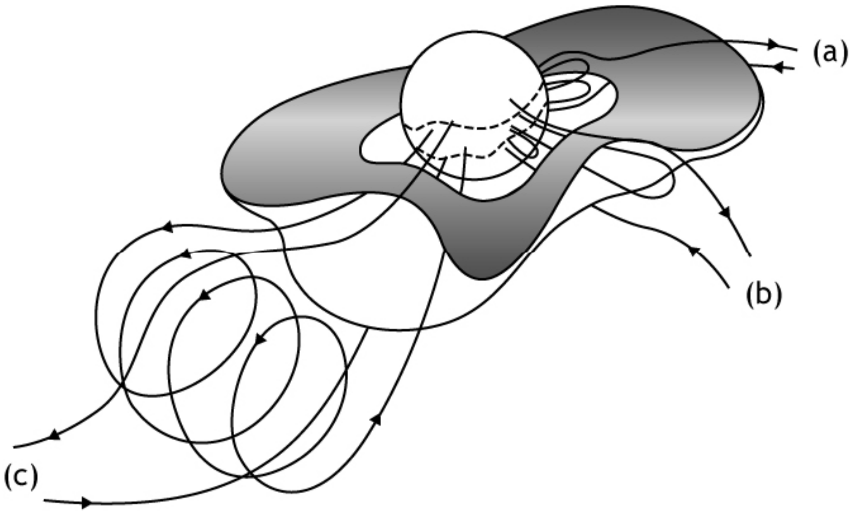
From Chaufrey et al., JGR 2007. The two lines are solar max and solar min

Observational and modeling results for Mars show a great range of escape ests.

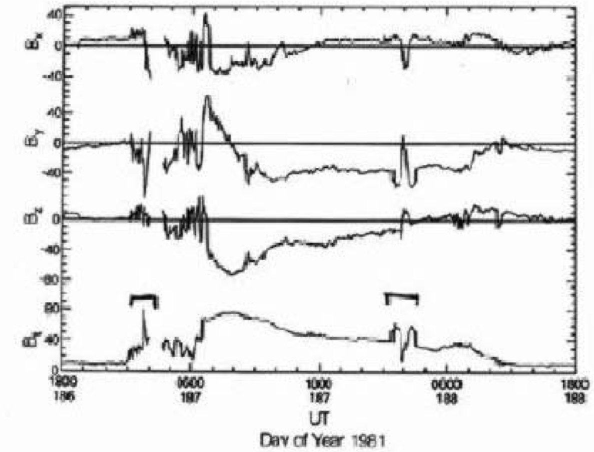
Loss process	Loss rate [s^{-1}]	Authors	Year
Thermal [Jeans]: H	1.5×10^{26}	Anderson and Hord	1971
Thermal [Monte Carlo]: H	1.0×10^{26}	Shizgal and Blackmore	1986
Thermal [Jeans]: H_2	3.3×10^{24}	Krasnopolsky and Feldman	2001
Pick up [PU]: H^+	1.2×10^{25}	Present work	2003
Pick up [PU]: H_2^+	1.2×10^{24}	Present work	2003
DR: O_2^+ ions → O^* (hot)	5.0×10^{24}	McElroy	1972
DR: O_2^+ ions → O^* (hot)	5.0×10^{24}	Lammer and Bauer	1991
DR: O_2^+ ions → O^* (hot)	3.0×10^{24}	Fox	1996
DR: O_2^+ ions → O^* (hot)	8.0×10^{25}	Luhmann et al.	1992
DR: O_2^+ ions → O^* (hot)	8.0×10^{25}	Zhang et al.	1993
DR: O_2^+ ions → O^* (hot)	6.0×10^{24}	Luhmann	1997
Sputtering [SP]: O	3.0×10^{23}	Luhmann et al.	1992
Sputtering [SP]: O	4.0×10^{24}	Kass and Yung	1995, 1996
Sputtering [SP]: O	6.5×10^{23}	Leblanc and Johnson	2001
Sputtering [SP]: O	3.5×10^{23}	Leblanc and Johnson	2002
Sputtering [SP]: CO_2	3.0×10^{23}	Luhmann et al.	1992
Sputtering:[SP]: CO_2	2.3×10^{23}	Kass and Yung	1995
Sputtering:[SP]: CO_2	5.0×10^{22}	Leblanc and Johnson	2002
Sputtering:[SP]: CO	3.7×10^{22}	Leblanc and Johnson	2002
Pick up [PU]: O^+	3.0×10^{25}	Lundin et al.	1990
Pick up [PU]: O^+	1.0×10^{25}	Lammer and Bauer	1991
Pick up [PU]: O^+	6.0×10^{23}	Luhmann et al.	1992
Pick up [PU]: O^+	8.5×10^{24}	Lichtenegger and Dubinin	1998
Pick up [PU]: O^+	3.2×10^{24}	Present work	2003
Ion loss [IL] O^+, O_2^+	1.0×10^{25}	Fox	1997
Ion loss [IL] O^+, O_2^+	2.7×10^{23}	Liu et al., Ma et al.	1999, 2002
Ion loss [IL] O^+, O_2^+	3.5×10^{25}–7.0×10^{25}	Hodges Jr.	2000

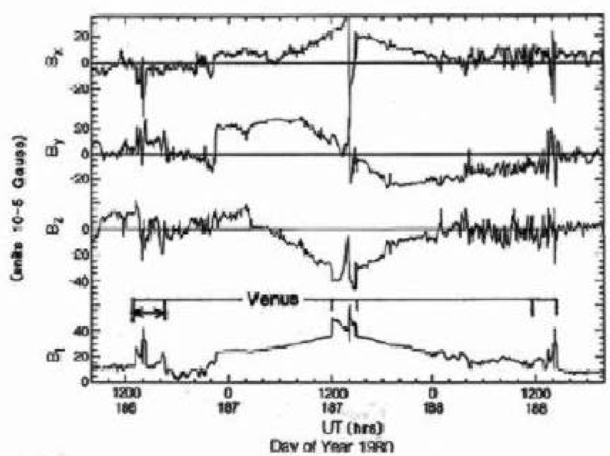
DR (hot neutral O)	1×10^{25} (solmin), 4×10^{25} (solmax)	Chaufray et al. 2007 (model)
Pickup O+	2×10^{23} (solmin), 3.4×10^{24} (solmax)	Chaufray et al. 2007 (model)
Nonthermal H	1.8-2.9×10^{26} (solmin)	Chaufray et al. 2007 (SPICAM)
Pickup O+, O_2+	1.6×10^{23}, 1.5×10^{23} (solmin)	Barabash et al. 2007 (ASPERA3)
Pickup CO_2+	8×10^{22} (solmin)	Barabash et al. 2007 (ASPERA3)

-And all these estimates neglect 'space weather'. Do ICME (or SIR/CIR) passages affect ion escape? e.g. pickup?



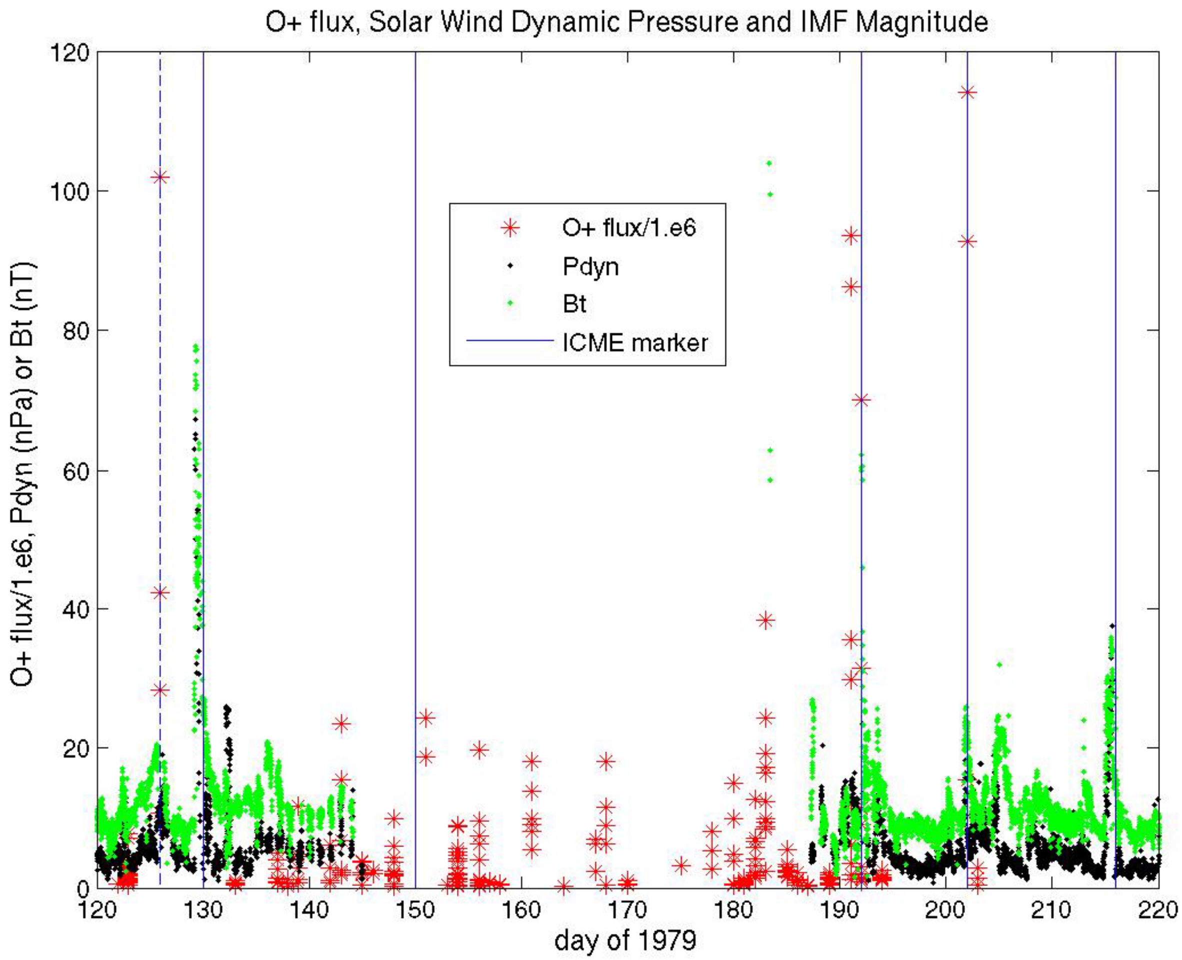
(from Crooker, 1993)





ICMEs produce strong, rotating interplanetary magnetic fields (examples at right).

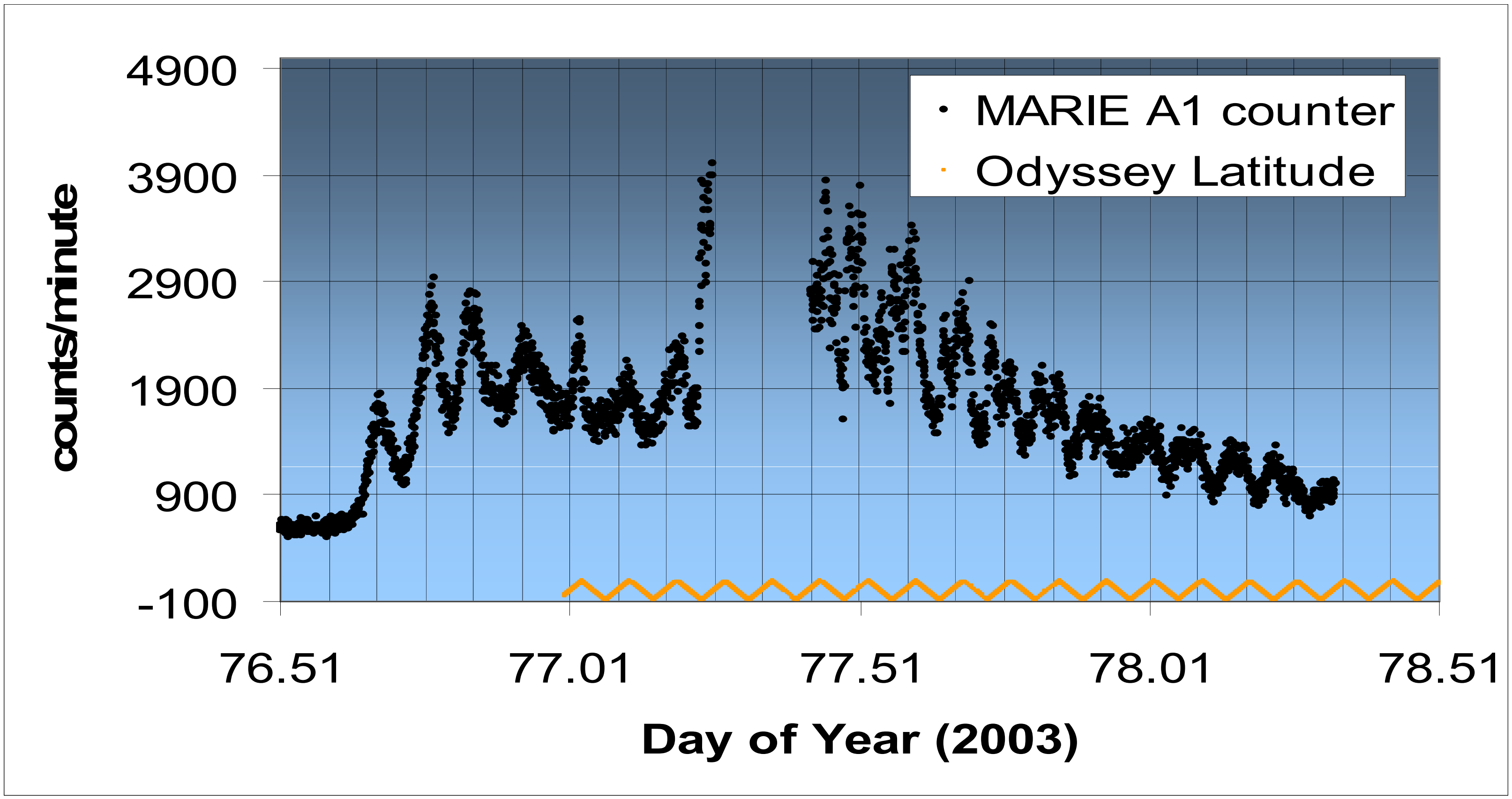
Pioneer Venus Orbiter >36 eV O+ data suggest Venus escape rates are significantly increased by passage of solar wind disturbances



From Luhmann et al., JGR, 2007

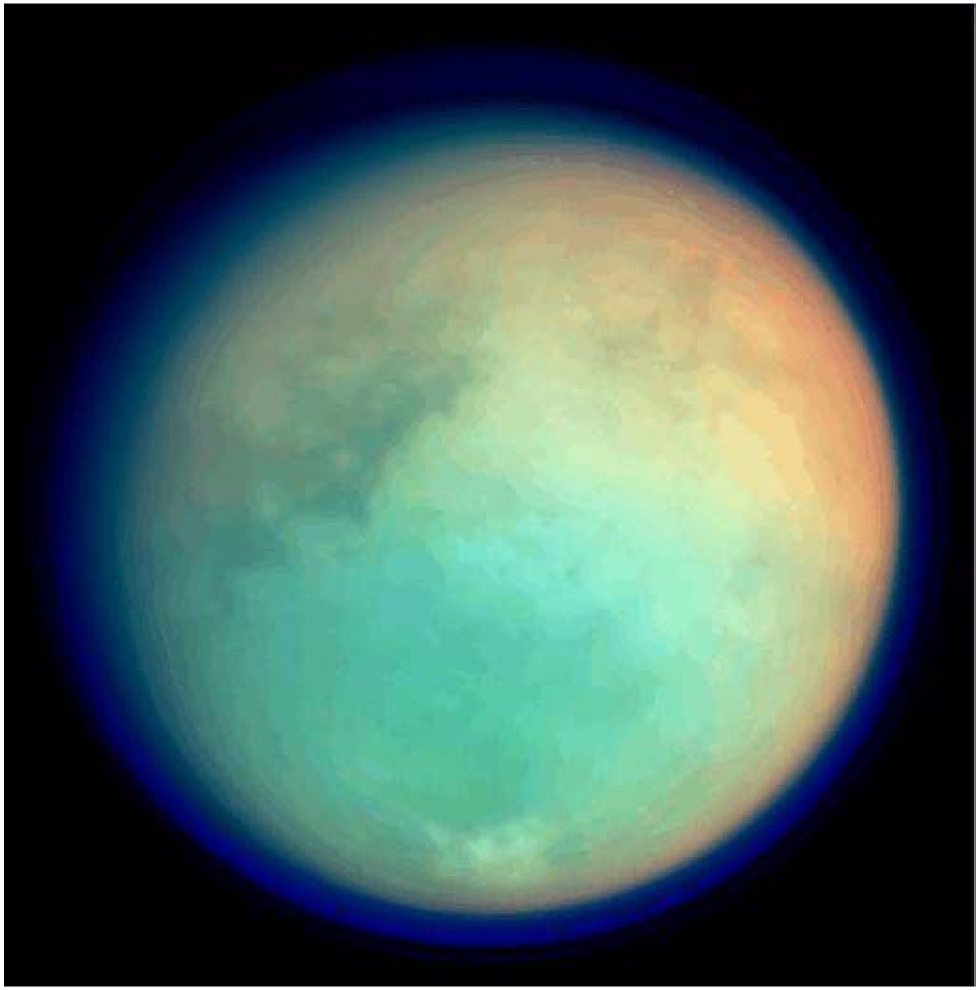
Some VEX results concur!.

A SEP event observed on Mars Odyssey: Orbital modulation indicates absorption by Mars



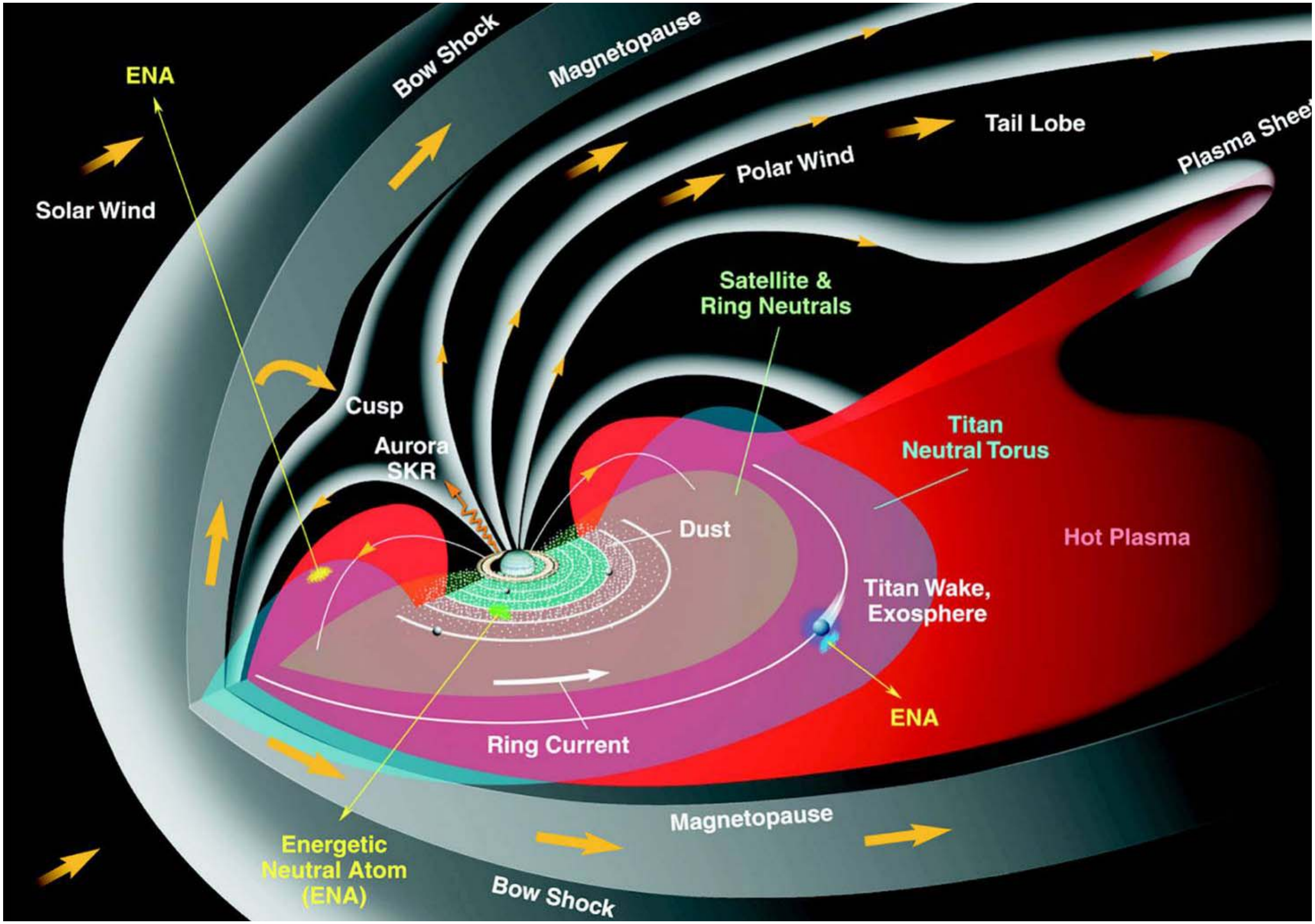
Similar behavior was reported in PHOBOS energetic particle data obtained by McKenna Lawlor et al. Are there **consequences?**

Titan



Cassini Image, NASA (C. Porco, PI)

Saturn’s Magnetosphere

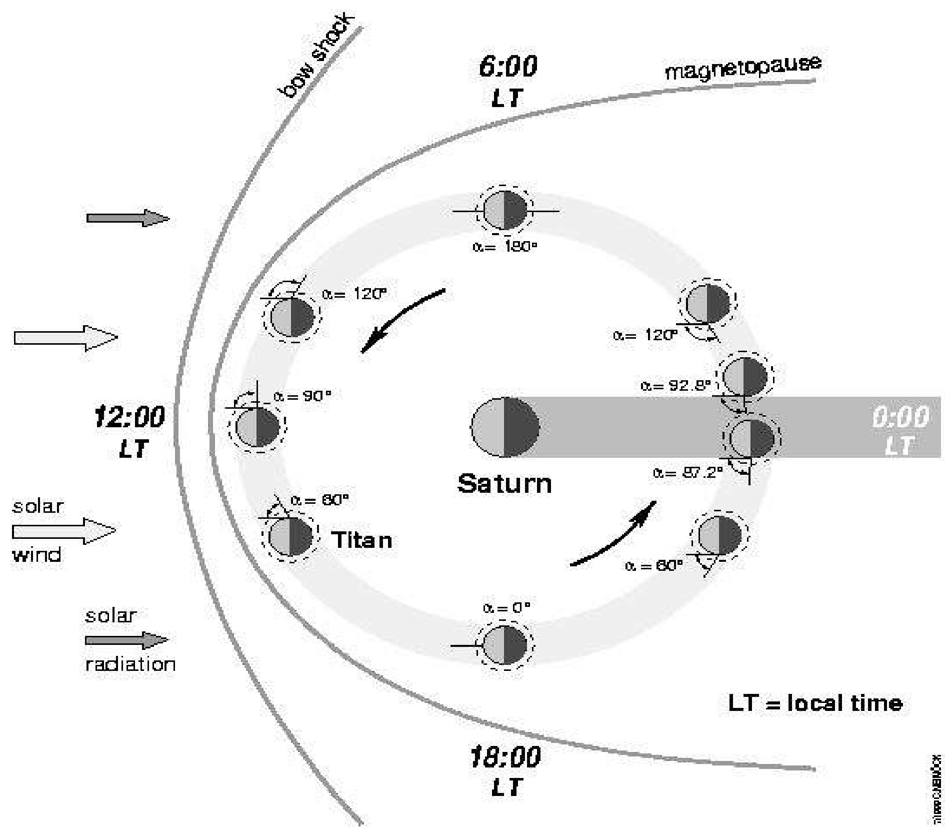


From a presentation by J-E Wahlund

Titan orbiting in Saturn's magnetosphere provides varying aspects of sun and incident corotating flows

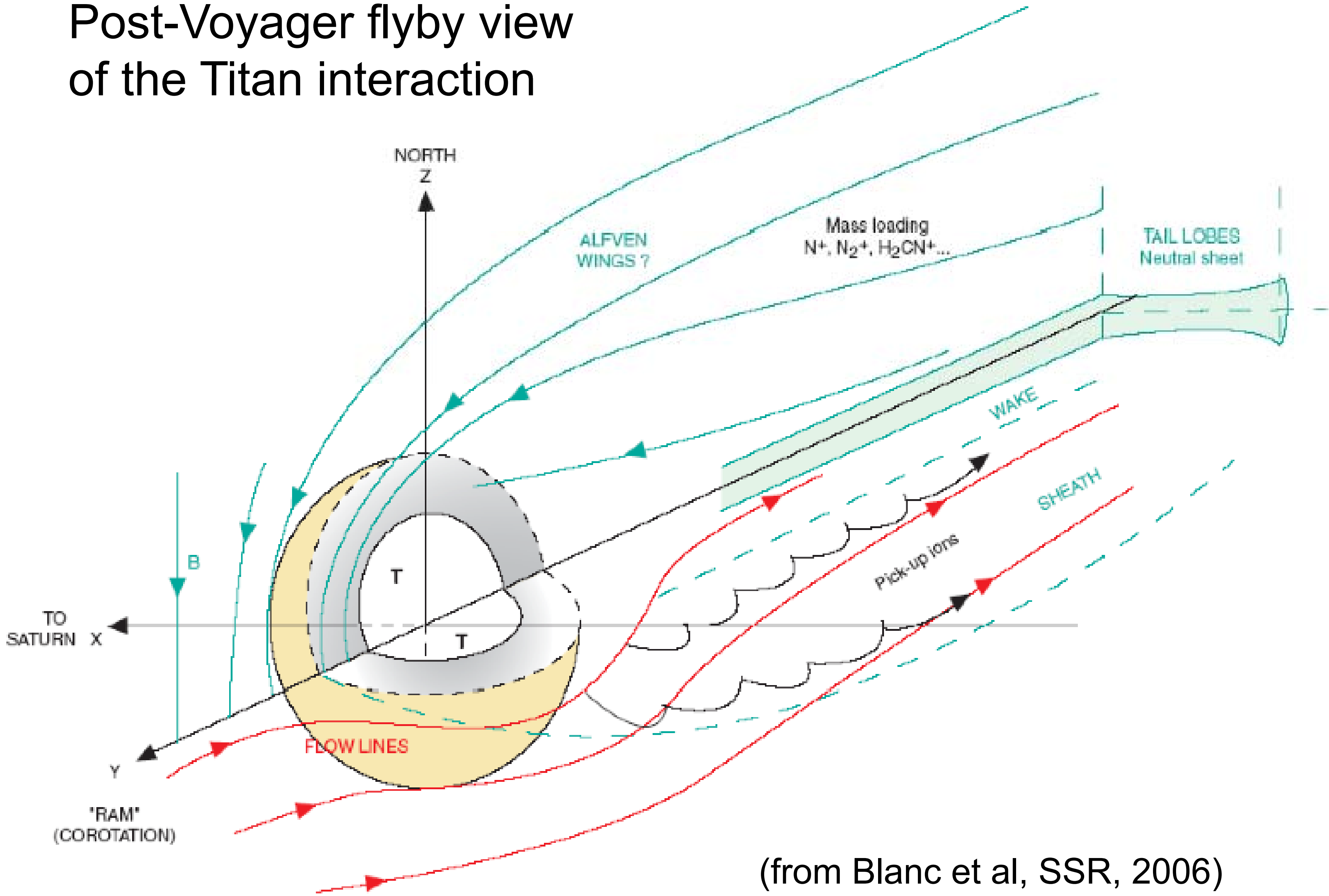
Plasma parameters inside Saturn's magnetosphere (near Titan's orbit)

- **Velocity : 80-150km/s**
- **Electron number density: ~0.3 cm^{-3}**
- **Major Ions: (H^+ and N^+ (O^+?))**
- **Magnetic field: ~5nT**
- **Estimated time Titan is outside the magnetopause is ~ 5%**



(slide courtesy of Yingjuan Ma)

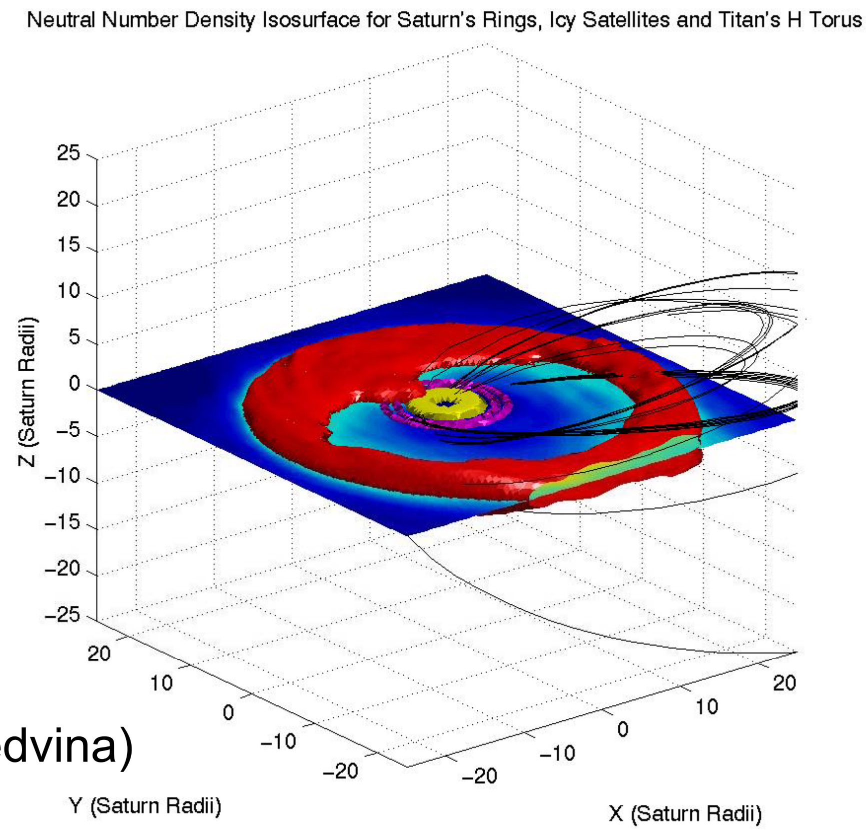
Post-Voyager flyby view of the Titan interaction



(from Blanc et al, SSR, 2006)

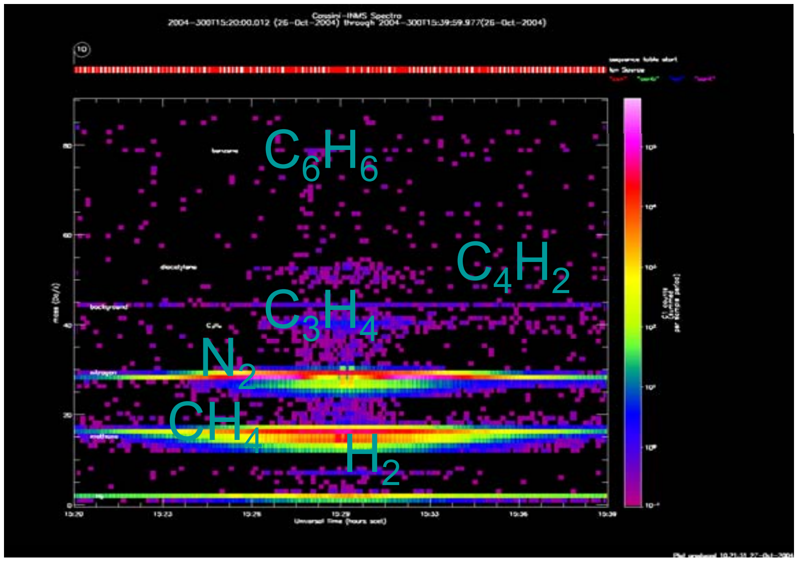
Pre-Cassini view of expected Saturn satellite and ring torus material distribution.
Cassini found no major Titan torus.

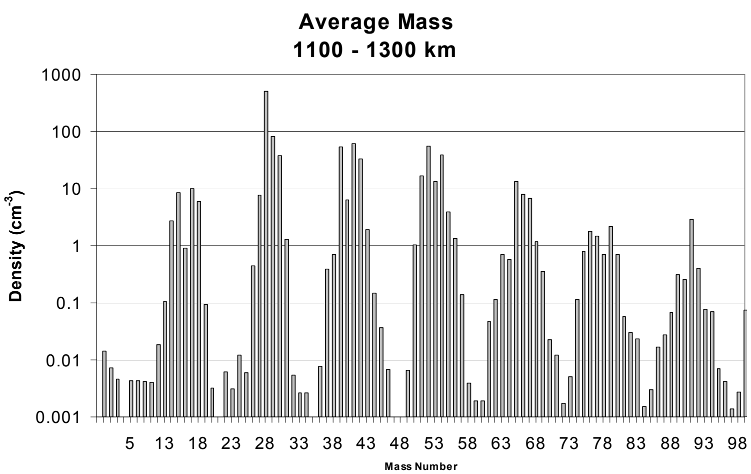
(ambient heavy ions are from the inner icy satellites).



(illustration from S.Ledvina)

Complex Carbon Nitrile Chemistry





- The neutral composition at 1200 km in addition to the primary constituents N_2, CH_4, and H_2 includes a host of hydrocarbons: C_2H_2, C_2H_2, C_2H_6,C_3H_4, C_3H_8, C_4H_2, HCN, HC_3N, C_2N_2, and C_6H_6.

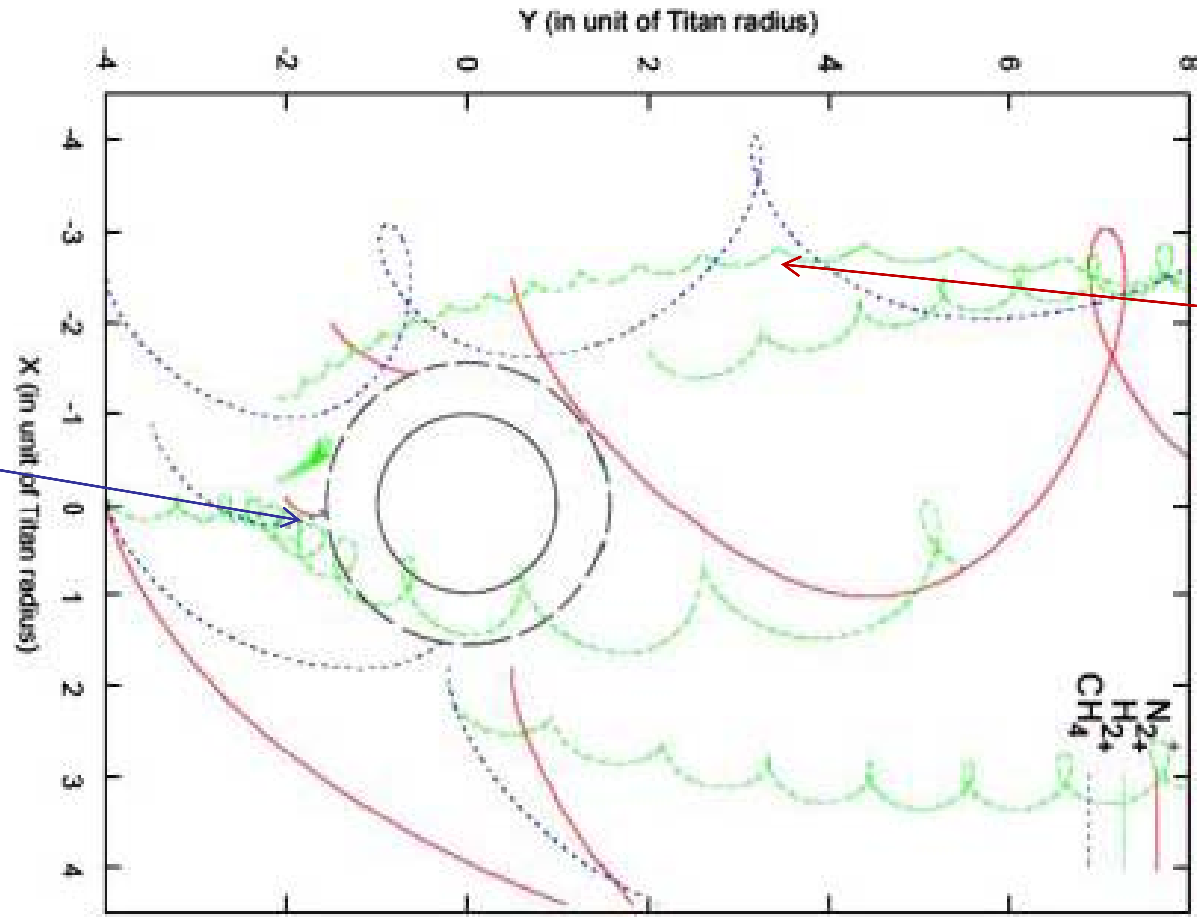
==> TITAN"S UPPER ATMOSPHERE IS A KEY SOURCE of CARBON NITRILE COMPOUNDS

- Correspondingly, the ionospheric composition has a complex hydrocarbon and nitrile chemistry that includes almost all possible hydrocarbon species through C7.

(Slide from Hunter Waite, INMS PI)

Test pickup ions in MHD model fields: their fate depends on their mass

Heavy ions impact



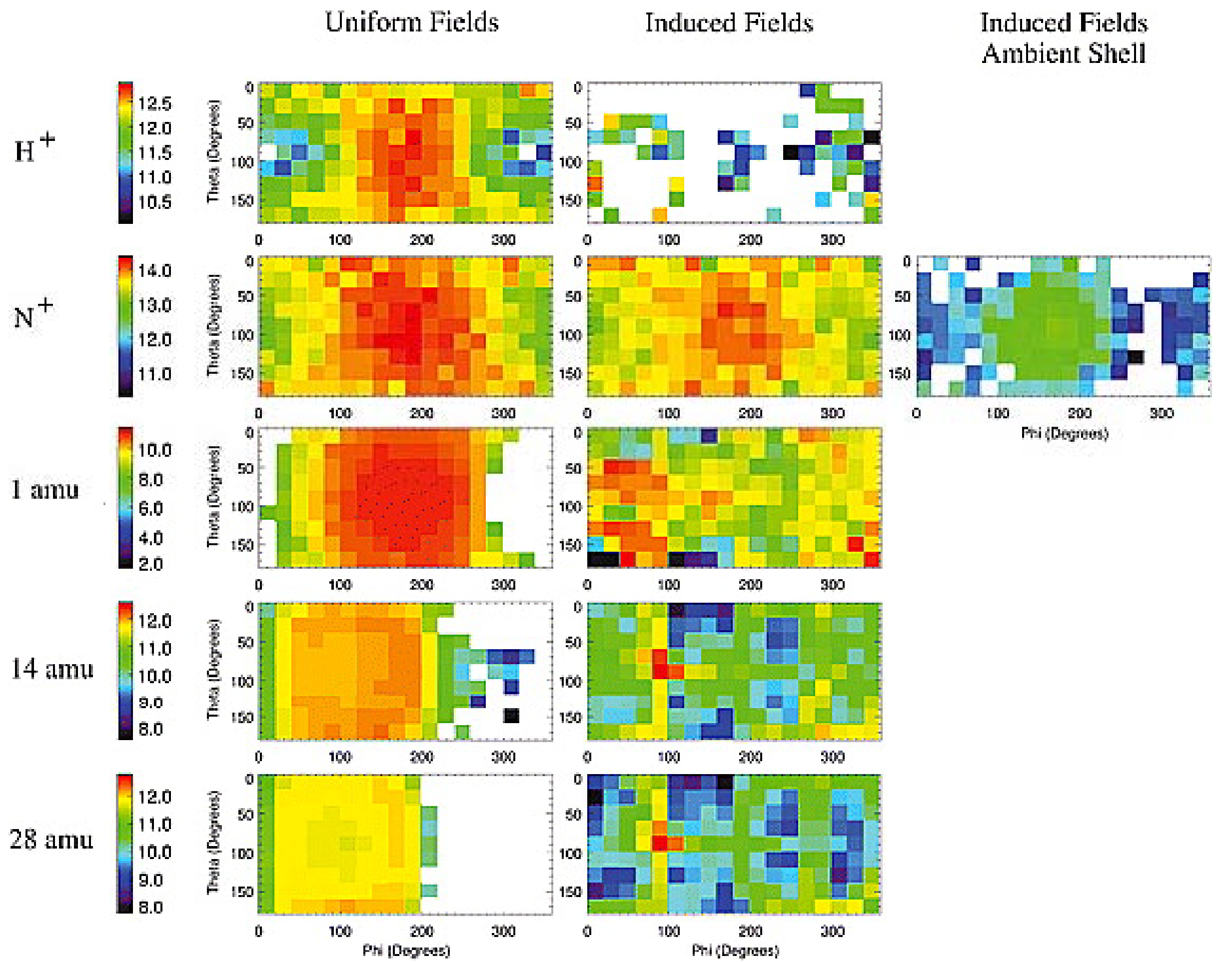
Light ions Flow around

(from Tseng and Ip, JASR, 2008)

Ambient and Pickup Ion fluxes incident on Titan's exobase (~1400 km)

(ambient)

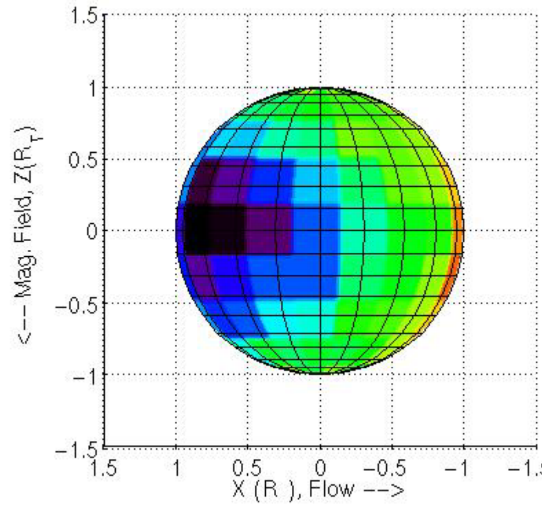
(pickup)

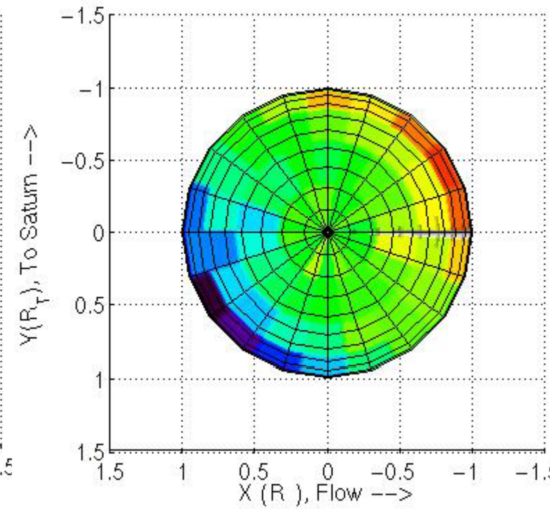


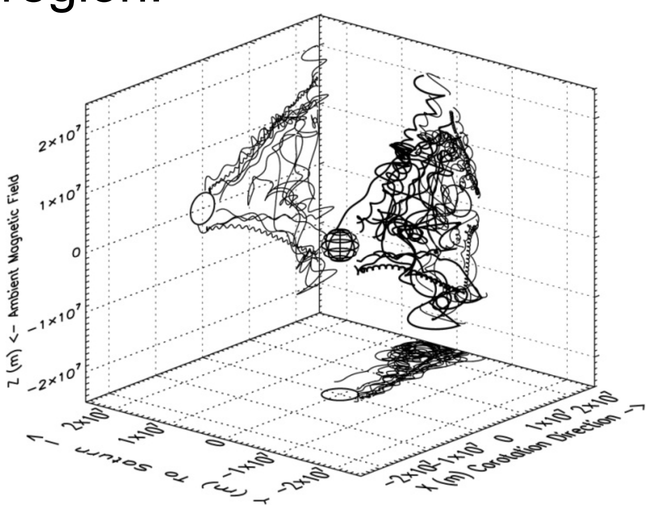
(fromLedvina et al., JGR 2005)

Ambient Energetic Magnetospheric Proton Flux into Titan's Exobase (model)

The energy flux into Titan's exobase from high energy magnetospheric protons is not uniformly distributed around Titan. The draped magnetic field funnels these ions into the wake region.

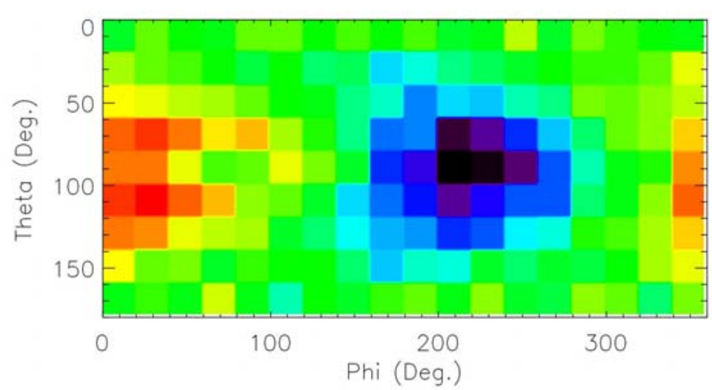


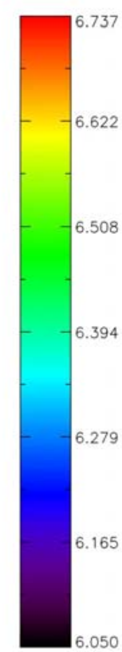




Sample 40 KeV proton trajectories

Log [Energy Flux (keV/cm^2 s^{-1})]

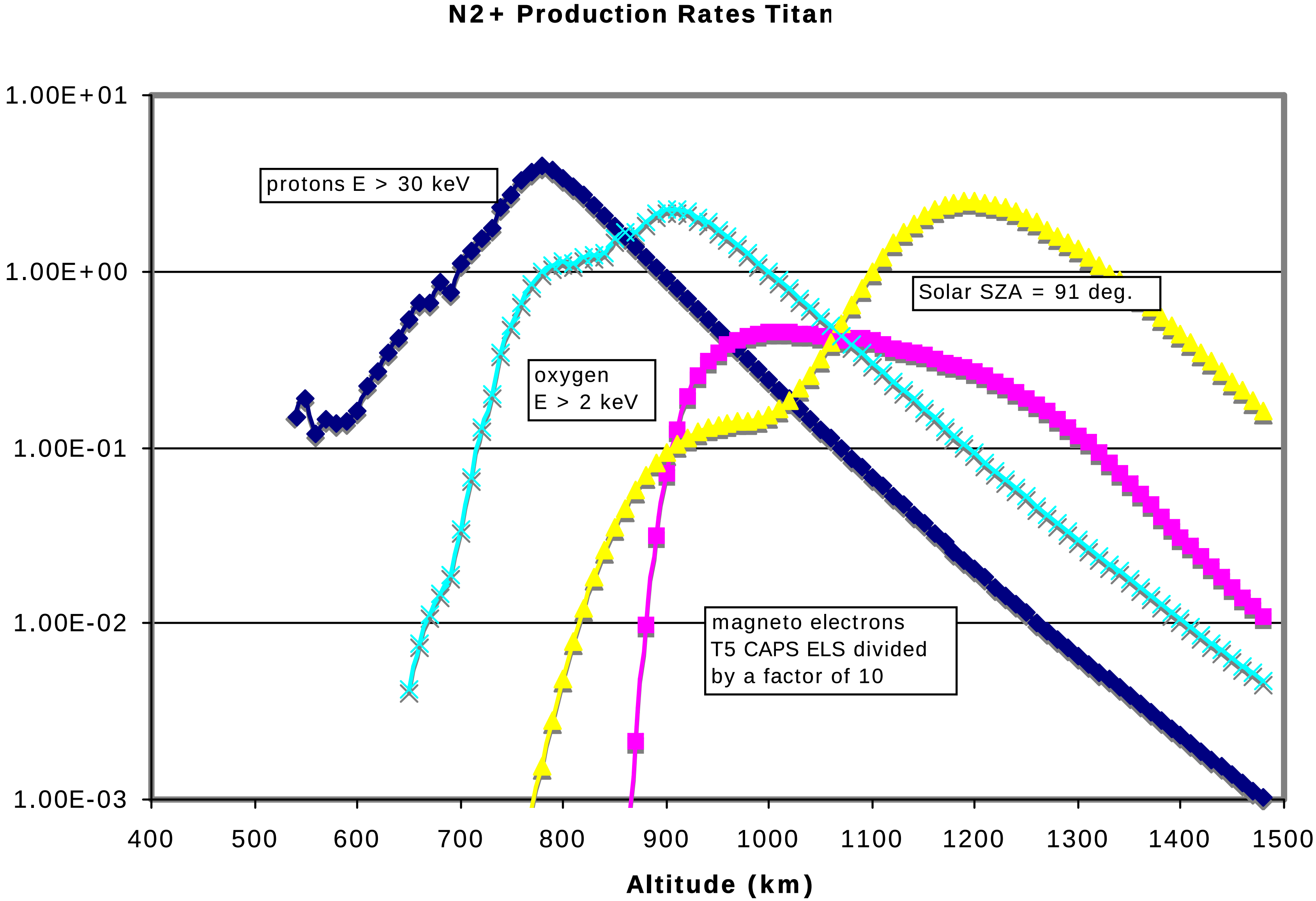




(S. Ledvina illustration)

Total energy flux = 4.4 x 10^{-4} ergs/cm^2/s

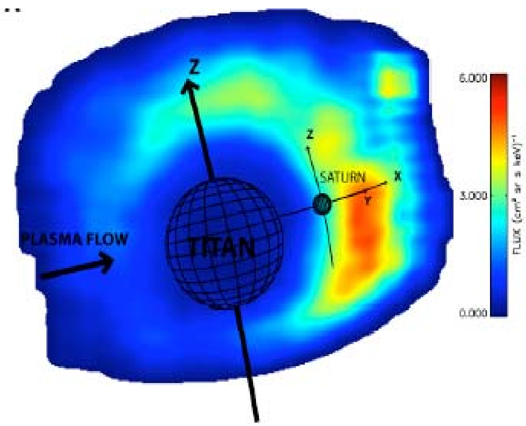
At Titan a challenge is to sort out all the energy/ionization sources..



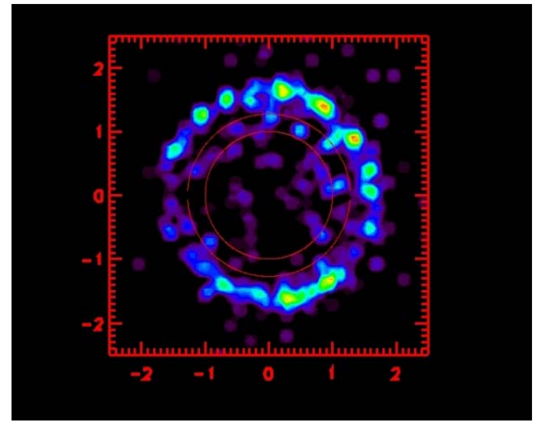
(from Cravens et al., JGR, 2008)

Cassini MIMI/INCA ENA image shows evidence of the energetic proton input

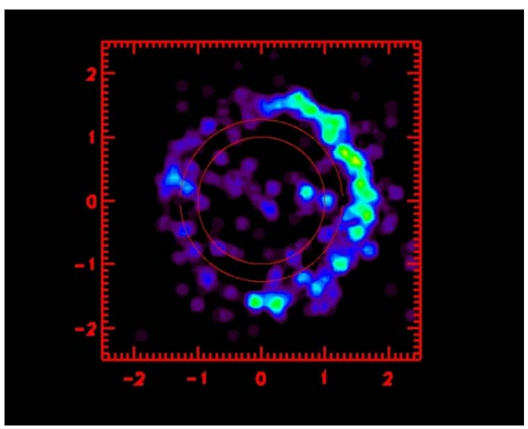
INCA



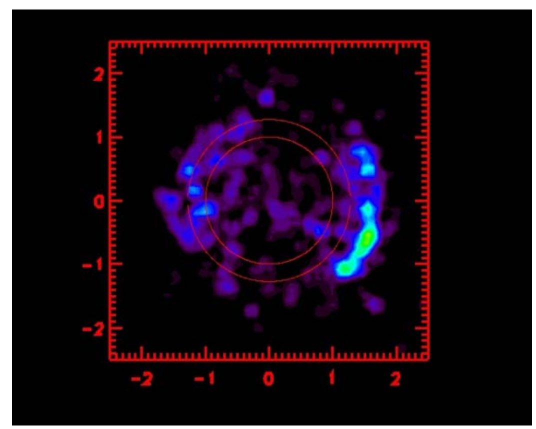
Uniform



TA-like



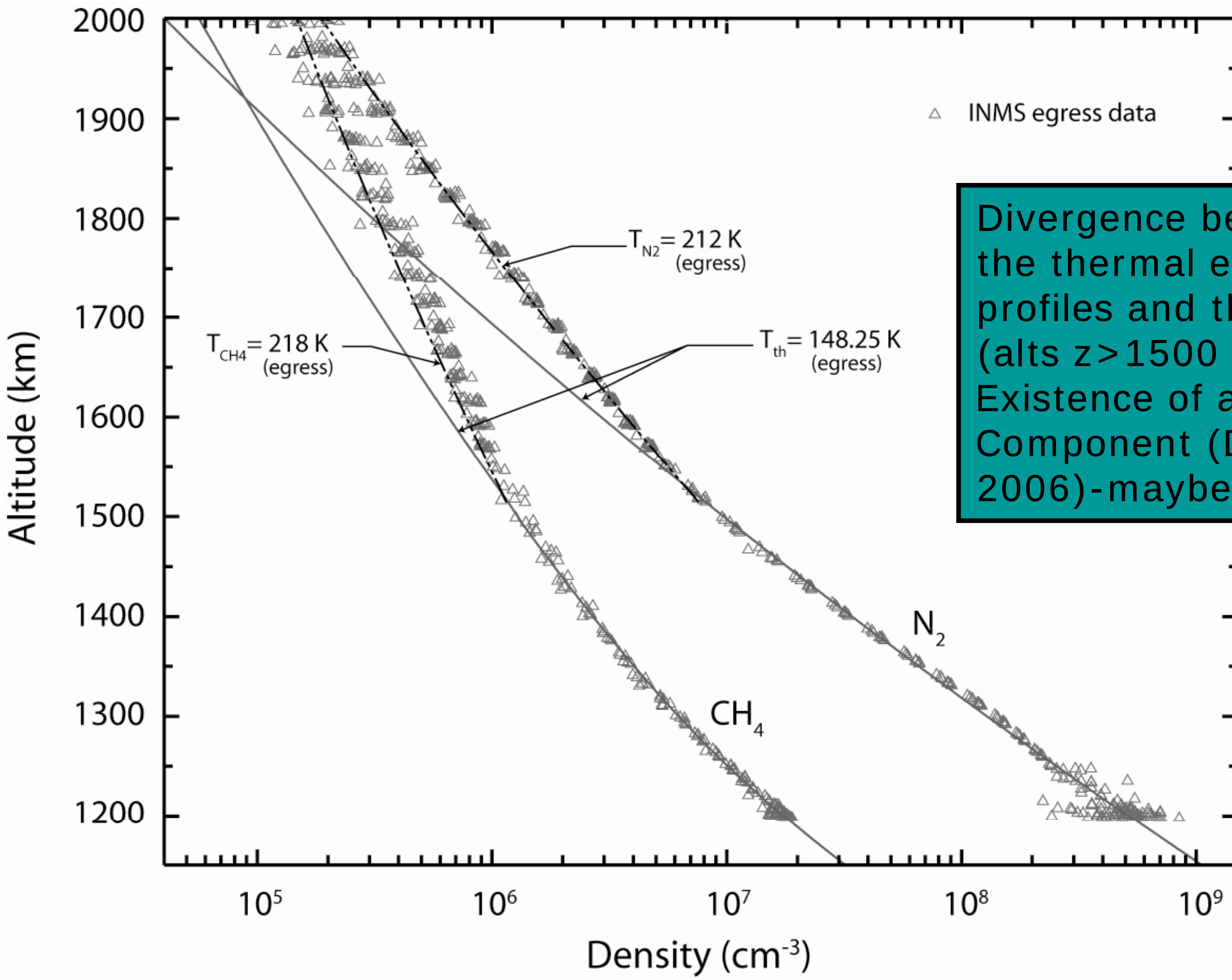
Voyager



Note: The contours are not on the same scale. However, they do show the location of the ENA peaks. The inflow direction is indicated by the arrows.

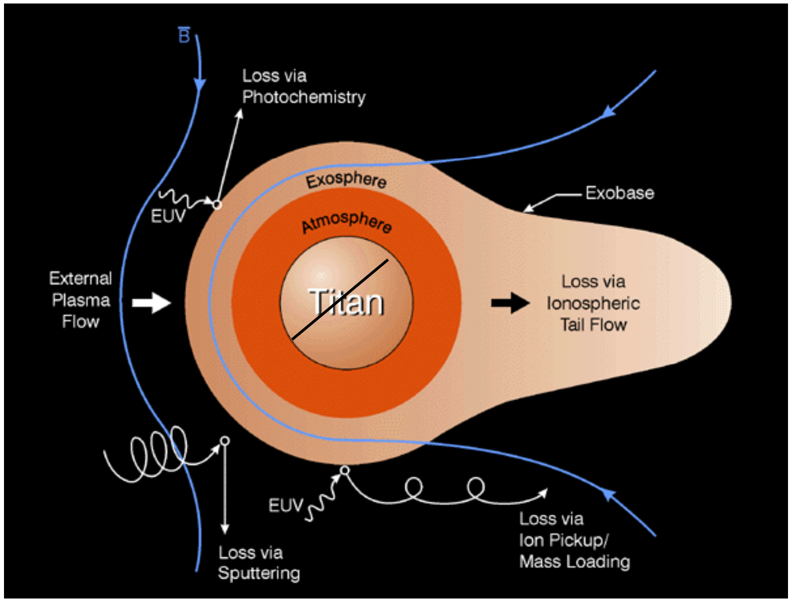
(Ledvina slide, using Cassini INCA data from D. Mitchell)

The neutral atmosphere data show 'hot' components that may be evidence of pickup ion sputtering (lines are fits to thermal exosphere models)

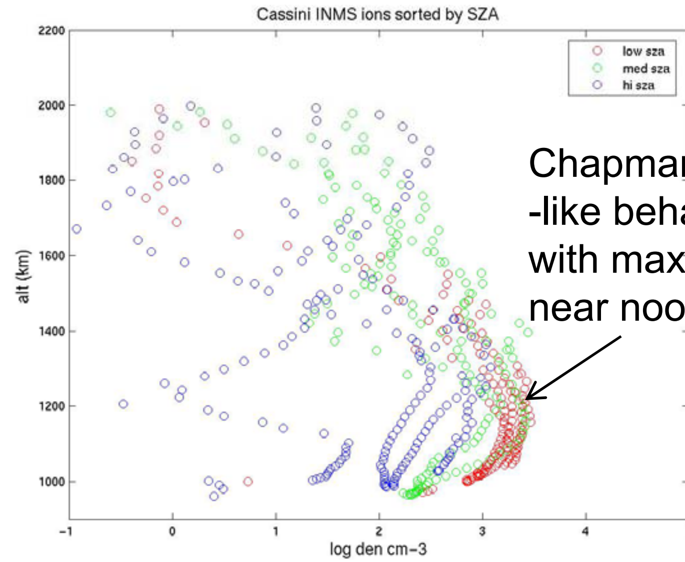


Divergence between the thermal exospheric profiles and the INMS data (alts z>1500 km) suggests Existence of a suprathermal Component (De la Hay, JGR, 2006)-maybe sputtered?

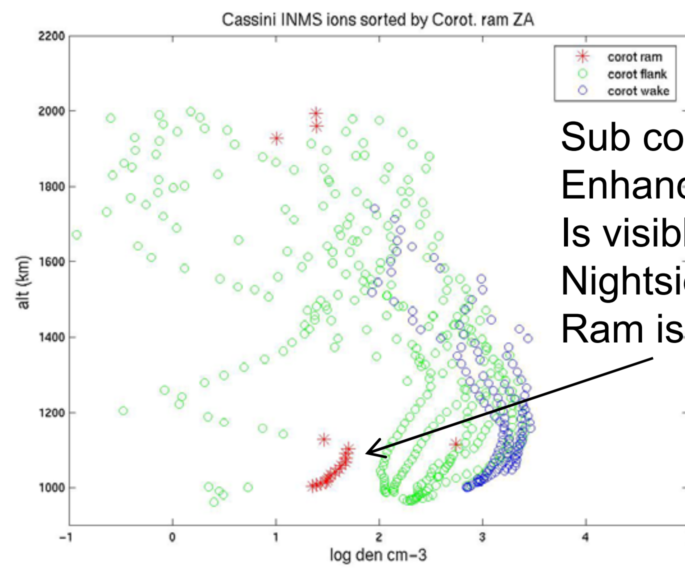
Sorting out ionosphere and exosphere heating sources: solar versus (magnetospheric) particle



The aggregate of INMS ion measurements suggest the relative importance of solar photon versus magnetospheric particle sources, from a sorting of all measurements according to Sun-ordered and corotation ram-ordered directions

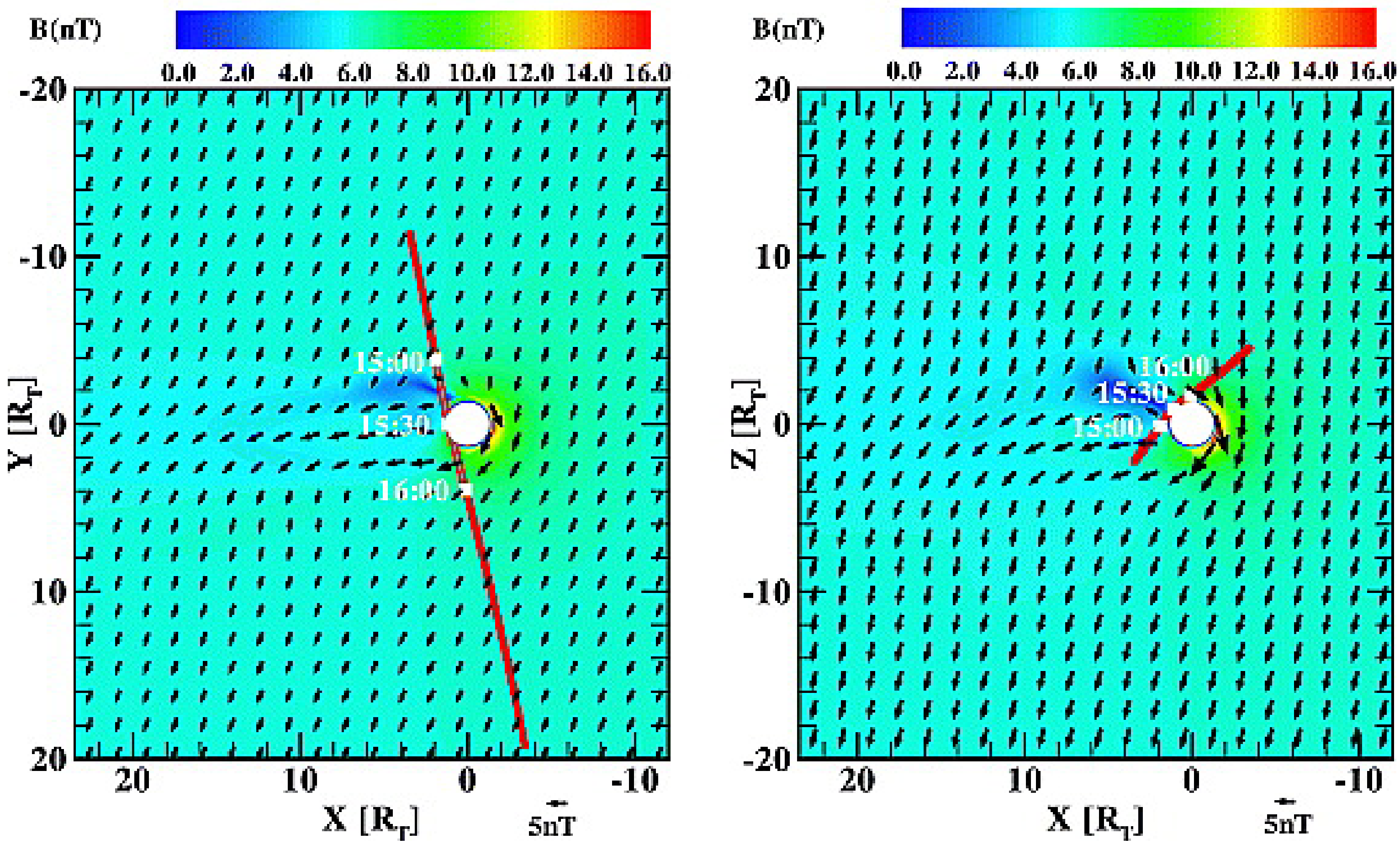


Chapman-layer -like behavior with max Ni near noon



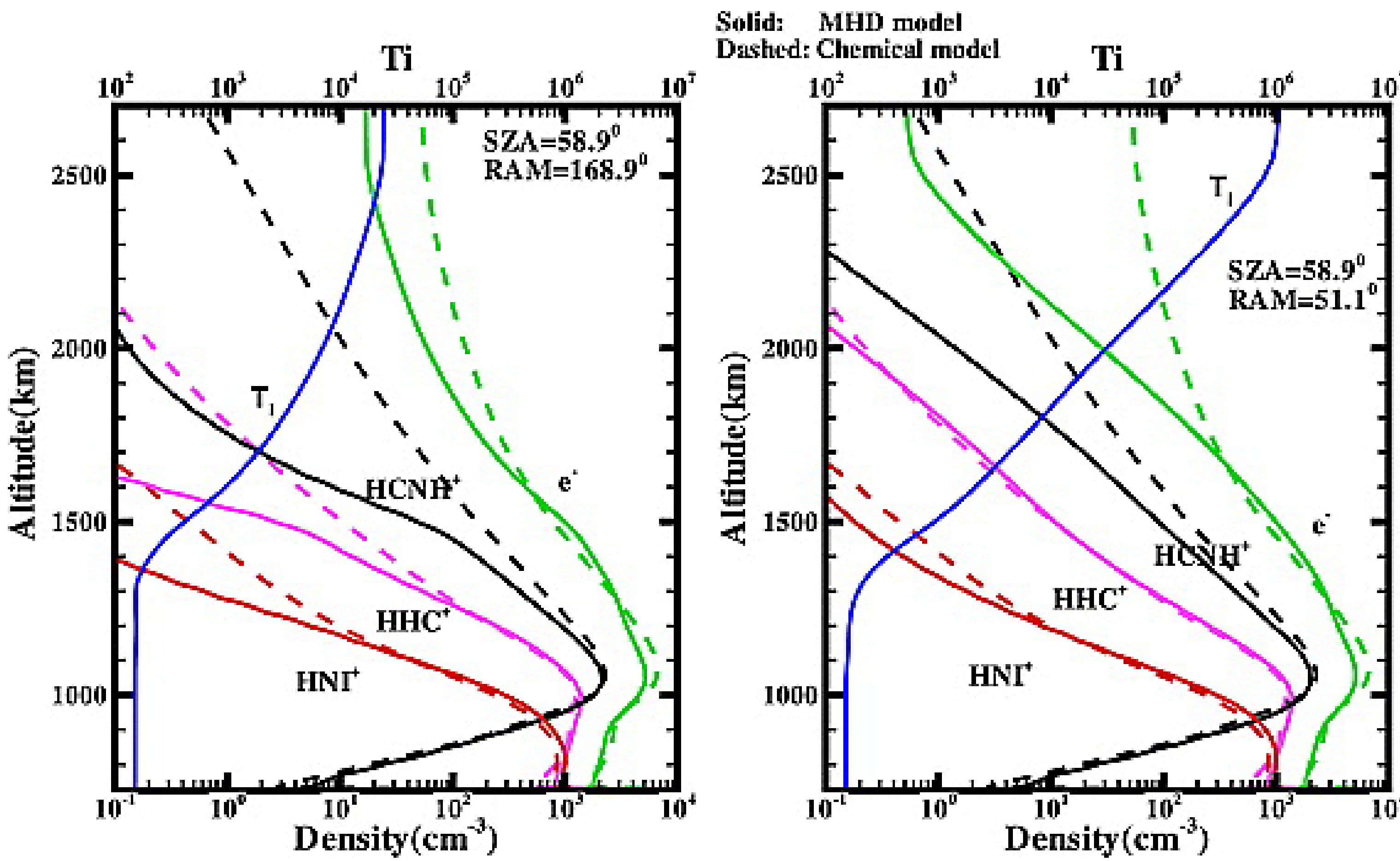
Sub corot. Ram Enhancement Is visible on the Nightside when Ram is at night

Y. Ma's MHD models for Titan must be tailored to upstream conditions and solar angle on each pass



(Ma et al., JGR 2005)

They also include a basic ionospheric model including solar EUV and particle impact sources



Expectations vs realities for Titan

- Expected Voyager-like field and flow geometry (dipole-like Saturn magnetosphere and corotating flow)
- Expected interaction with Titan's own torus
- Expected a Venus-like interaction, though submagnetosonic and with some asymmetries from different sub-ram and subsolar locations

- Got magnetodisk-like field geometry and routine off-angle subcorotating flows
- Saw mainly water product ions from inner satellites, ~no Titan torus
- Got a much more complicated interaction
- Caught one flyby with Titan passing through magnetopause

Current State of Knowledge: Weakly magnetized planets

Venus:

Venus' interaction to first order (at solar max) resembles flow around a conducting sphere provided by the ionosphere.

Venus' version of magnetic storms during solar max consists of Magnetized Ionospheres on the dayside, disappearing ionospheres on the nightside, and possibly enhanced atmosphere escape. Enhanced UV 'auroras' are also seen.

Effect of the plasma interaction (and lack of a planetary field) on atmosphere evolution is still TBD

Mars:

Mars' versions are still under study, but are similar to Venus with some effects from the solar wind interaction with the crustal magnetic fields. The Martian aurora has also been found to be sensitive to solar wind conditions. Same bottom line on evolutionary effects

‘Universal Processes’ for this topic (?)

-Pressure Balance
-ionization (photo, electron impact, charge exchange)
-dissociative recombination
-Ion Pickup and related sputtering, energy deposition and escape
-mass loading (related to the above)
-boundary (e.g. shear) instabilities
-flux rope creation (ionospheric)
-dust heating of atmospheres

Process ‘holes’ in present knowledge/thinking/modeling
-involvement of lower atmosphere/surface/interior
-contributions of ‘ion outflow’, wave-related and ‘bulk’ ionosphere erosion processes to escape
-responses to solar/interplanetary activity events