Particle and chemical sputtering as a source for the exosphere of Mercury: modeling and data comparison

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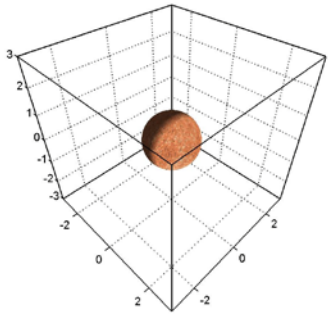
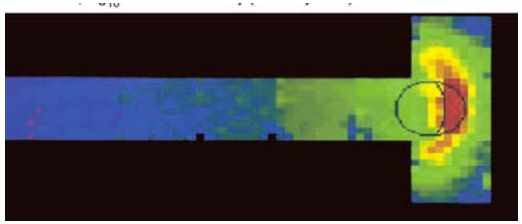
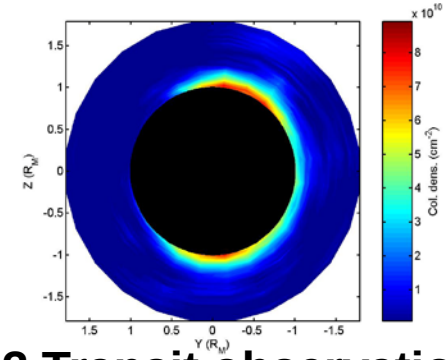
A. Milillo, V. Mangano, H. Lammer



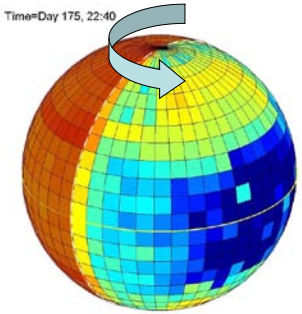
1 Model description



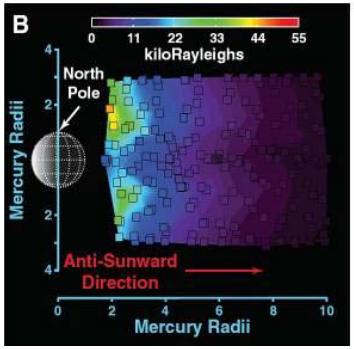
2 Mercury tail and radiation pressure



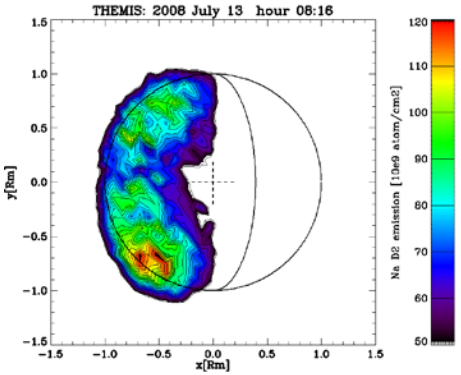
3 Transit observation and modeling: chemical sputtering



4 A Monte-Carlo model with planetary rotation

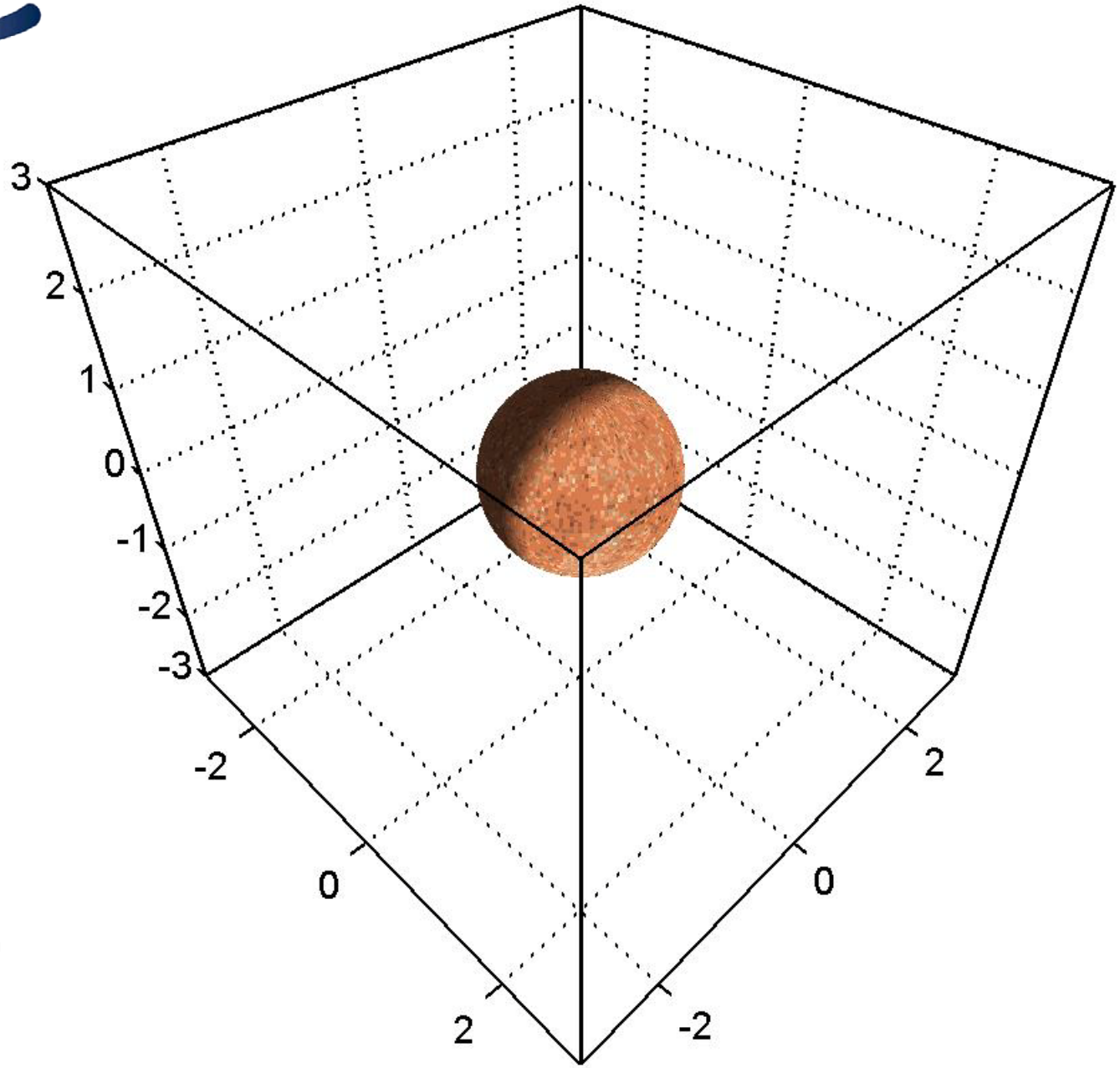


5 MESSENGER observations and modeling: neutral and ion tails

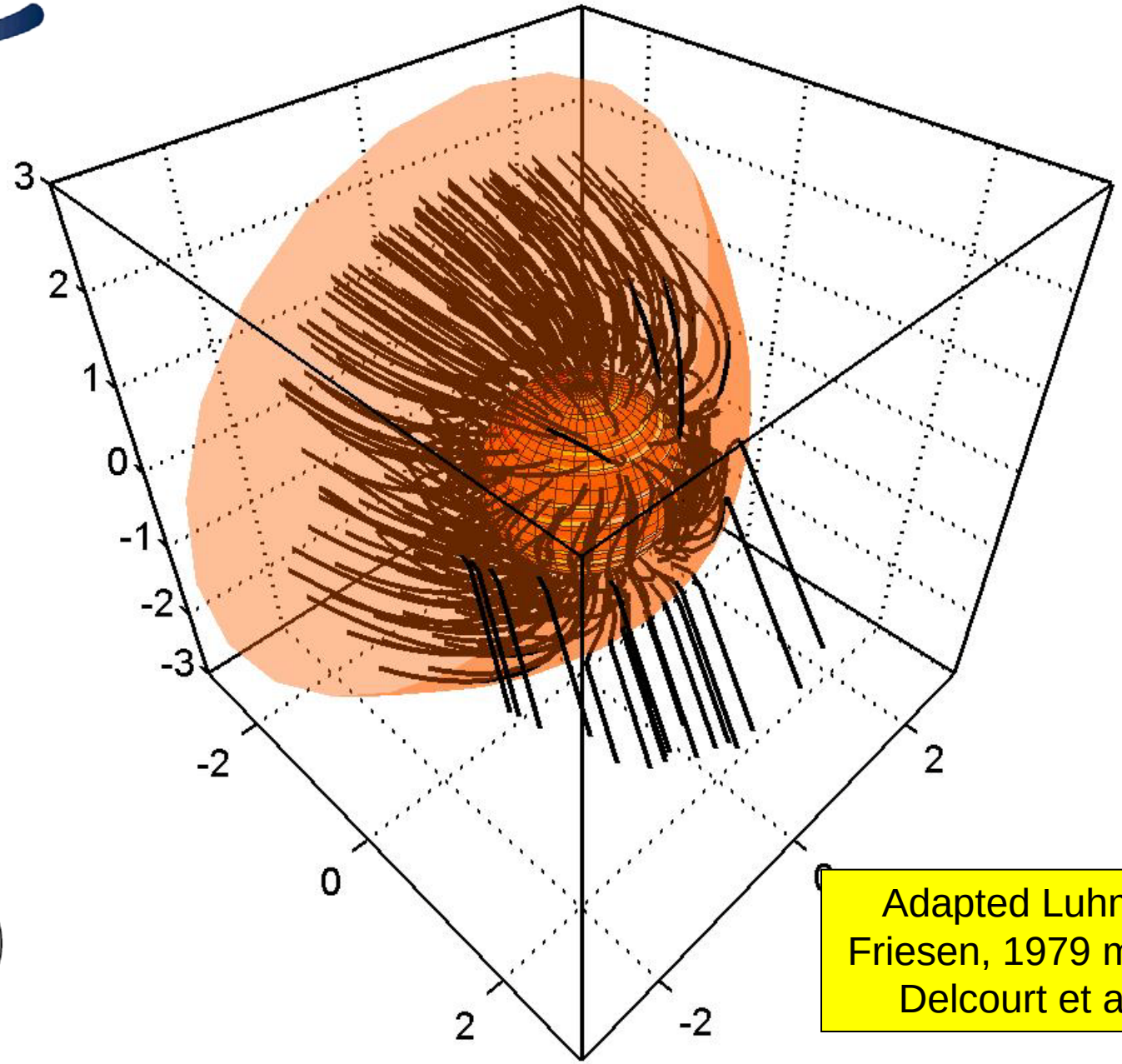


6 Themis observations and modeling: Sodium migration time-scales

Exosphere-magnetosphere model

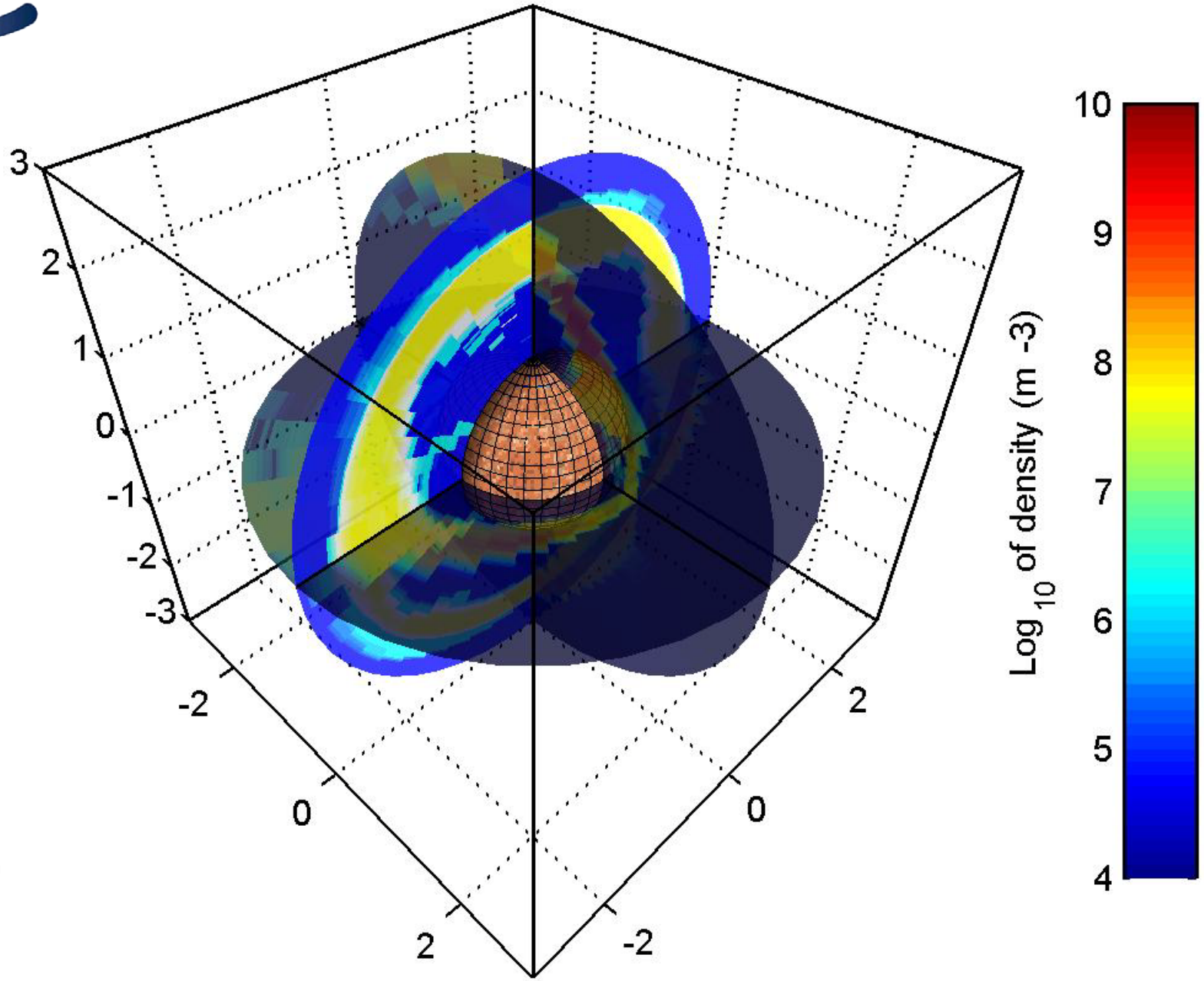


Magnetic and electric field

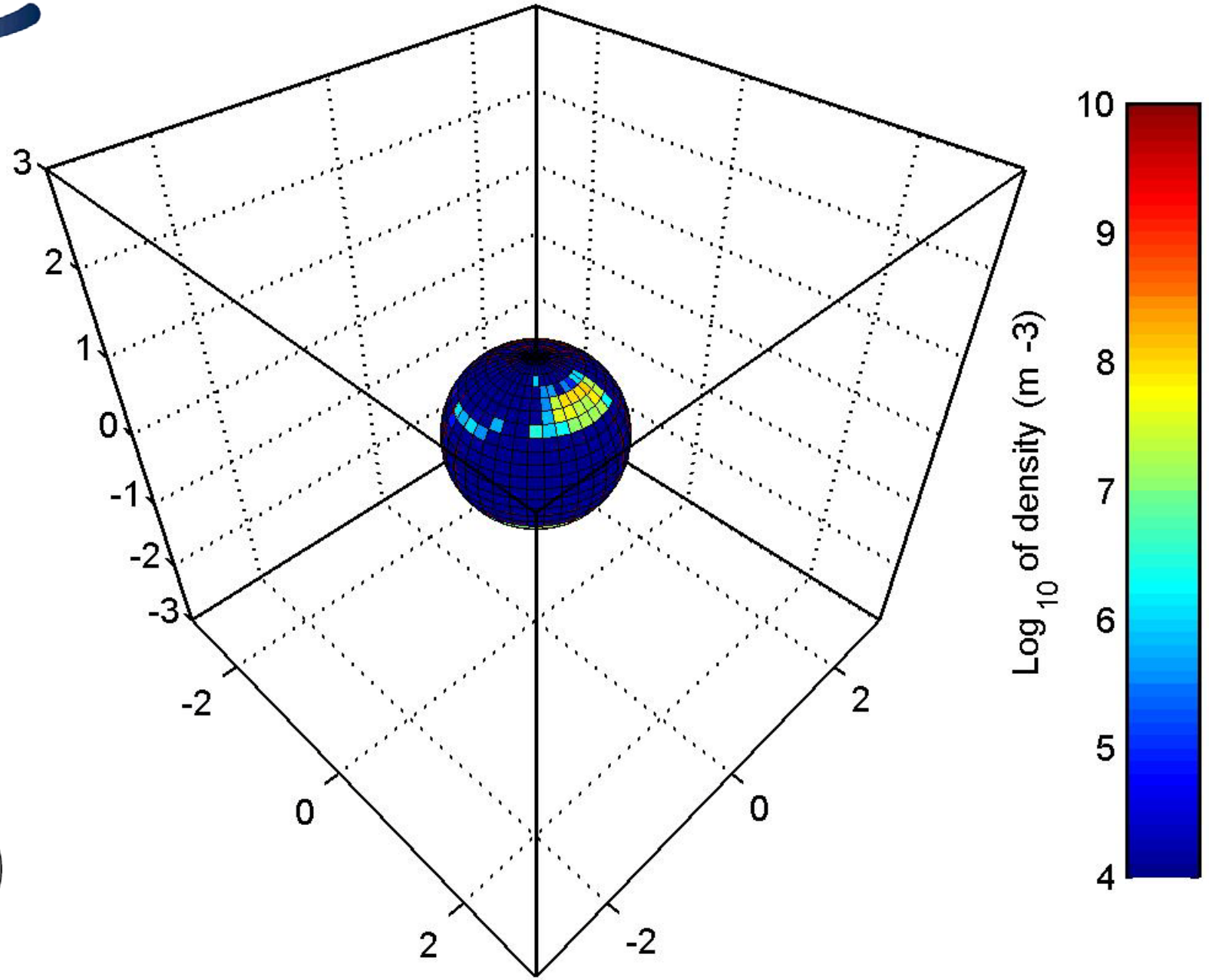


Adapted Luhmann and Friesen, 1979 model (as in Delcourt et al., 2003)

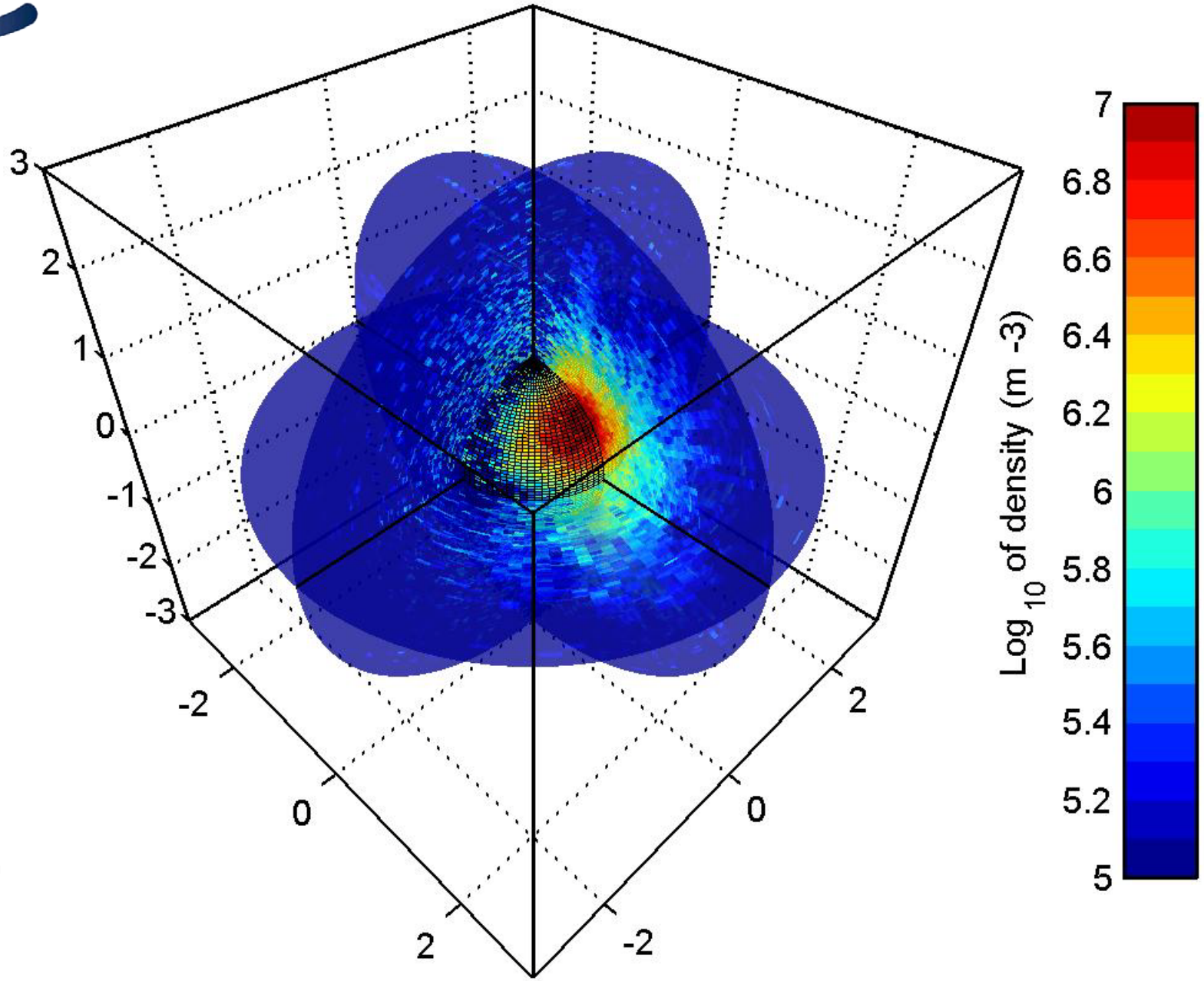
Proton circulation



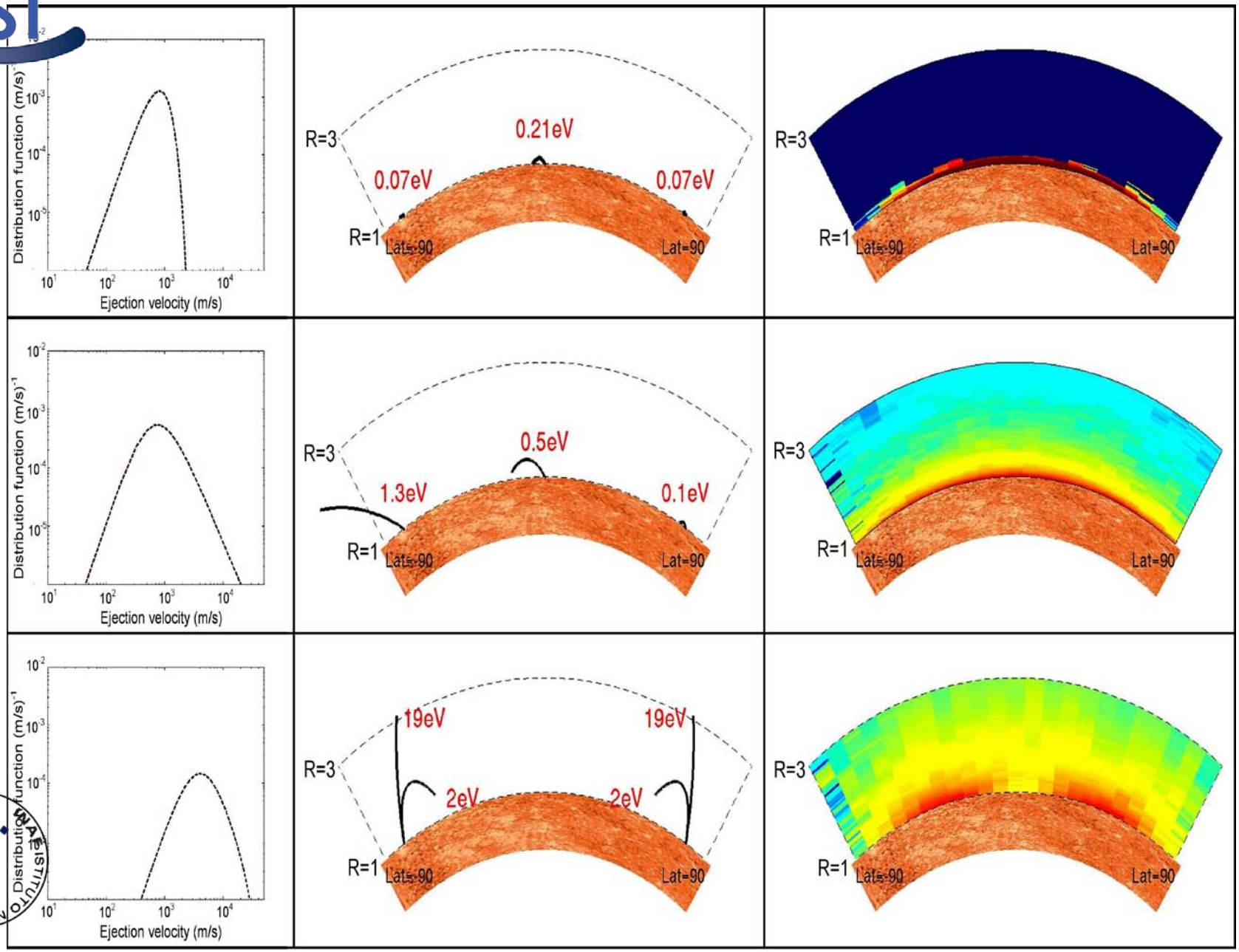
Proton precipitation



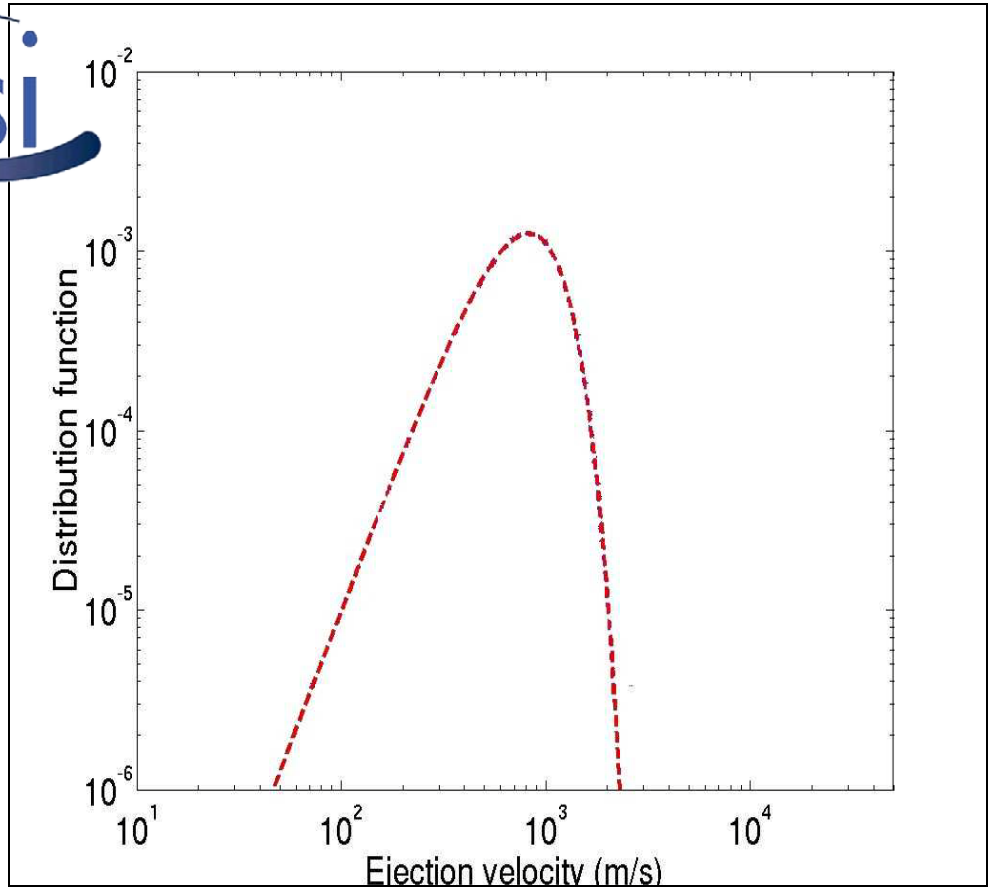
Proton precipitation

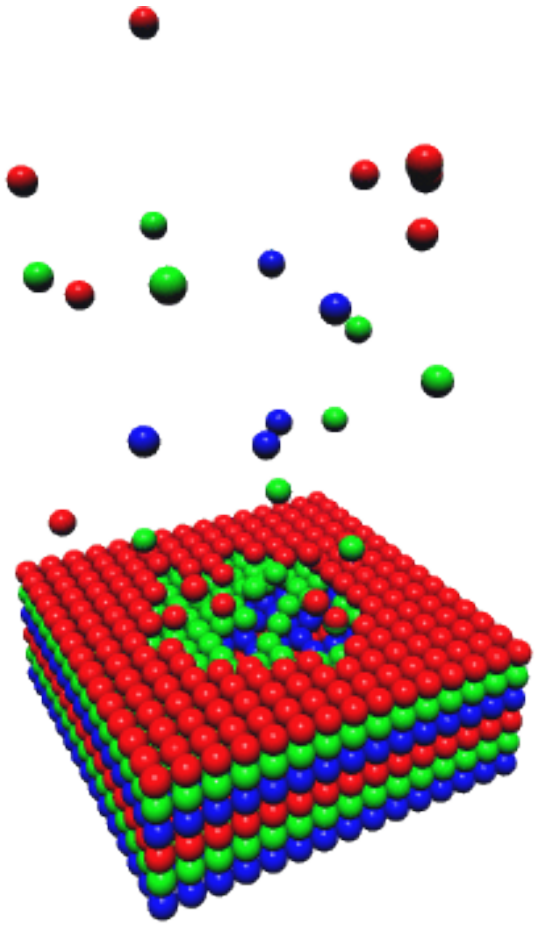


Mercury surface processes



Thermal desorption

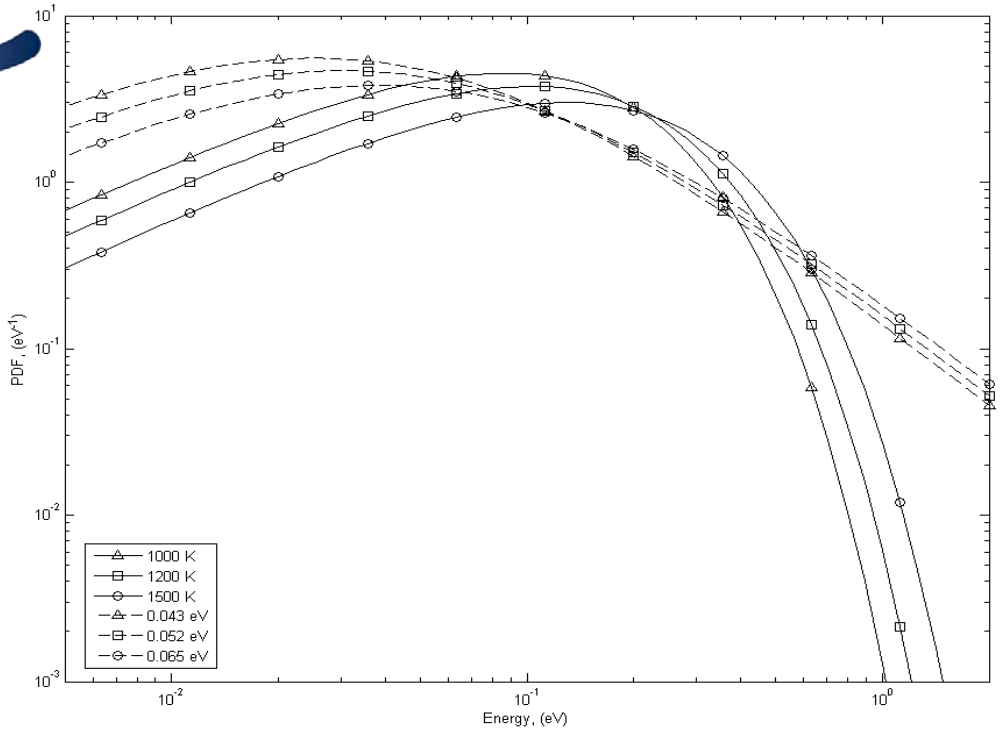


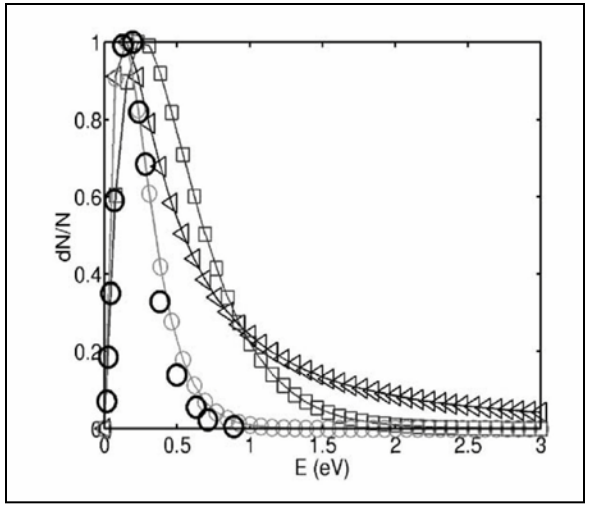


$$T(\alpha) = T_n + (T_d - T_n)\left[\cos(\alpha)\right]^{1/4},$$

$$\Phi_{TD}(t) = \nu N C(t) e^{-U_{TD}/k_B T}$$

PSD

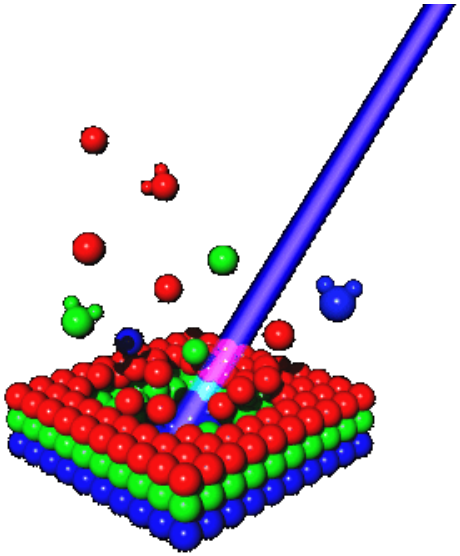




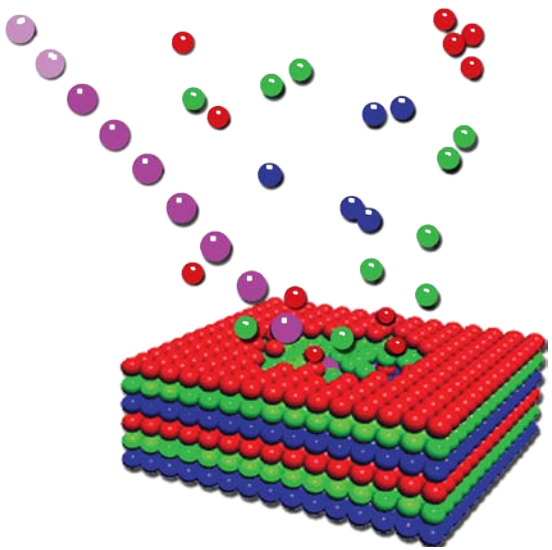
$$f(E) = \frac{E}{(k_B T)^2} e^{(-E/k_B T)},$$ Gaussian

$$f(E) = \beta(1+\beta)\frac{E U^{\beta}}{(E+U)^{2+\beta}},$$ Non-Gaussian

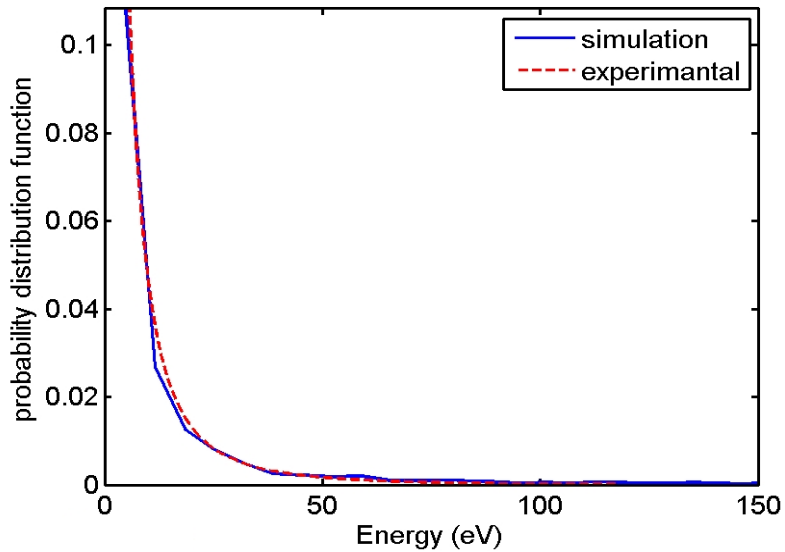
Johnson et al., 2002



Ion sputtering spectrum



SRIM Code by Ziegler and Manoyan, 1988

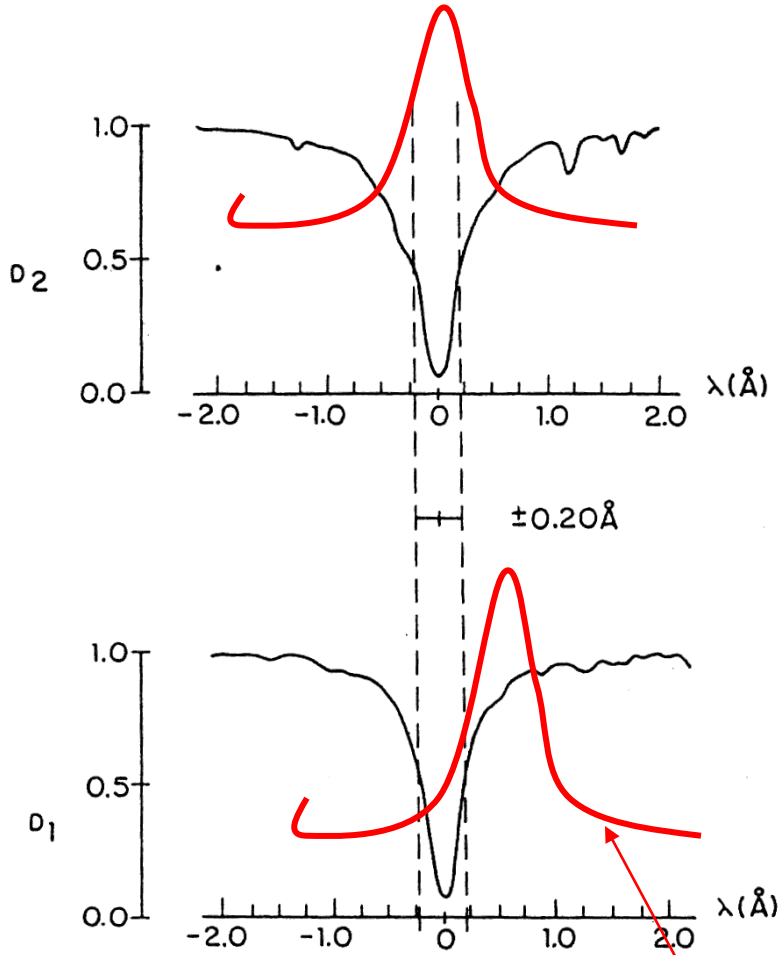


Sigmund, 1969; Betz and Wien, 1994

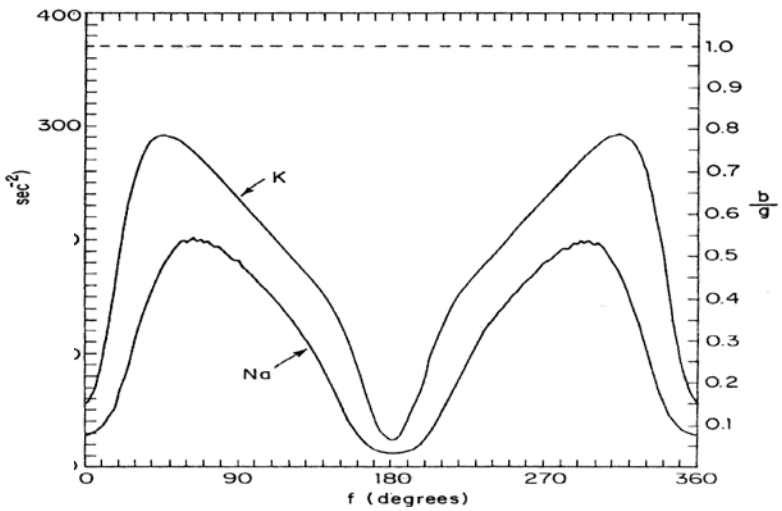
$$f_S(E_e) \propto \frac{E_e}{(E_e+E_b)^3}\left[1-\left(\frac{E_e+E_b}{E_i}\frac{(m_H+m_{Na})^2}{4m_H m_{Na}}\right)^{\frac{1}{2}}\right]$$

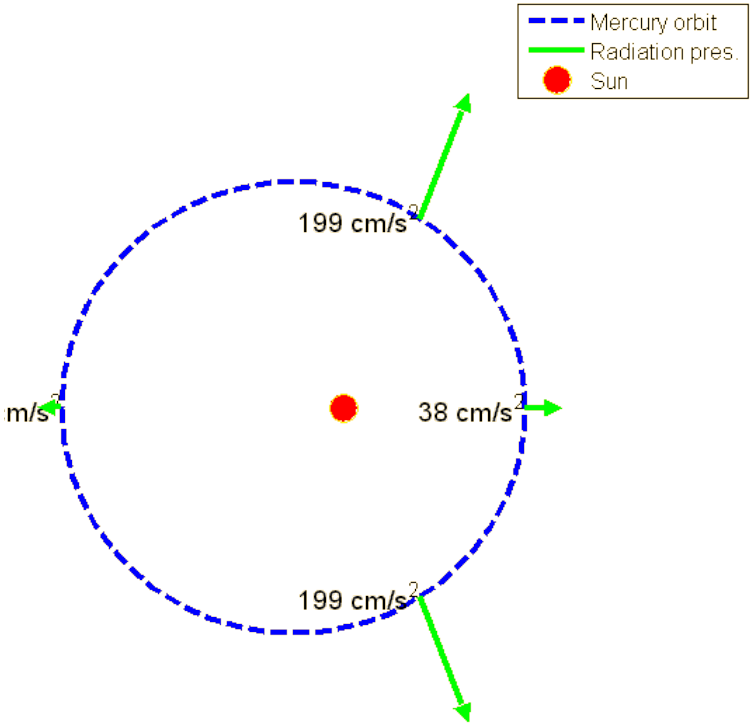
- H+ can't give all its energy to a single heavy target atom
- The sputtering energy spectrum falls at 50-100 eV

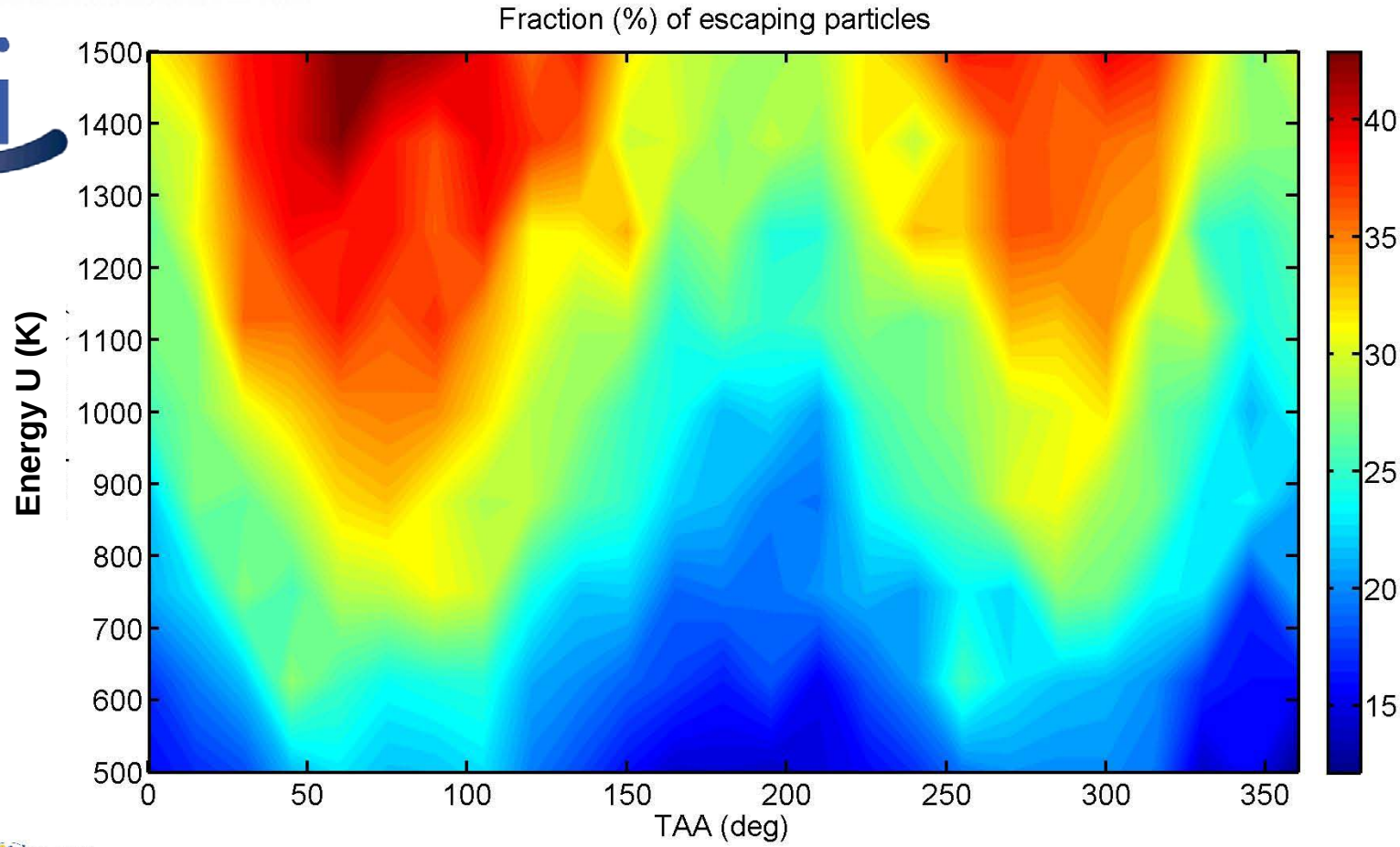
Smyth and Marconi, 1995



Doppler shifted

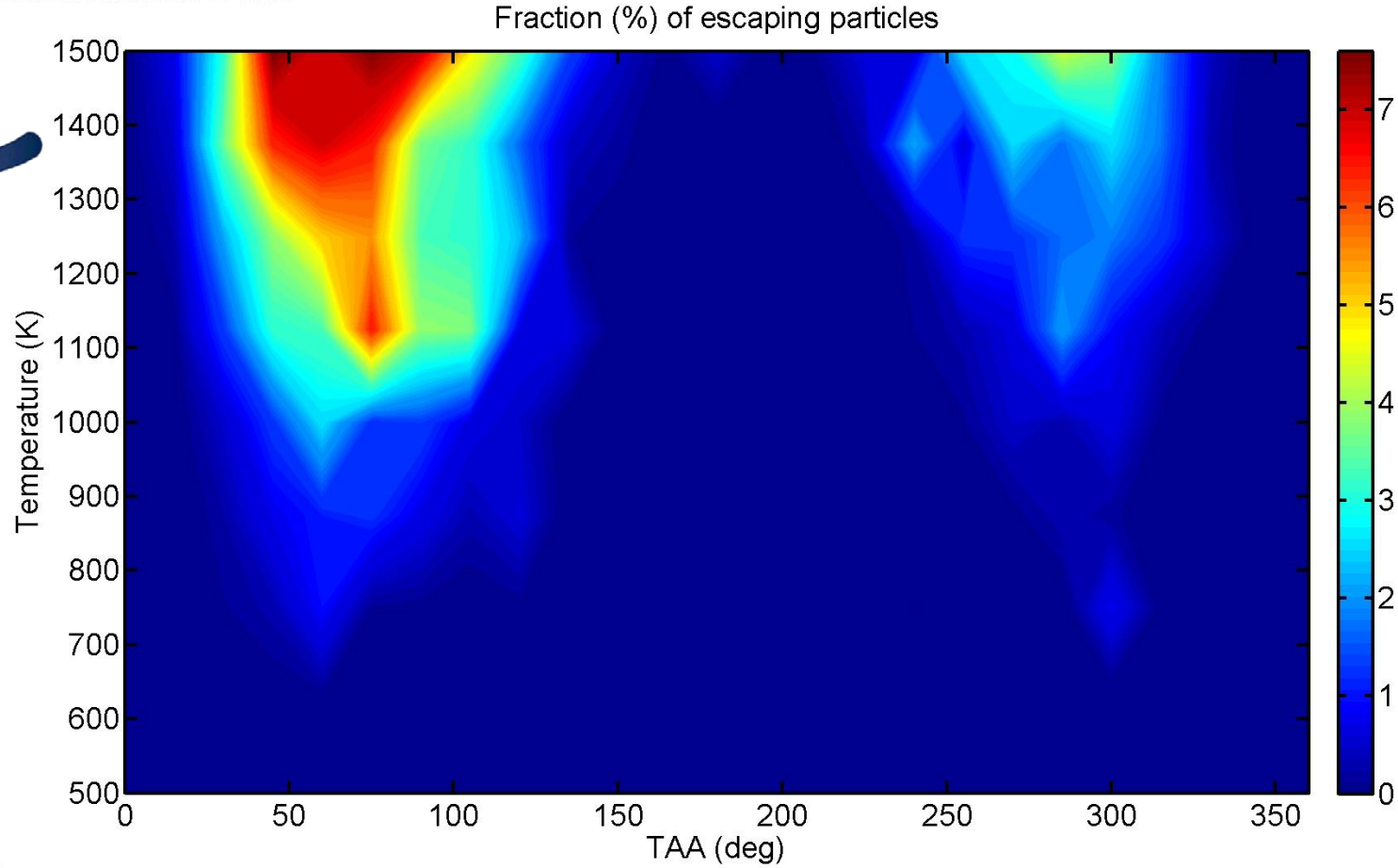






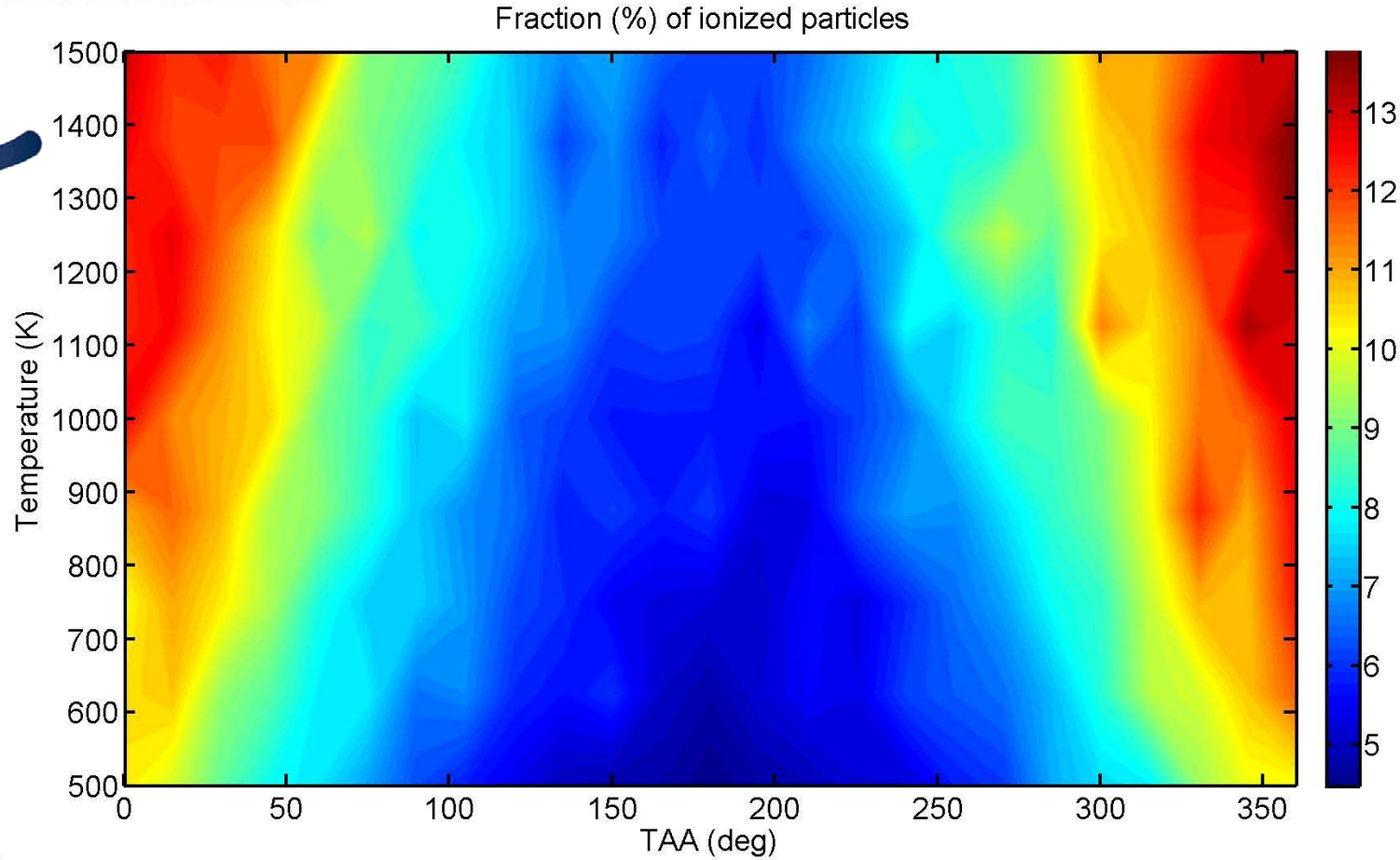
$$p_1 + p_2 \cdot \cos(2\alpha) + p_3 \cdot \cos(\alpha) + p_4 \cdot \cos(\alpha/2)$$

$$p_1 = 10.21 + 0.017 \cdot U$$
$$p_2 = -2.89 - 0.0015 \cdot U$$
$$p_3 = 1.352 + 0.00026 \cdot U$$
$$p_4 = 1.0759 + 0.001073 \cdot U$$



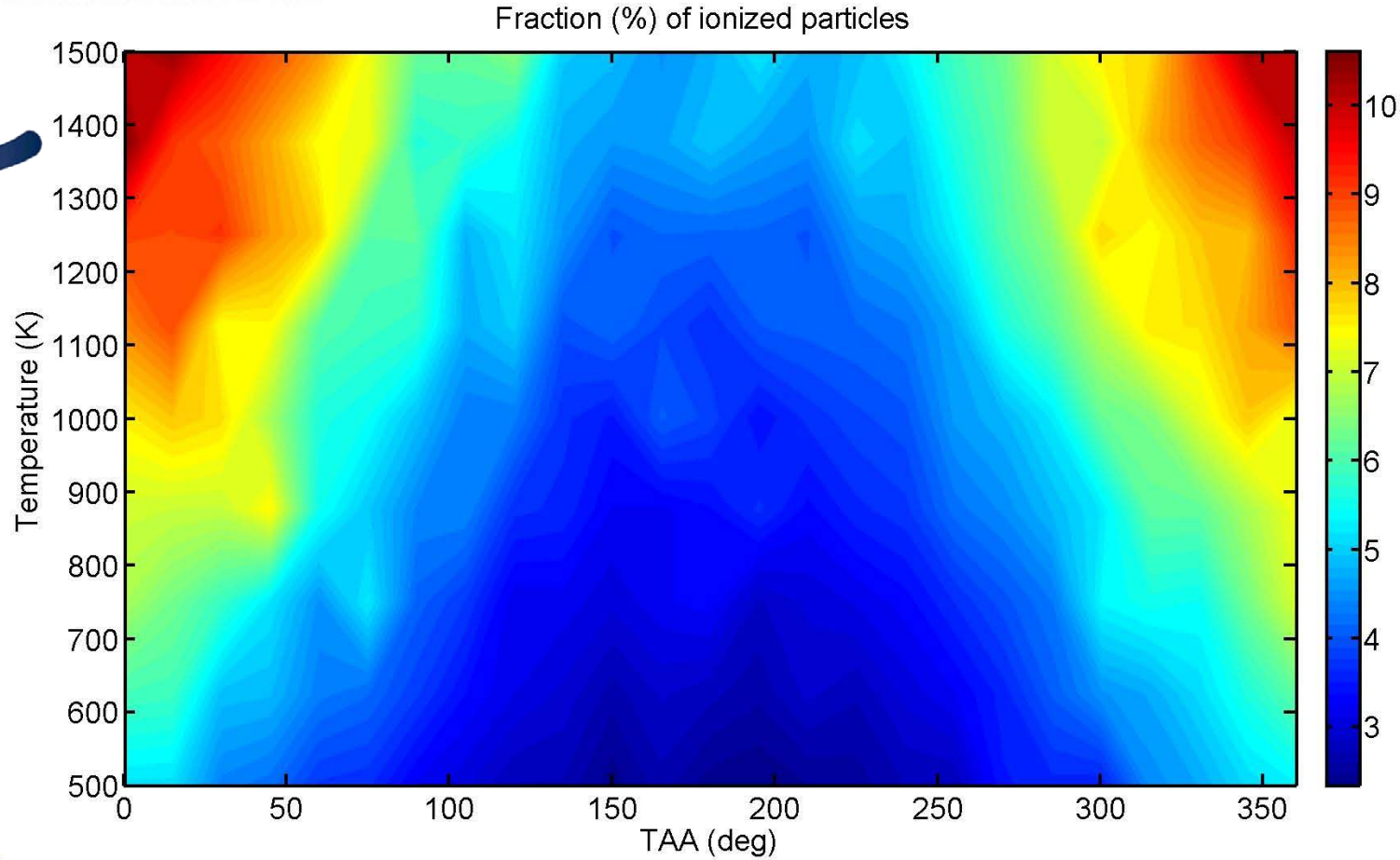
$$p_1 + p_2 \cdot \cos(2\alpha) + p_3 \cdot \cos(\alpha) + p_4 \cdot \cos(\alpha/2)$$

$$p_1 = -1.514 + 0.0024 \cdot T$$
$$p_2 = 2.091 - 0.0029 \cdot T$$
$$p_3 = -0.3567 + 0.00079 \cdot T$$
$$p_4 = -0.1799 + 0.0009 \cdot T$$



$$(0.779 + 0.000313 \cdot T)/R^2$$

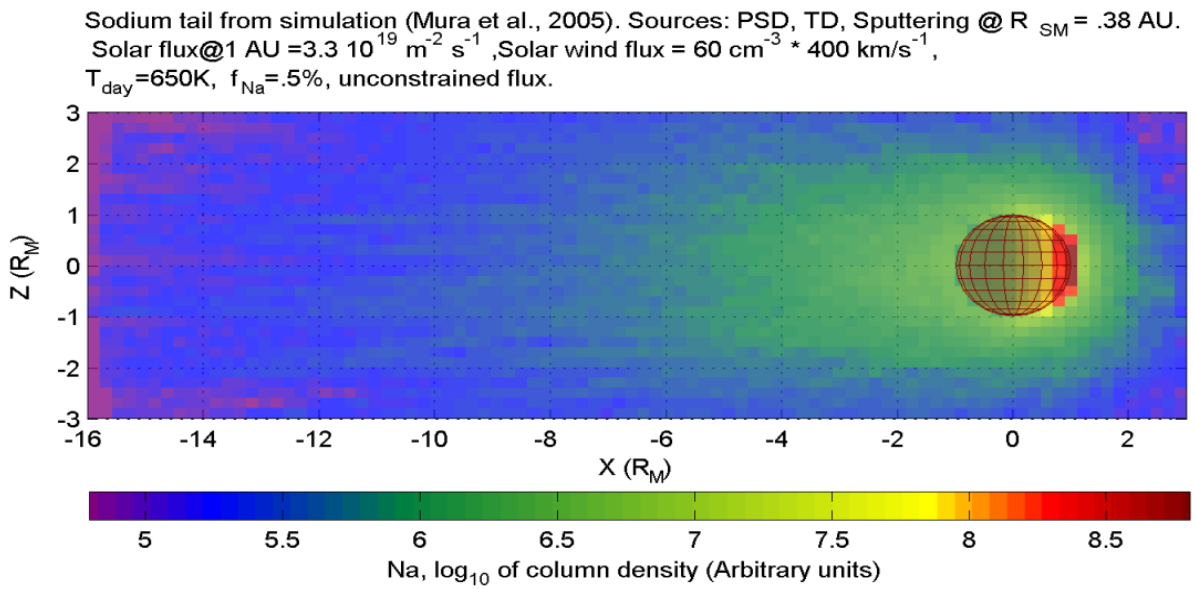
(R in AU)

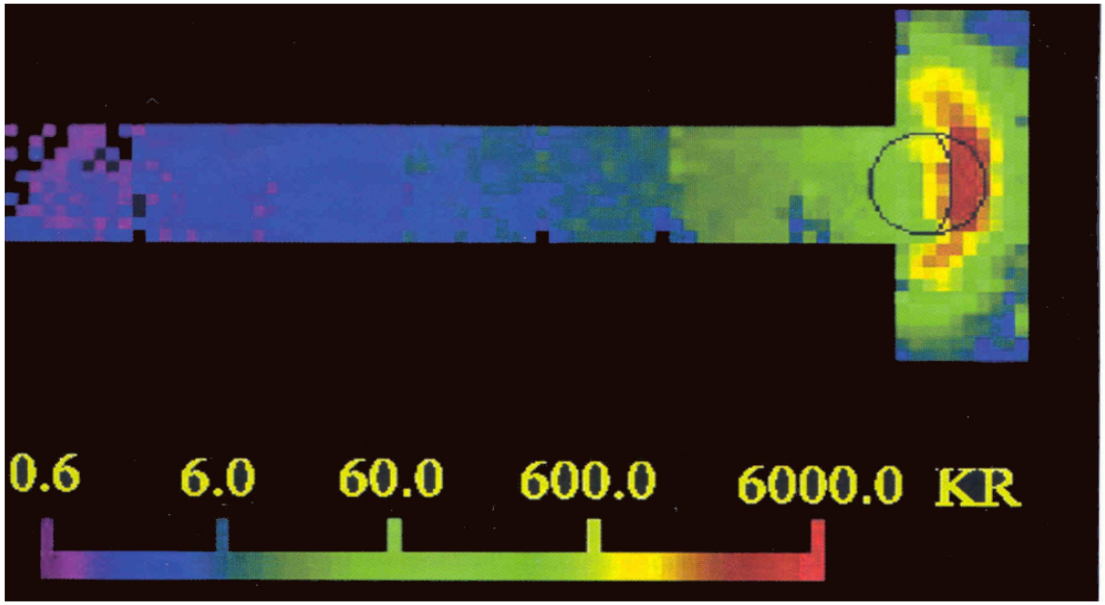


$$(0.23374 + 0.000468 \cdot T)/R^2$$

(R in AU)

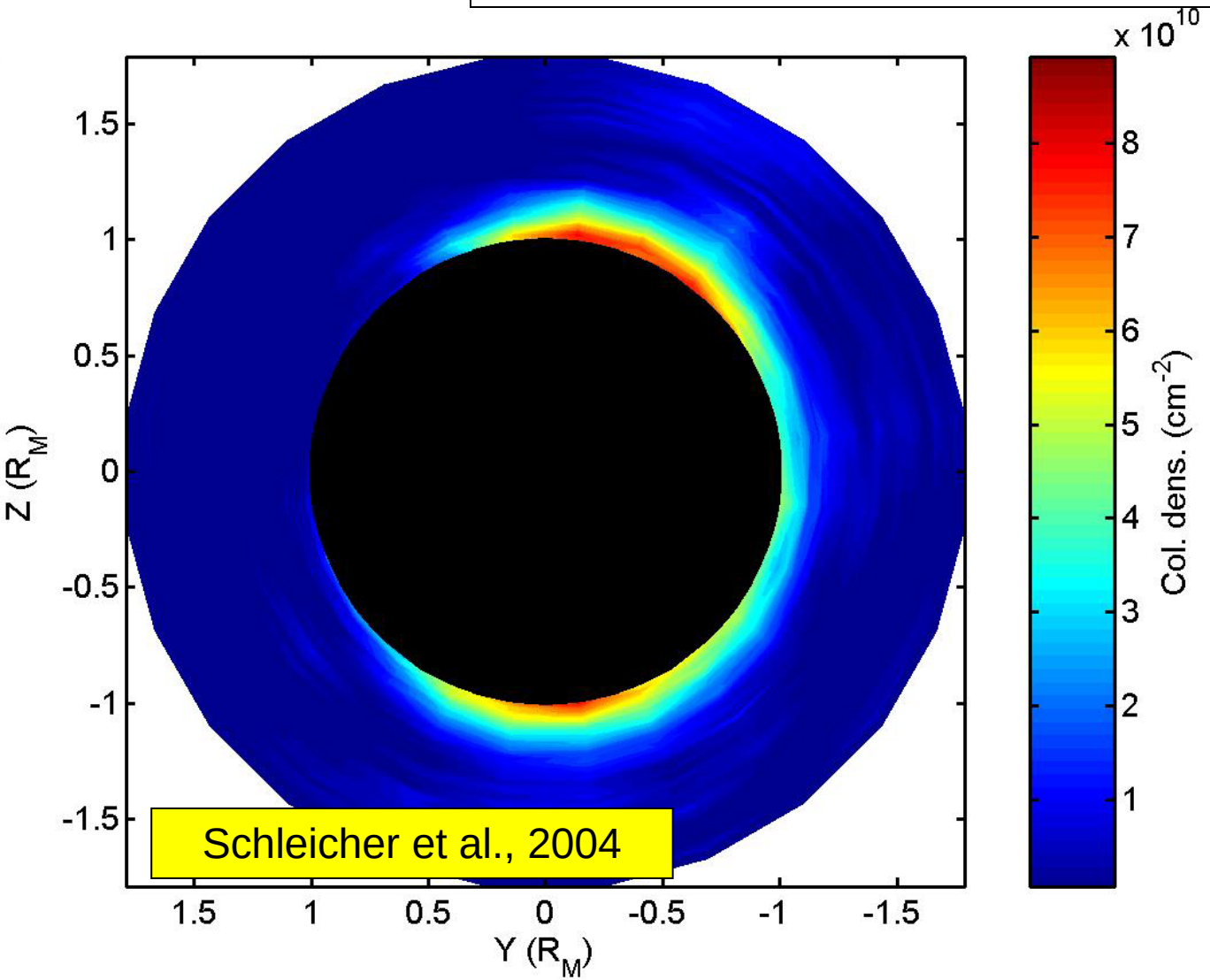
Mercury Sodium Tail





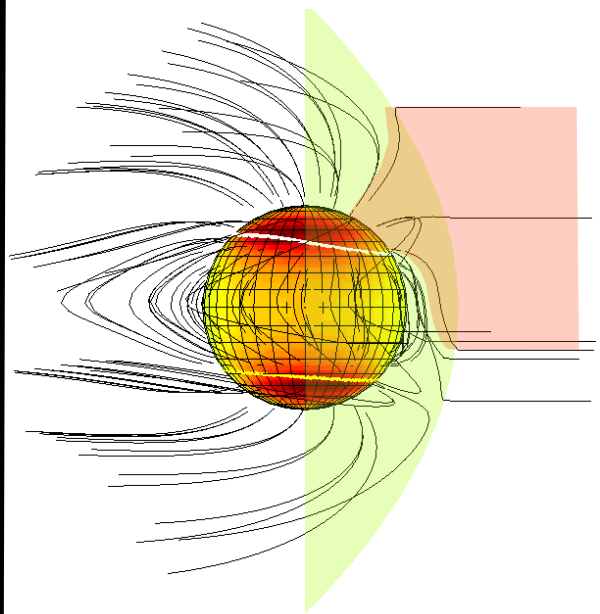
From *Potter et al.*, (2002)

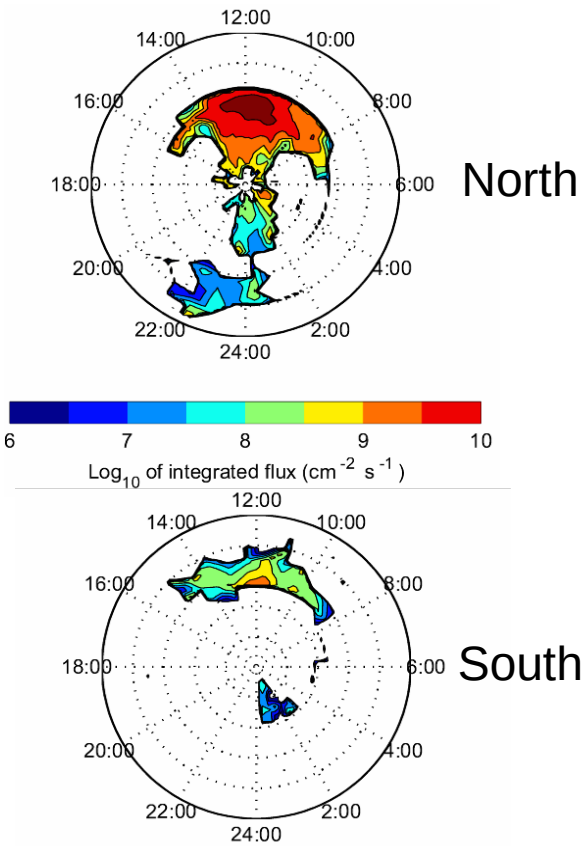
Observations of Mercury's sodium exosphere



Schleicher et al., 2004

- North-south asymmetry: north column density is higher
- Dawn-dusk asymmetry: dawn column density is higher

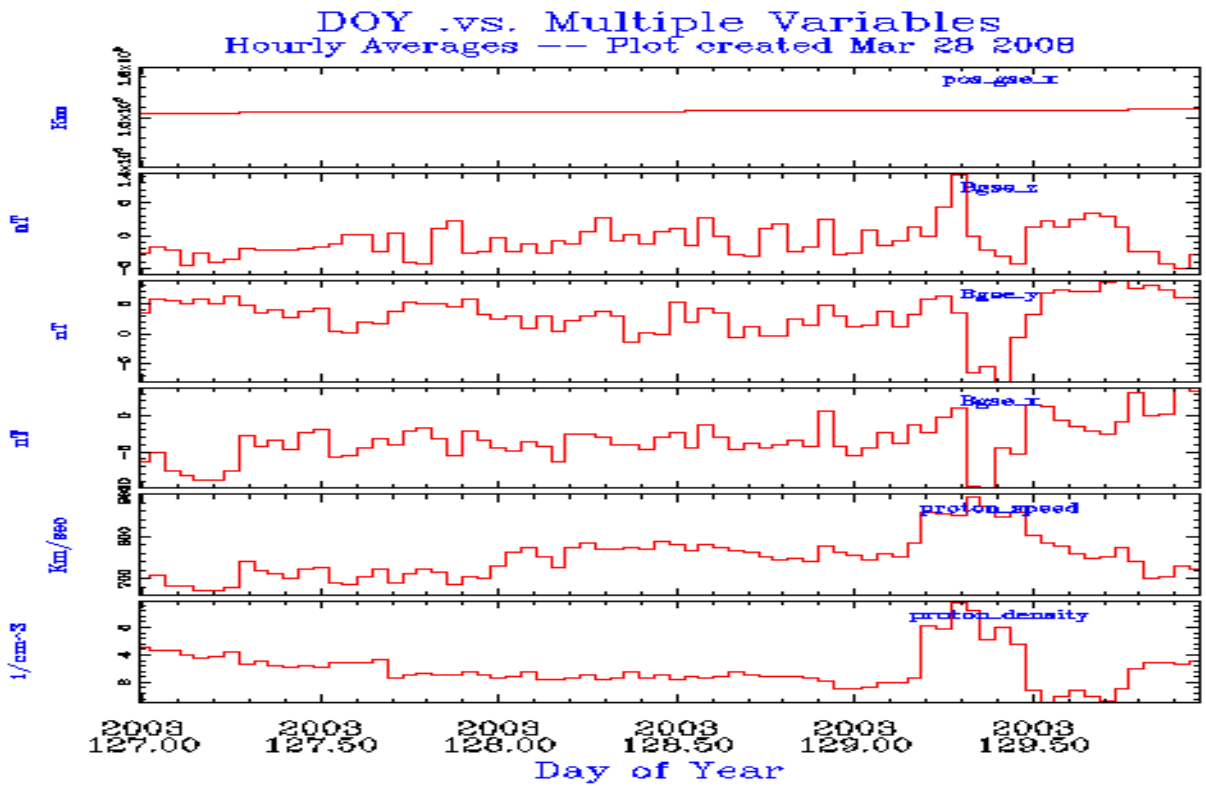




Negative Bx component of IMF causes reconnection in the North Emisphere

Sarantos et al., 2003, Kallio et al, 2003)

Reconnection in the North Emisphere causes higher S/W proton precipitation fluxes



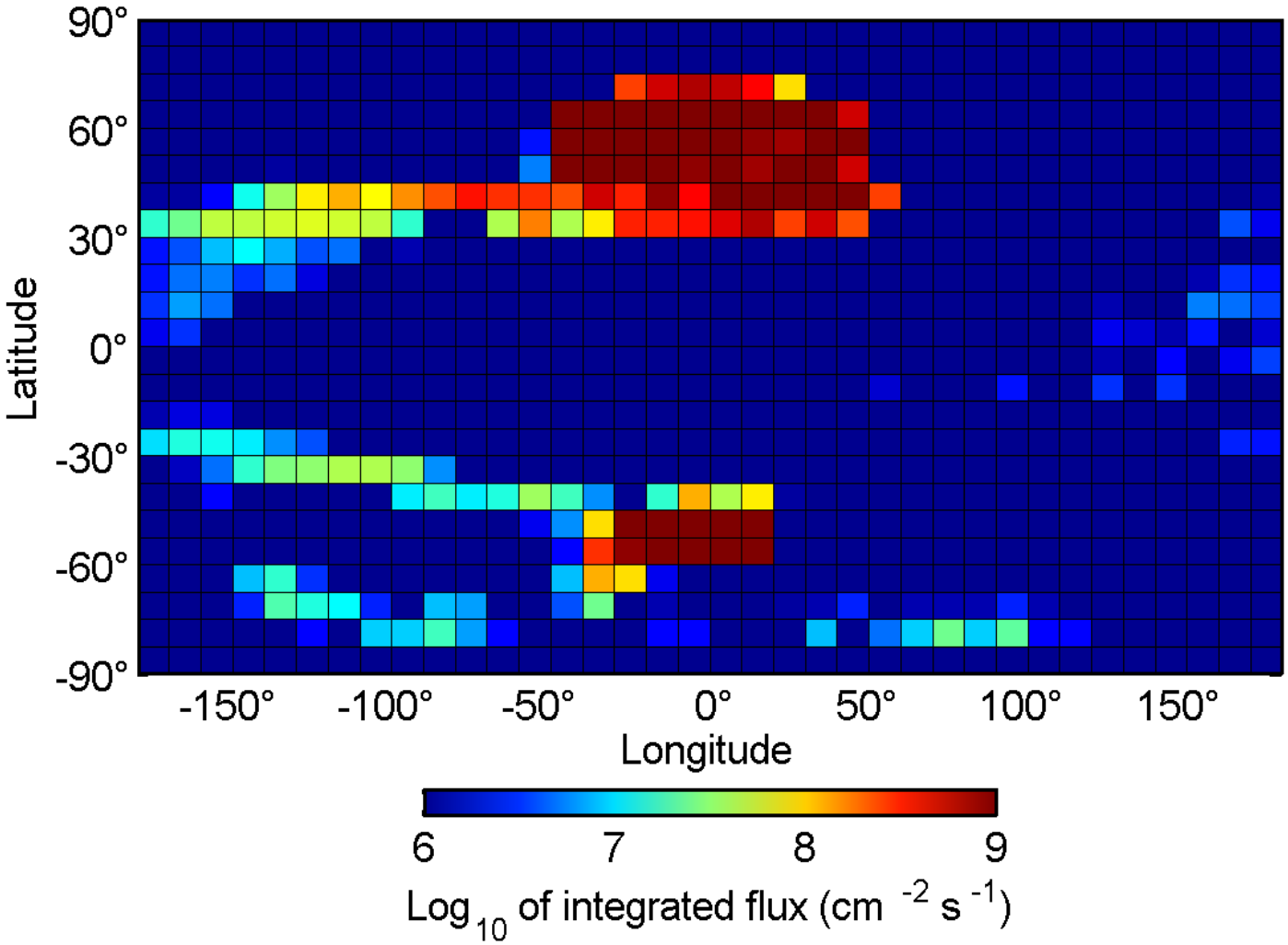
Measured by ACE, during May 7-9, 2003, distance from spacecraft to Earth, components of magnetic field, solar wind proton speed and density

(http://www.srl.caltech.edu/ACE/ASC/level2/index.html).

Anomaly	150°
Distance	0.45 AU
S/W velocity	700 km/s
IMF	-20, 10, -10 nT
Radiation pressure	-60 cm/s^2

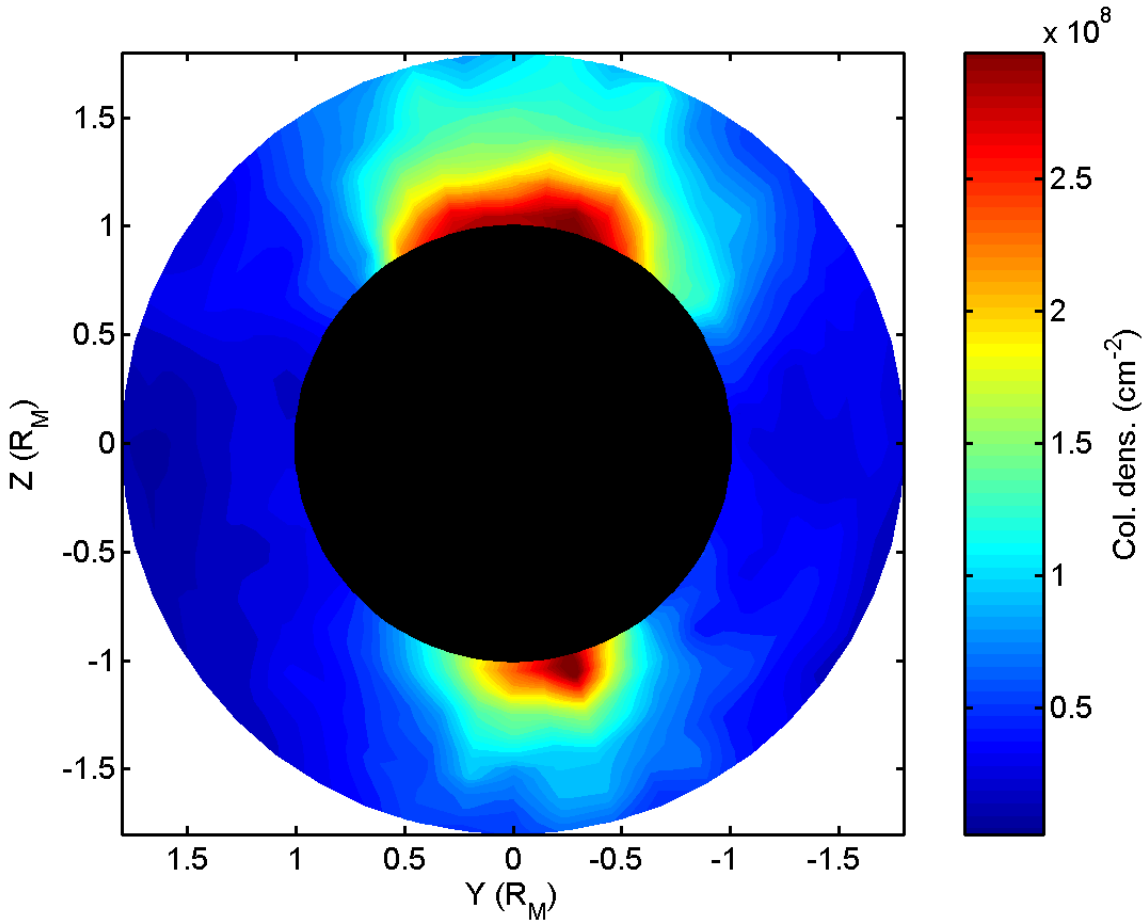
Proton precipitation map

IMF = [-30, 5, -10] nT



- We assumed that IMF-x condition could explain the N/S asymmetry
- We modeled the H+ flux onto the surface with a numerical model

Ion sputtering



The N/S asymmetry is explained but…
Scale high is too large
Column densities are lower by a factor 100
Dawn/dusk asymmetry is not explained

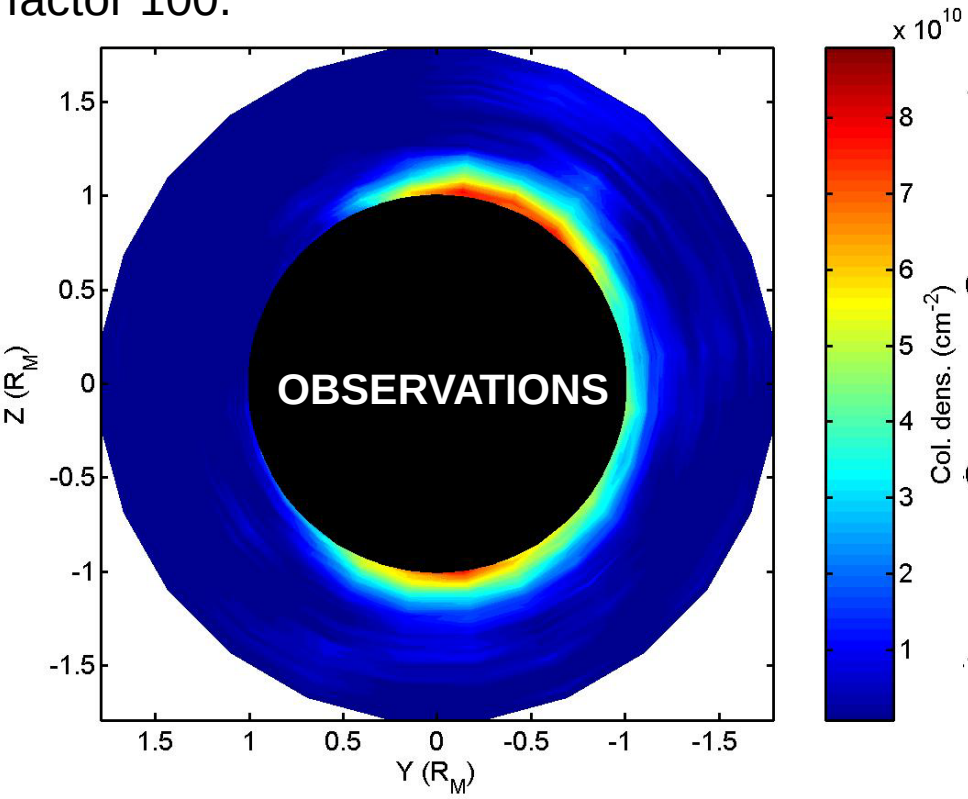
MIV

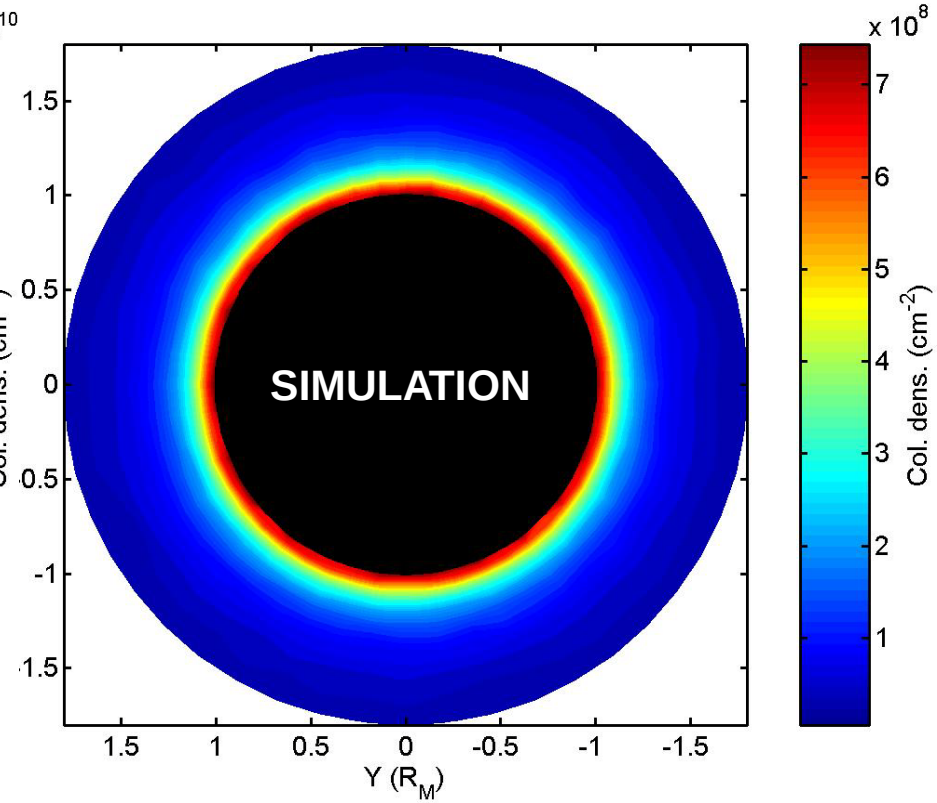
Morgan et al. (1988) reported an average value of 2×10^5 (cm^{-2} s^{-1}) released Na at aphelion, a factor 2 higher than the value reported by Cintala (1992)

The first value is a factor 100 lower than our averaged PSD flux.

We assume that the ejecta have a thermal velocity distribution at about 2500 K (Killen et al., 2007)

The simulated tangential column densities are lower than the observed ones by a factor 100.





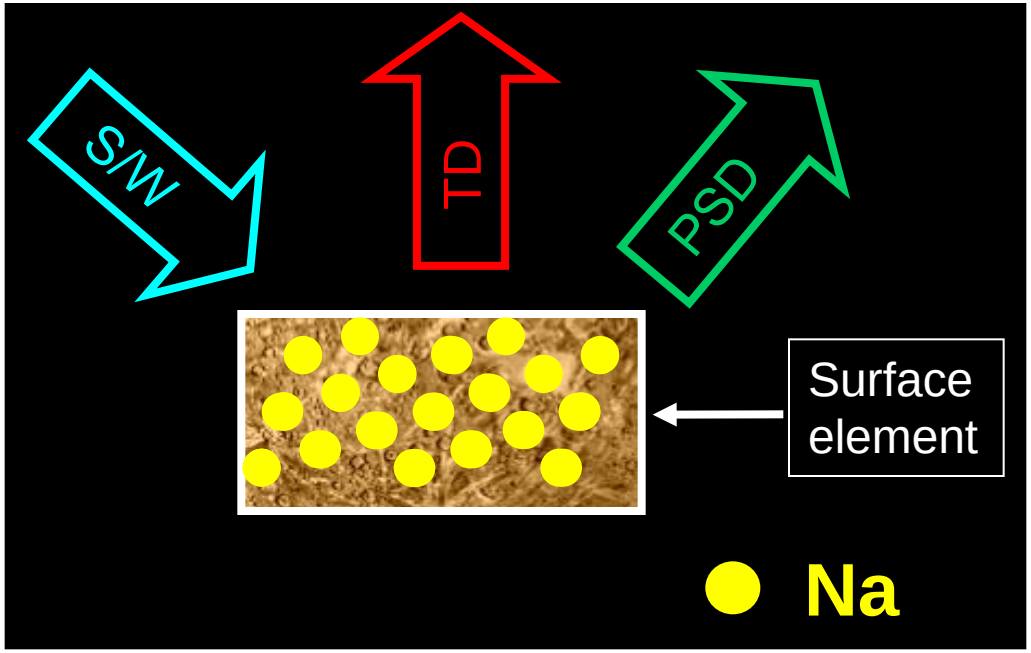
Production of sodium and water by proton sputtering of sodium-bearing silicates was considered by the chemical sputtering mechanism

Potter, 1995

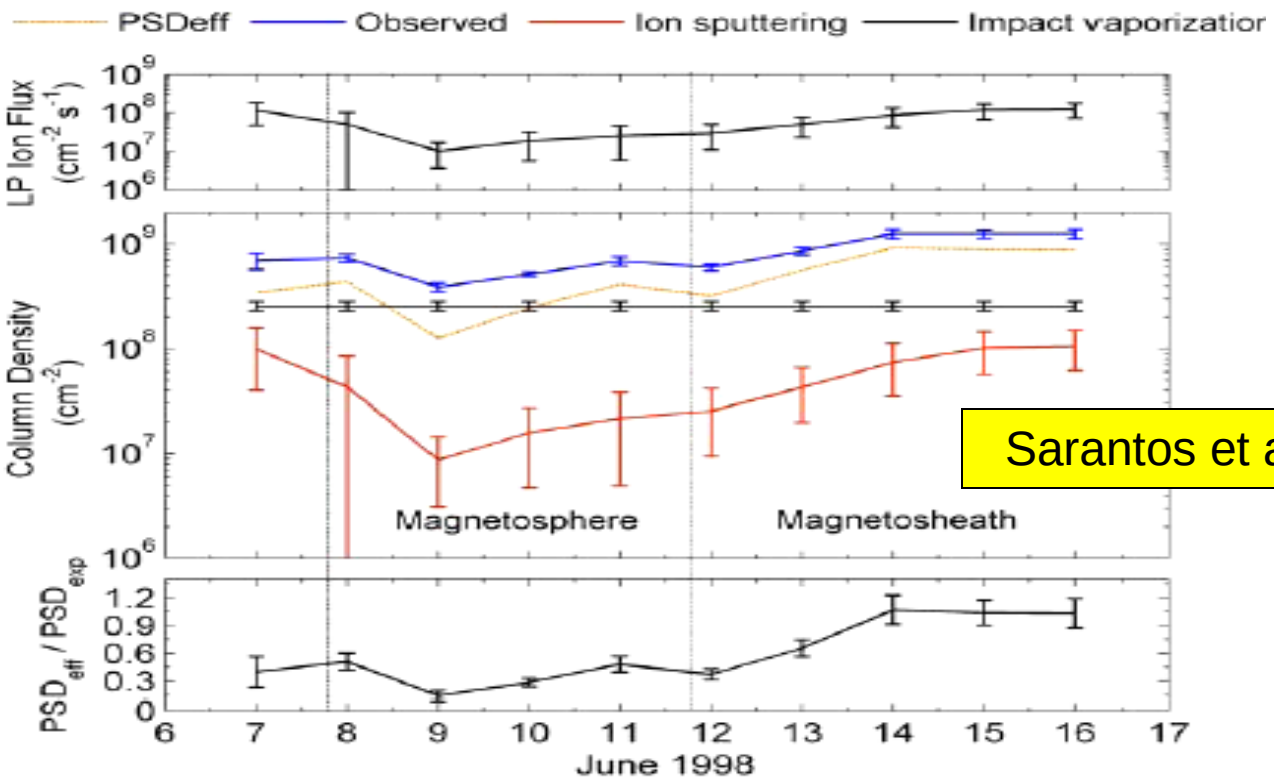
$$2H + Na_2SiO_3 \rightarrow 2Na + SiO_2 + H_2O$$

1) Thermal desorption and PSD deplete Na contents

2) S/W causes chemical alteration of the surface, freeing the Na atoms from bounds in the crystalline structure on the surface



Enhanced diffusion due to proton precipitation

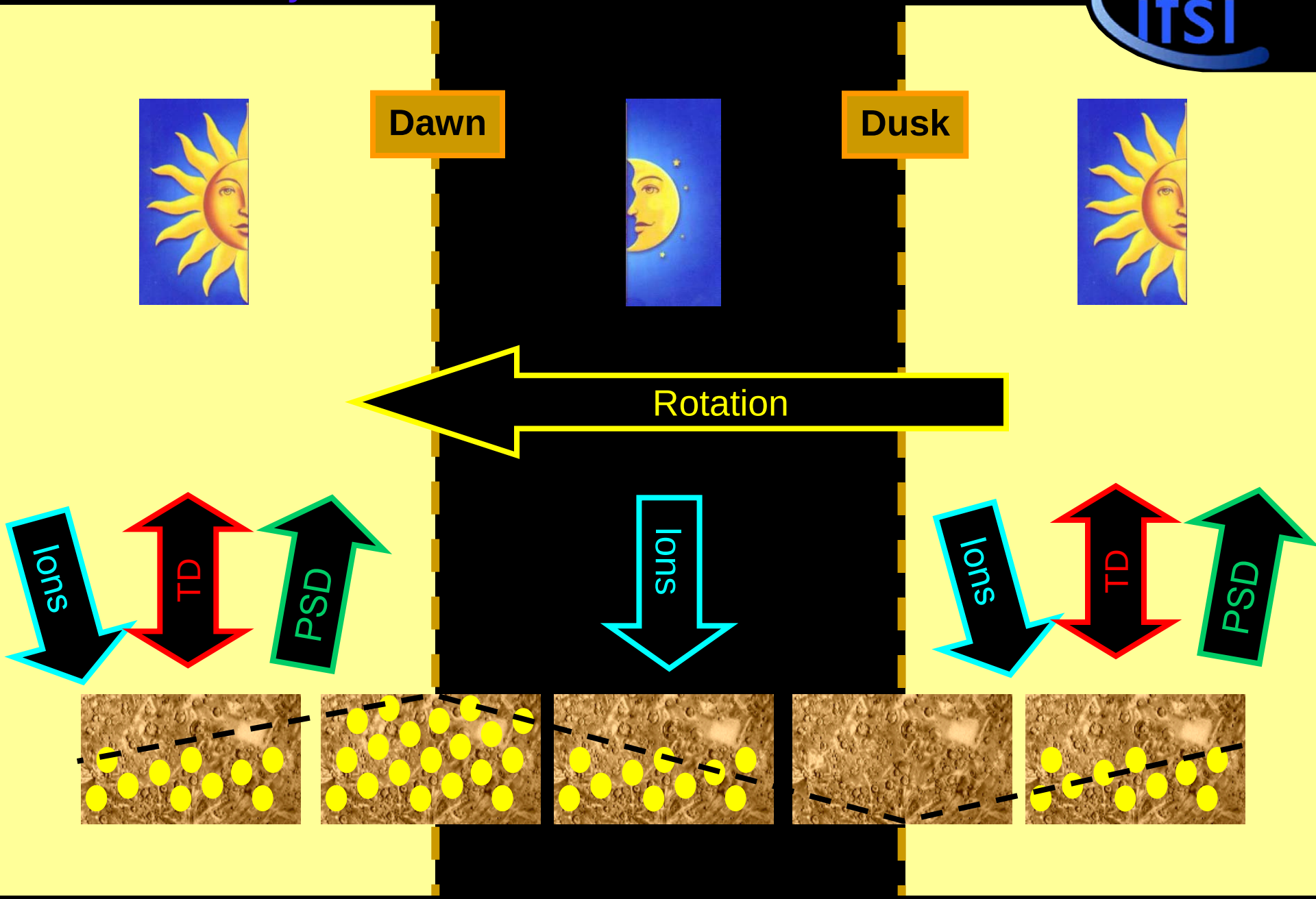


Sarantos et al., 2008

- Proton precipitation can also enhance the diffusion of Na atoms inside surface grains
- The effect due to precipitation is able to enhance the diffusion-limited PSD by a factor 2

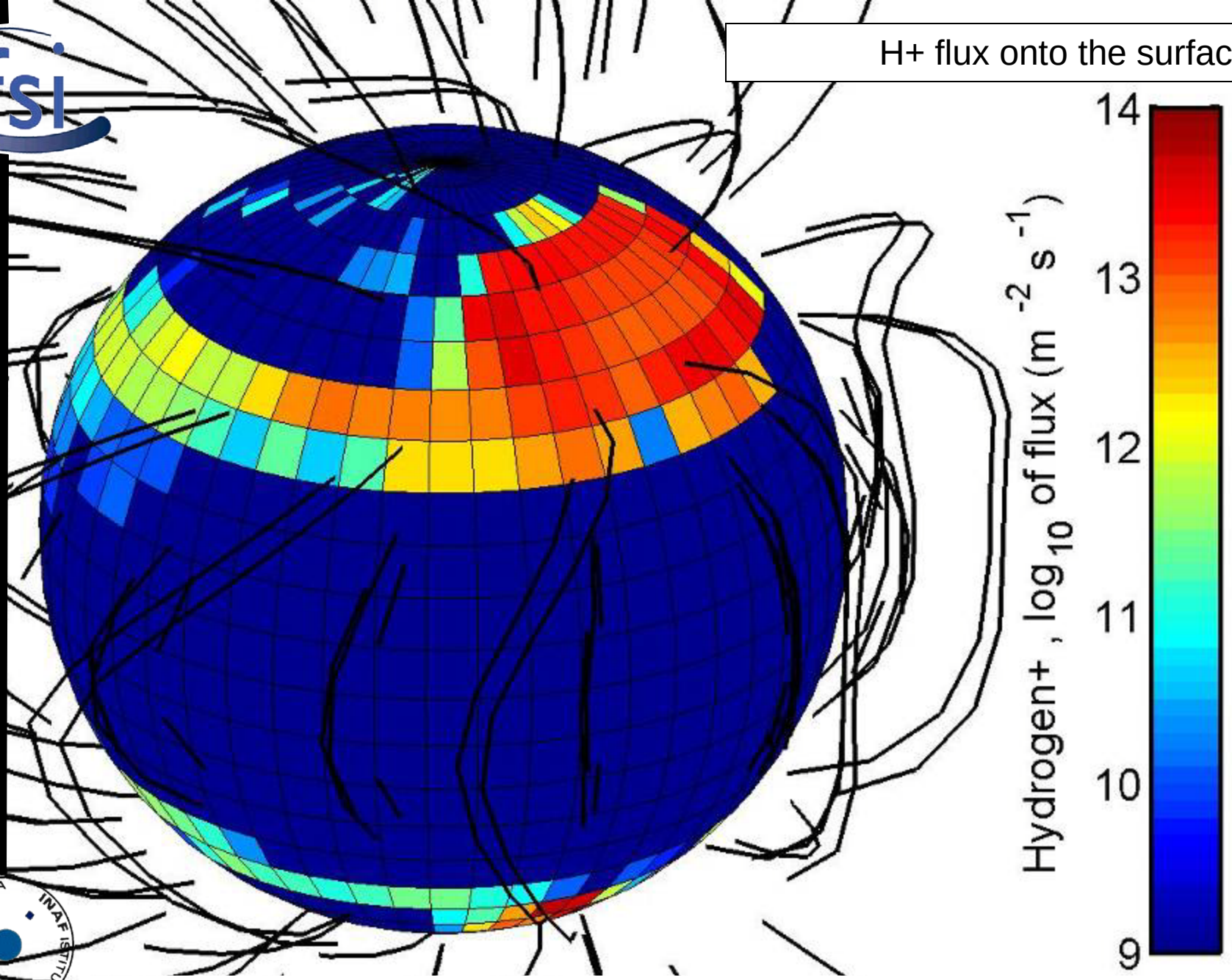
$$\Phi_{Na} = \varepsilon \ \Phi_{+} + \Phi_{diff}$$

Sodium variability



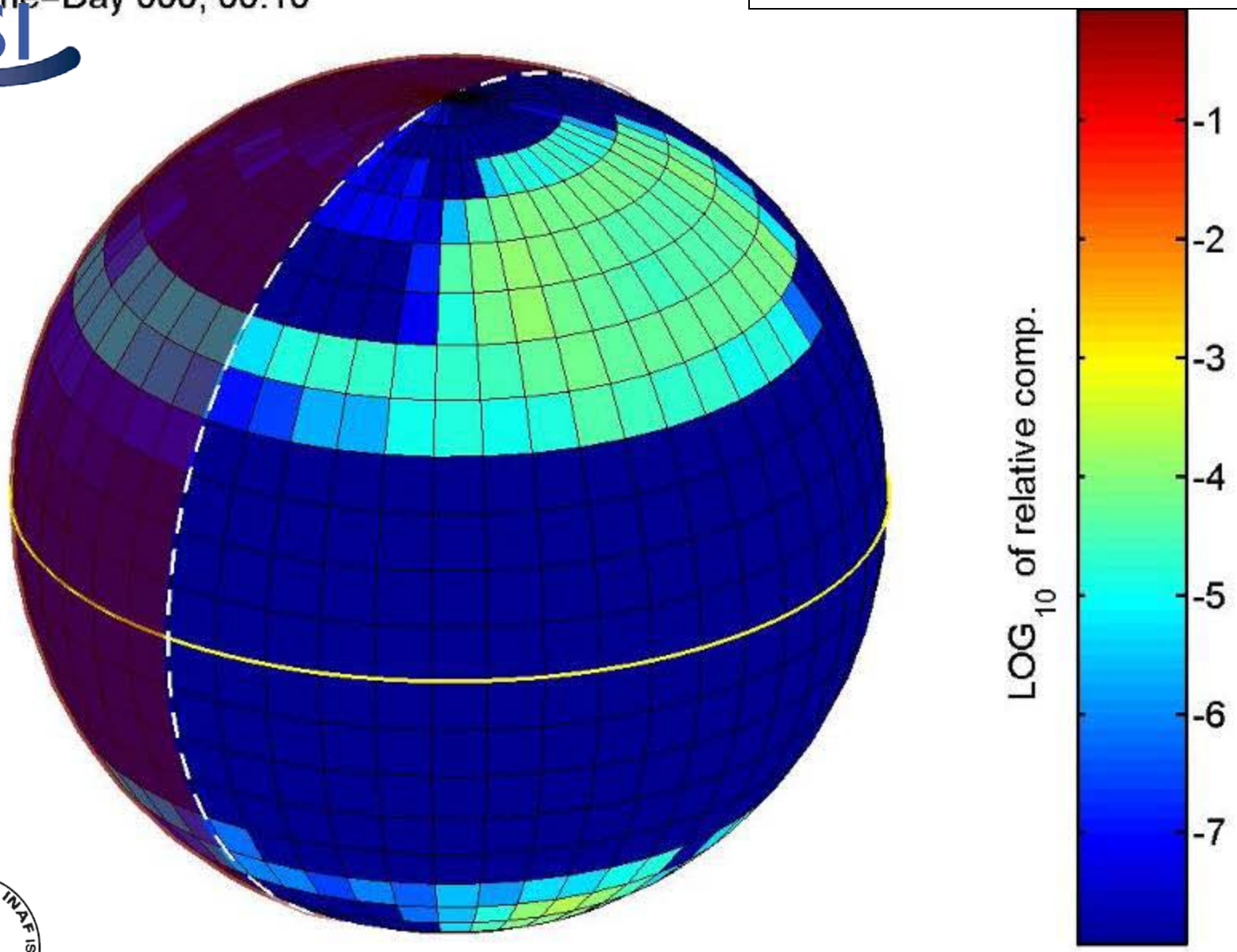
Magnetic field

H+ flux onto the surface



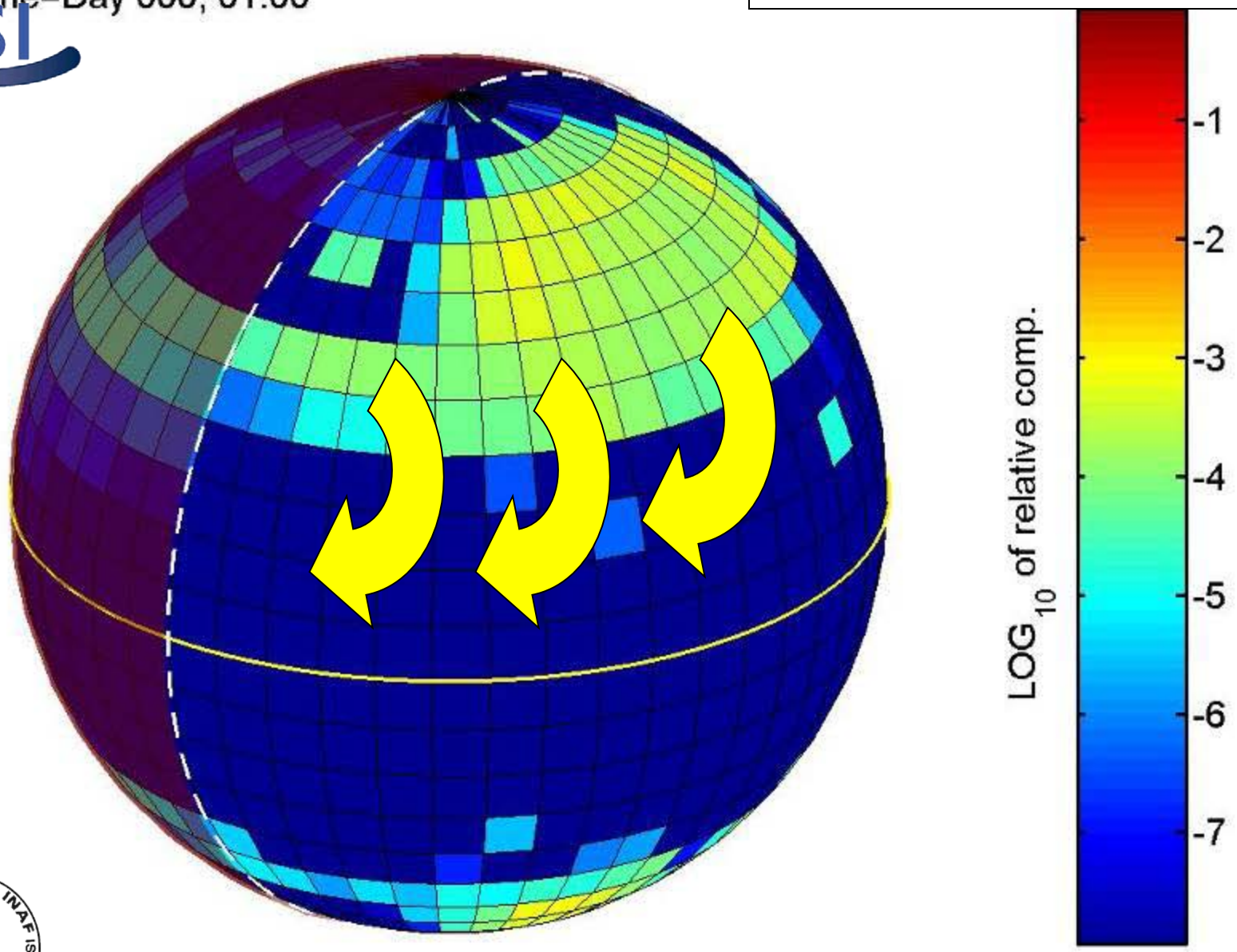
H+ precipitate in the open field-line regions (cusps) and in the nightside

Chemical Sputtering



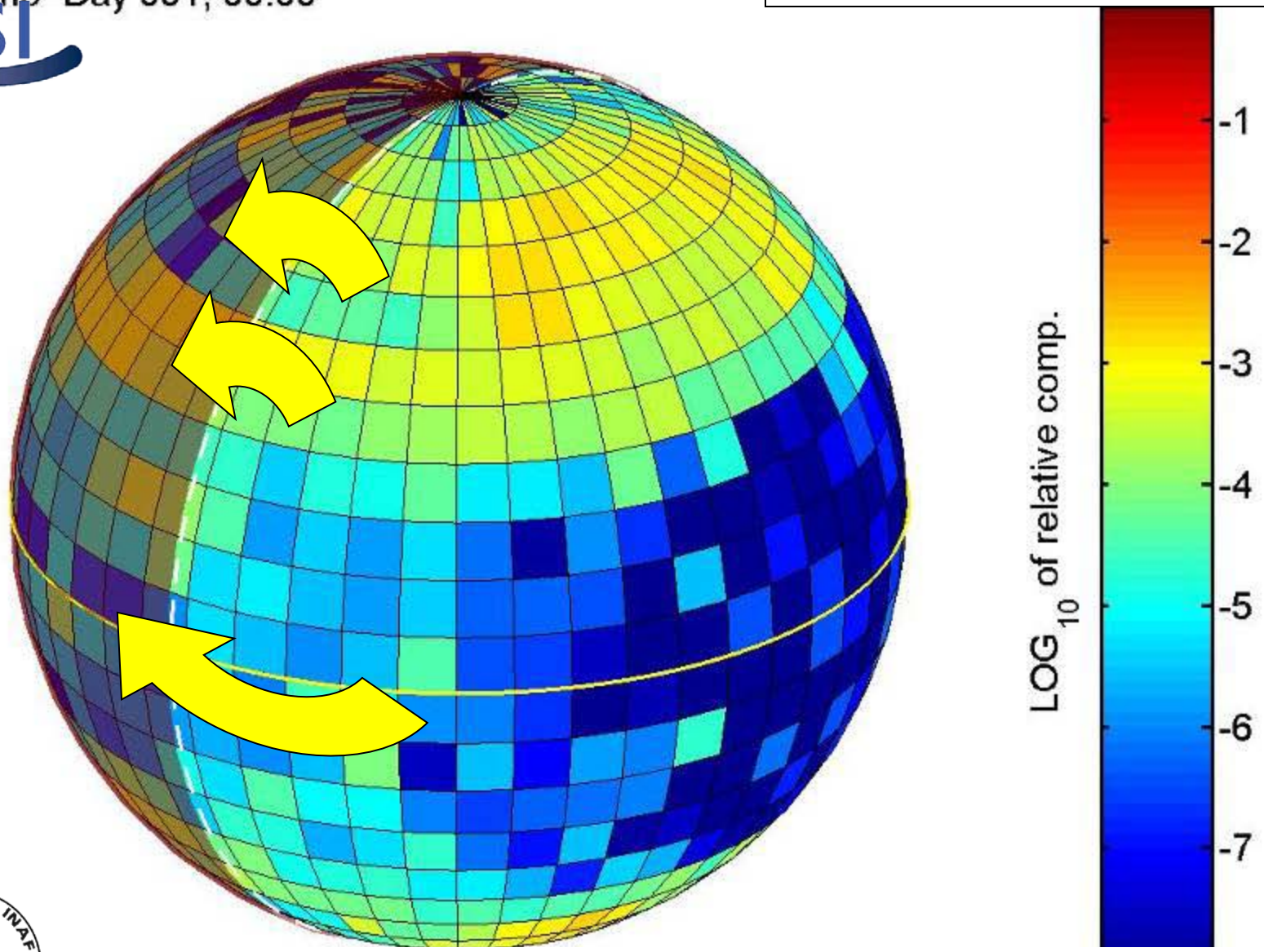
Starting from a Na-poor surface, H+ flux enriches the Na surf. abundance

Na migration



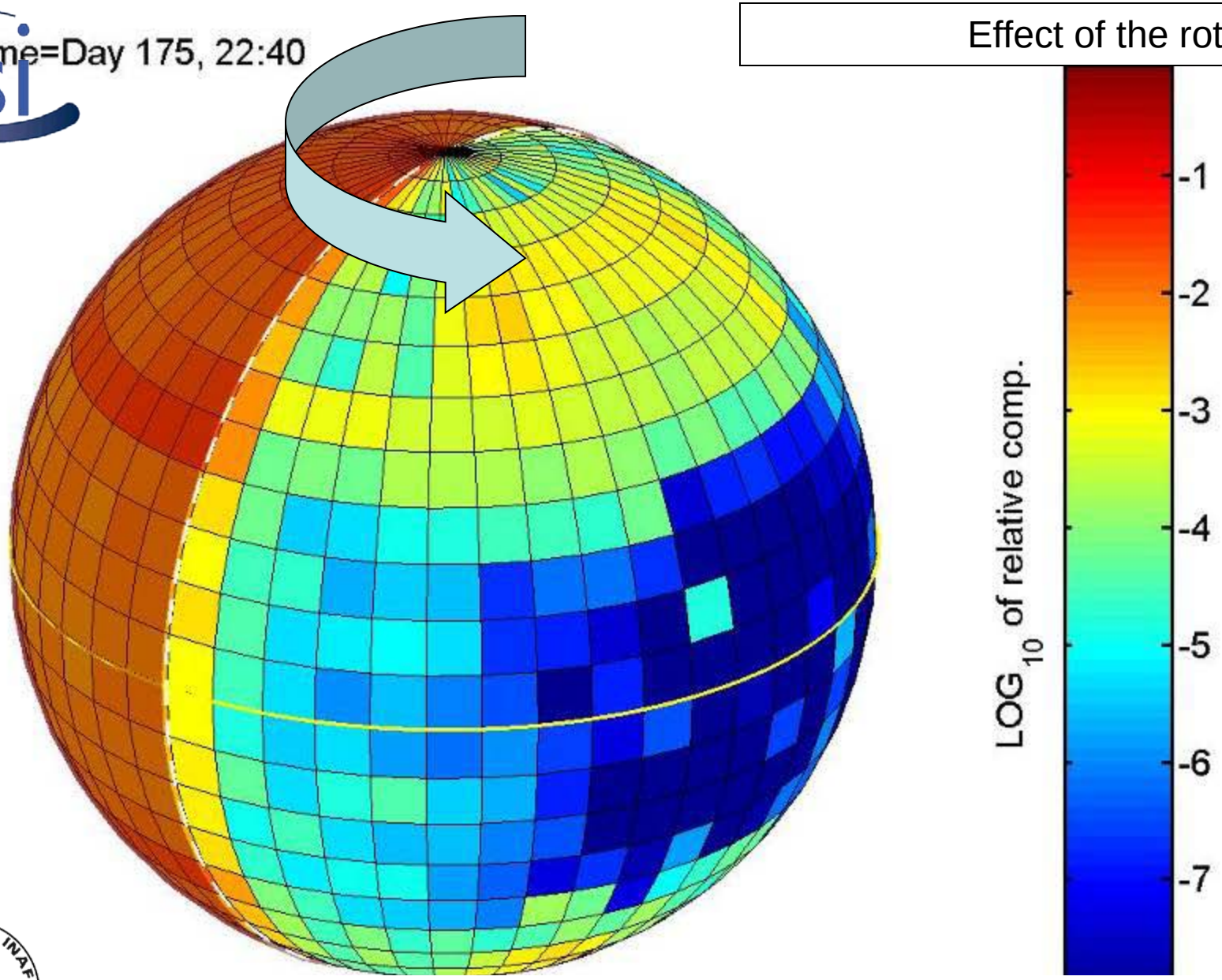
PSD and TD release Na particles that migrate (ballistic traj.) to a larger area

Na migration



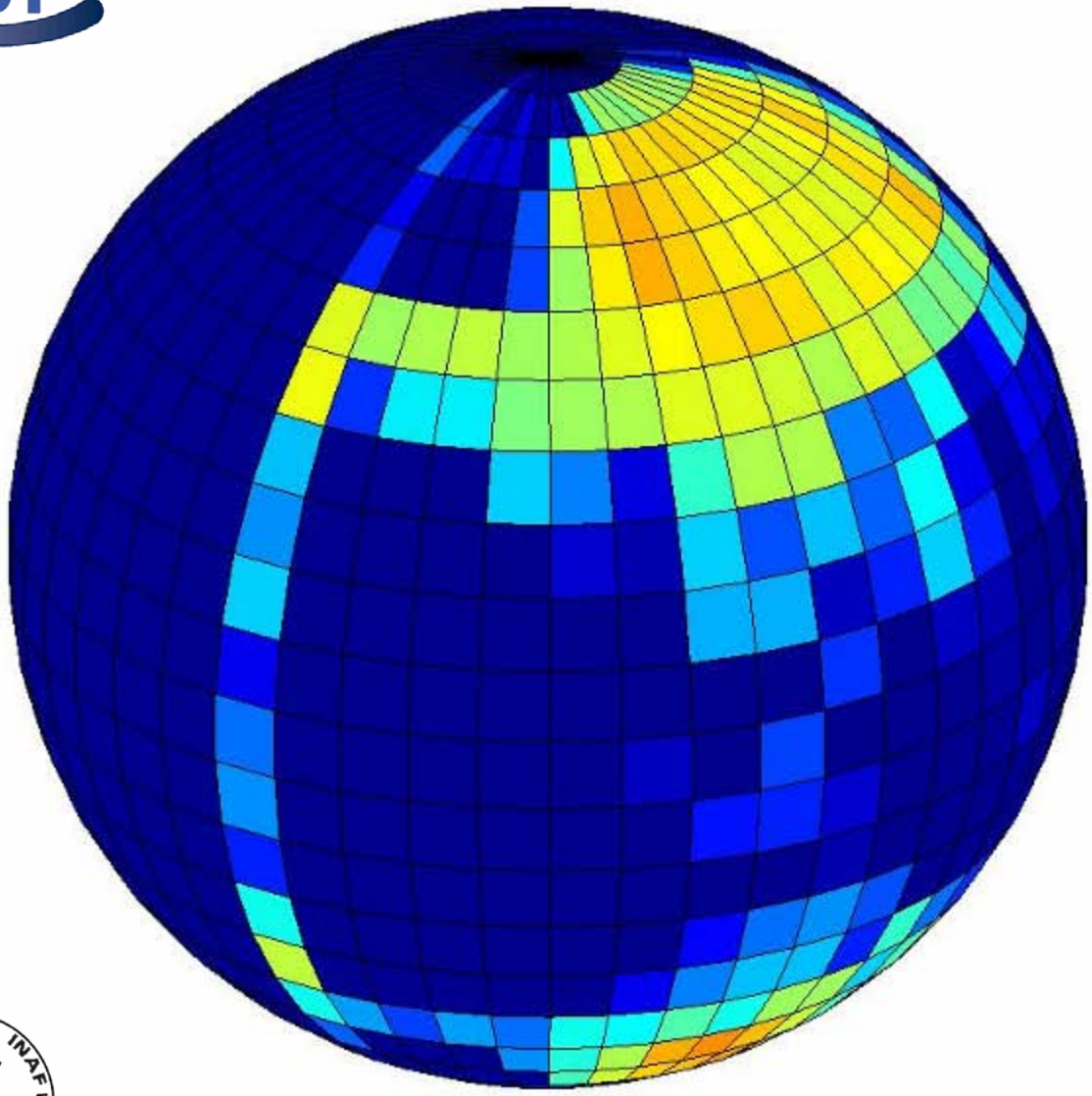
- Na abundance is lower where PSD anb TD processes are more effective
- The Na abundance in the night side is enhanced

Effect of the rotation

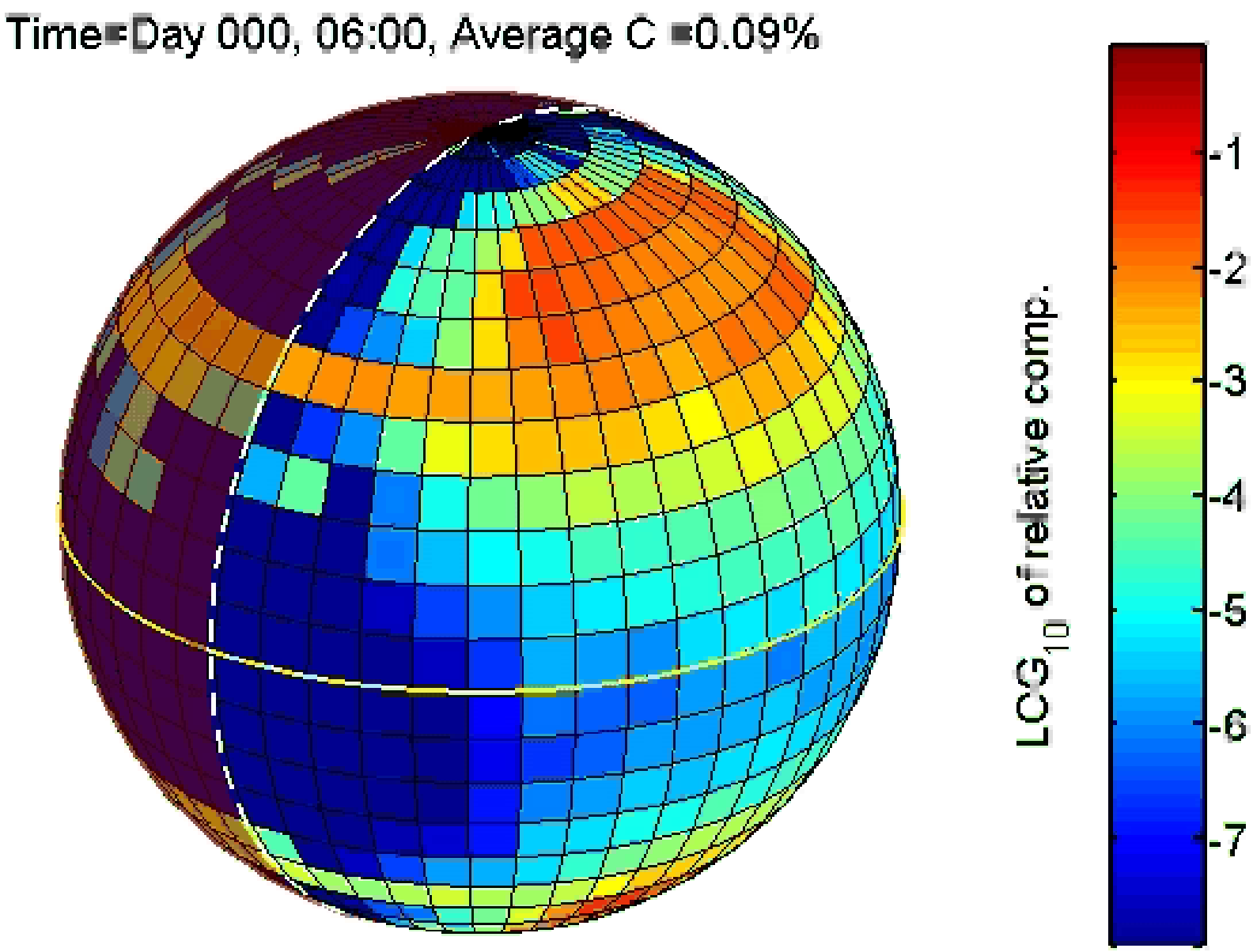


•As soon as the rotation brings a surface element to the dayside, PSD and TD deplete the Na abundance again

PSD flux from the surface

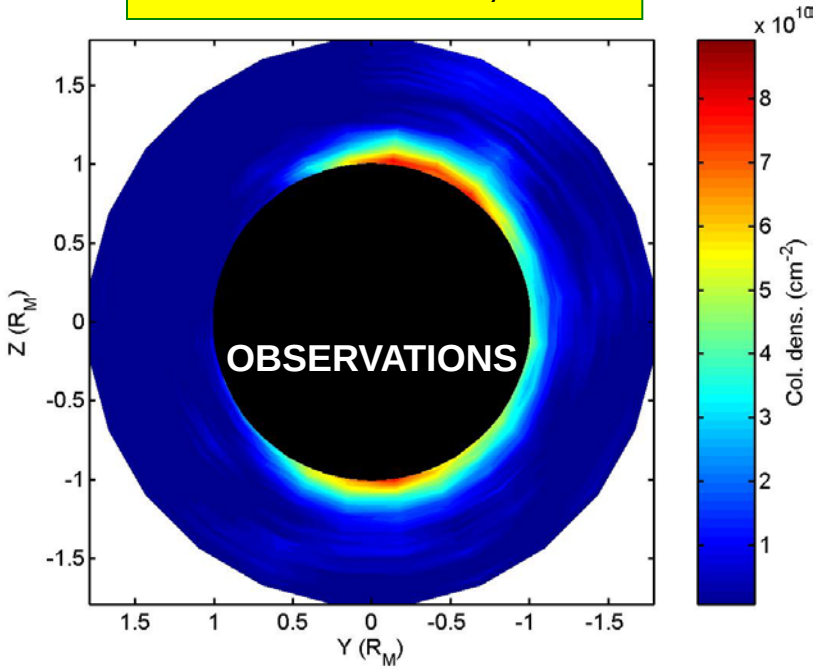


At the equilibrium, the Na flux from the surface is similar to the H+ one, but broadened and with a “dawn” feature

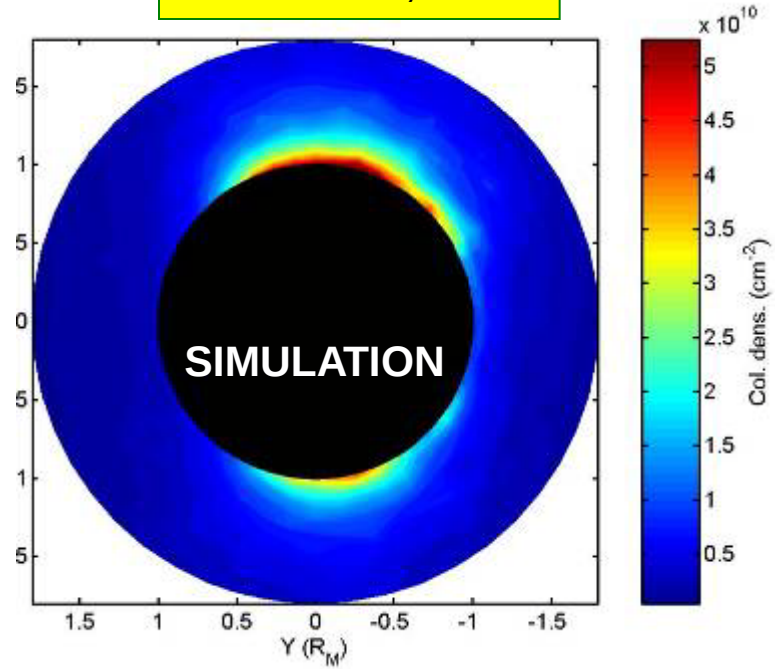

Time=Day 000, 06:00, Average C =0.09%
LCG10 of relative comp.
-1
-2
-3
-4
-5
-6
-7

Comparison between data and simulation

Schleicher et al., 2004



Mura et al., 2008

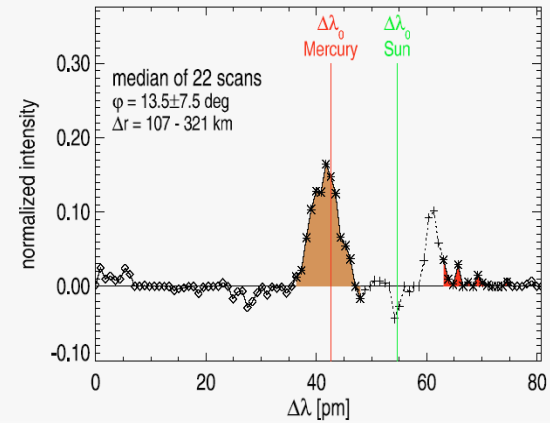


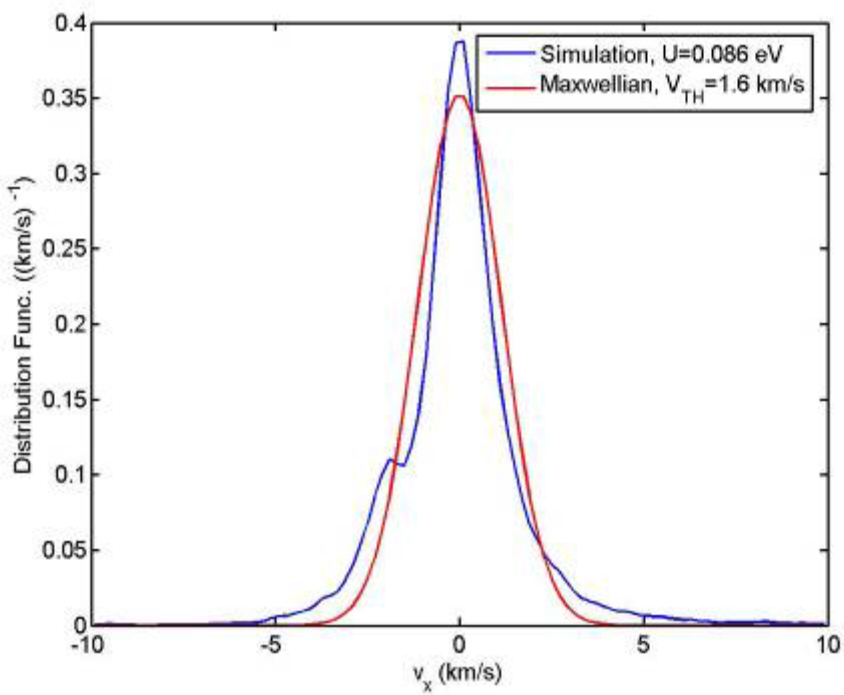
Parameter	Data	Simulation
Density (max)	2500 cm^{-3}	1000 cm^{-3}
Column dens. (max)	$7 \cdot 10^{10}$ cm^{-2}	$5 \cdot 10^{10}$ cm^{-2}
Total amount	$4 \cdot 10^{27}$	$5 \cdot 10^{27}$ (*)
Scale height	200÷500 km	~1000 km
parallel doppler width	1.6 km/s	1.4 km/s

- The model reproduces well all asymmetry features
- The model reproduces well column density (within a 50% error)

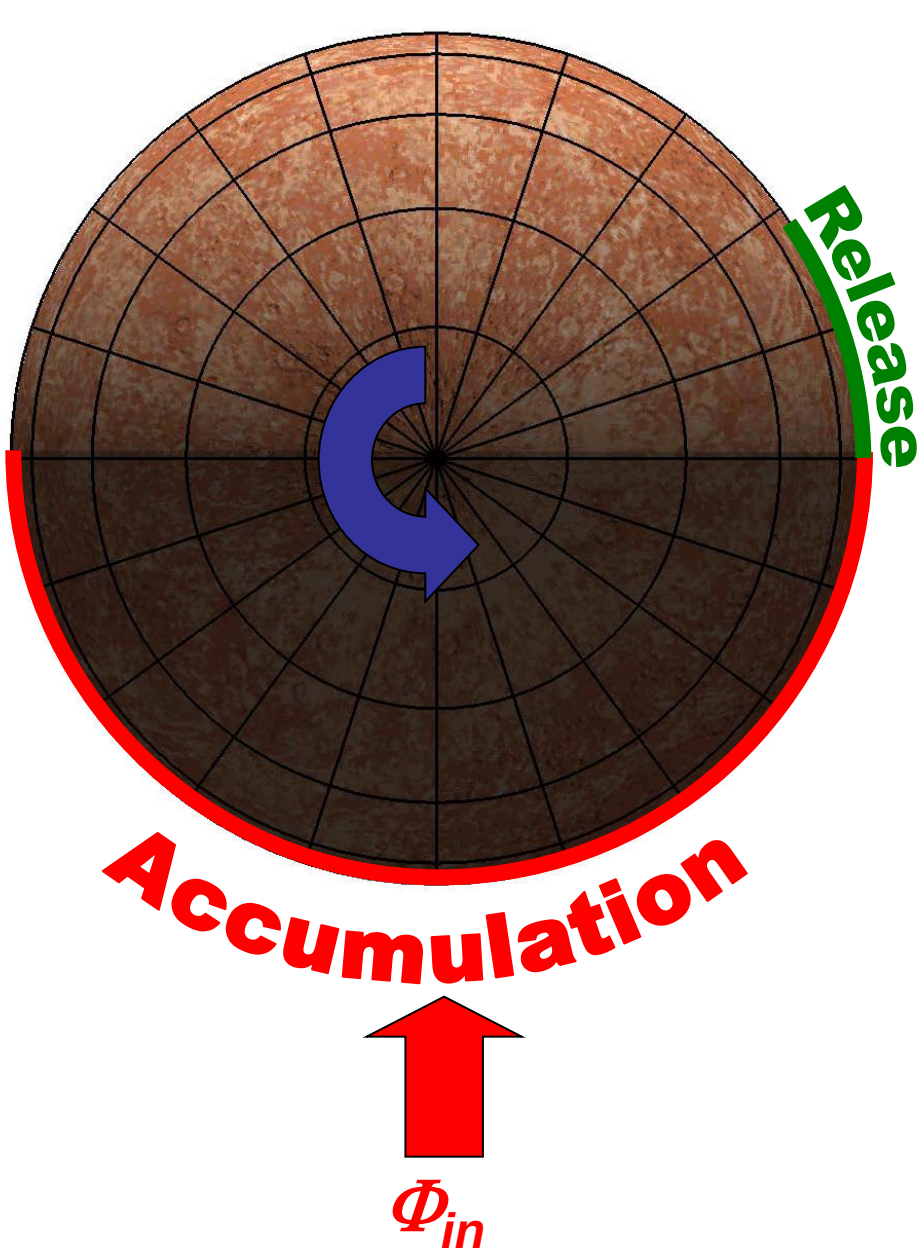
6. The wavelength dependence of the excess absorption (see Fig. 3) can be approximated by a Gaussian profile $\sim\exp(-(\Delta\lambda/\Delta\lambda_D)^2)$ with $\Delta\lambda_D = 3.3$ pm. Taking into account the spectral resolution of the spectrograph, the intrinsic Doppler width is 3.1 ± 0.1 pm, corresponding to a velocity distribution along the line-of-sight of 1.6 ± 0.1 km s^{-1}. No significant spatial variation of the line widths is found.

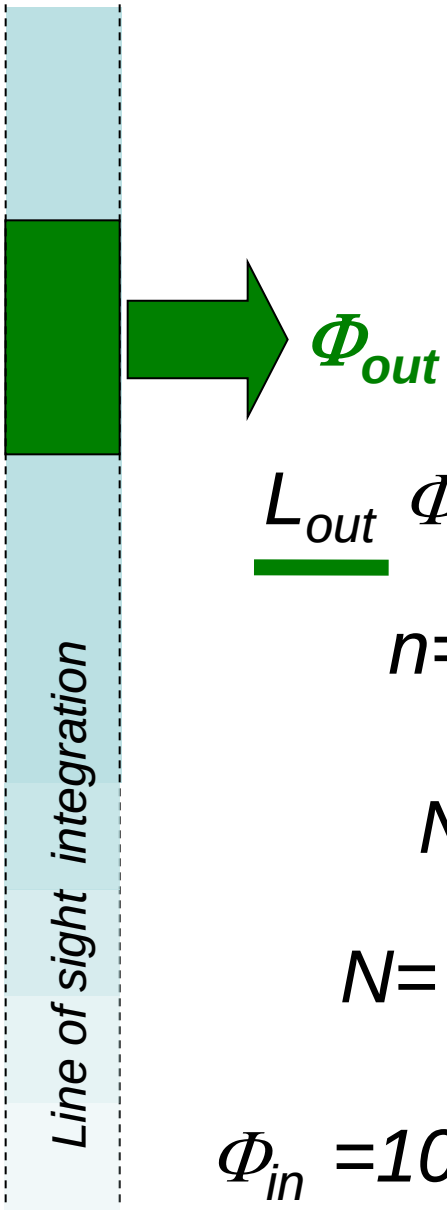
From Schleicher *et al.*, 2004





Parallel (*x*) velocity distribution of the simulated particles (blue line). The simulated data can be fitted by using a gaussian function: $\sim\exp(-v^2/v_{th}^2)$, with v_{th} = 1.4 km/s. The observed velocity distribution can be reproduced by a gaussian function with with v_{th} = 1.4 km/s (in red).





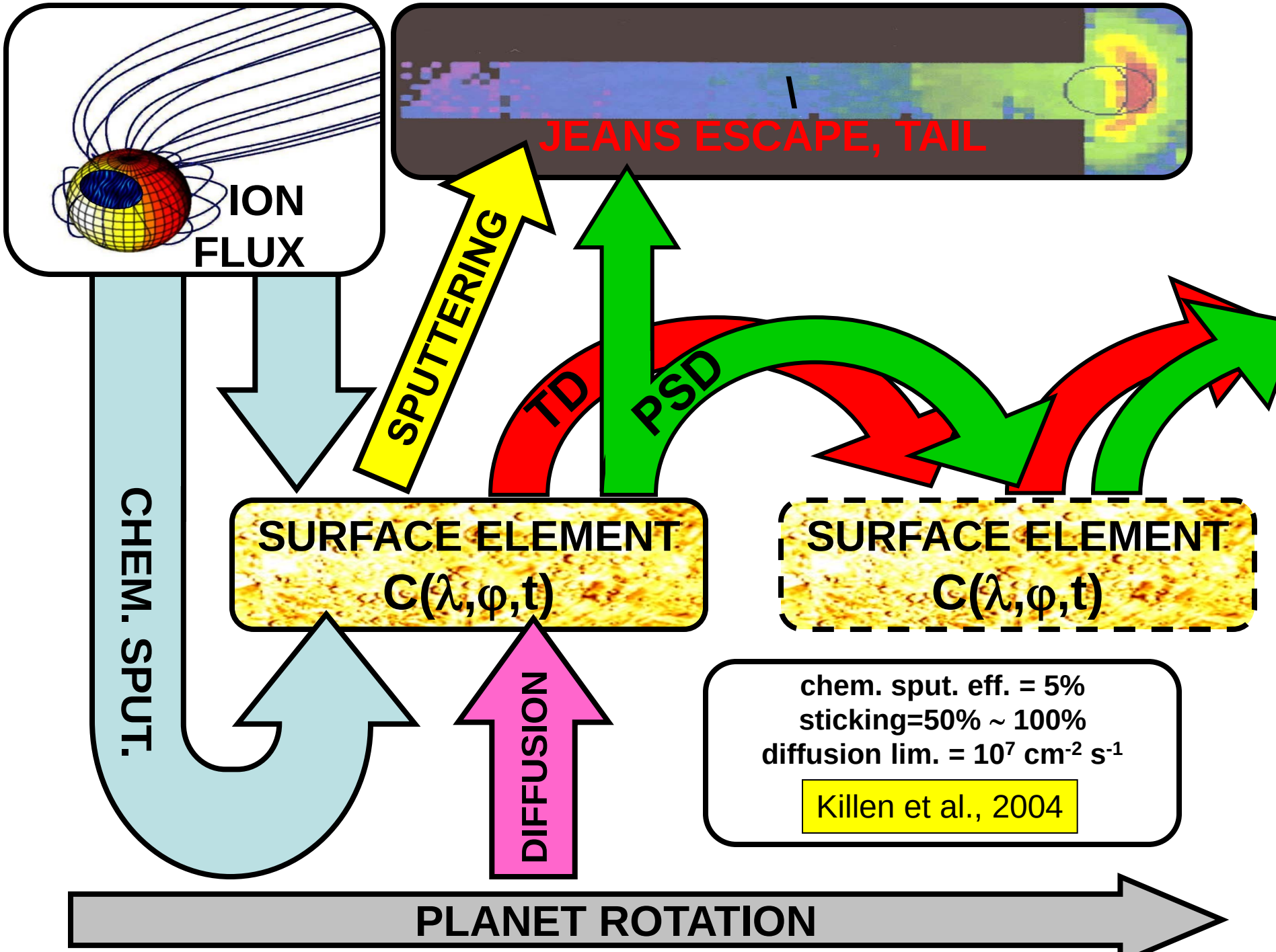
$$L_{out}\ \Phi_{out} = L_{in}\ \Phi_{in}$$

$$n = \Phi_{out} / v$$

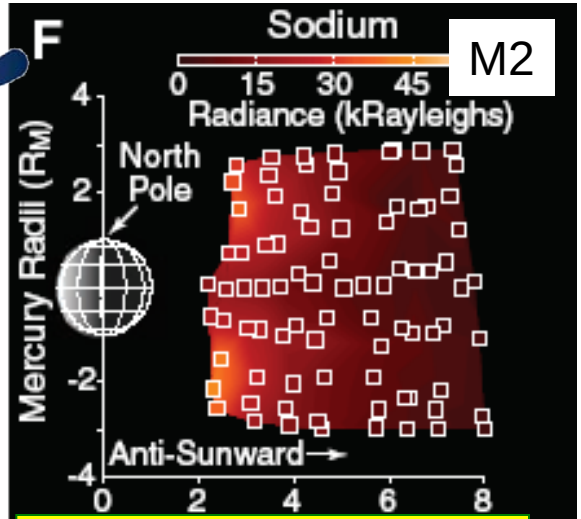
$$N = n\ L_{out}$$

$$N = \Phi_{in}\ L_{in} / v$$

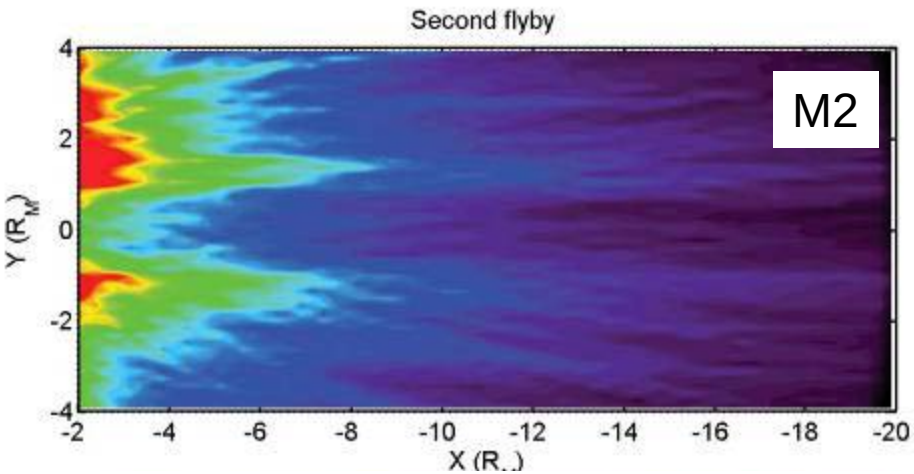
$$\Phi_{in} = 10^{6} \sim 10^{7}\ cm^{-2}\ s^{-1}$$

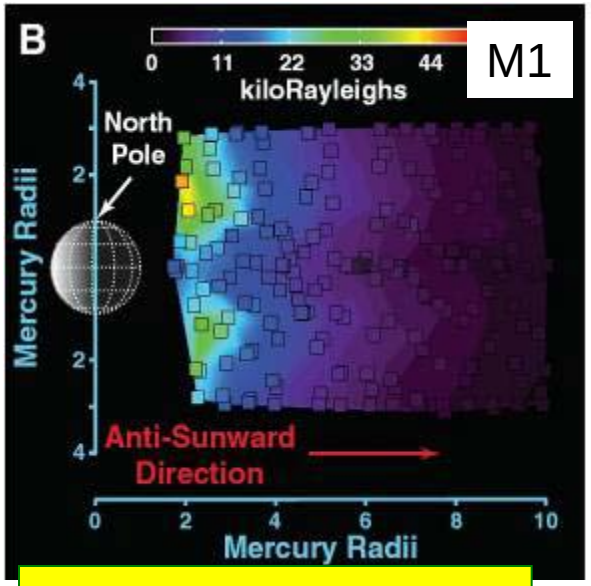

ION
FLUX
JEANS ESCAPE, TAIL
SPUTTERING
TD
PSD
CHEM. SPUT.
SURFACE ELEMENT
C(λ,φ,t)
SURFACE ELEMENT
C(λ,φ,t)
DIFFUSION
chem. sput. eff. = 5%
sticking=50% ~ 100%
diffusion lim. = 10^7 cm^-2 s^-1
Killen et al., 2004
PLANET ROTATION

Sodium observations (MESSENGER)

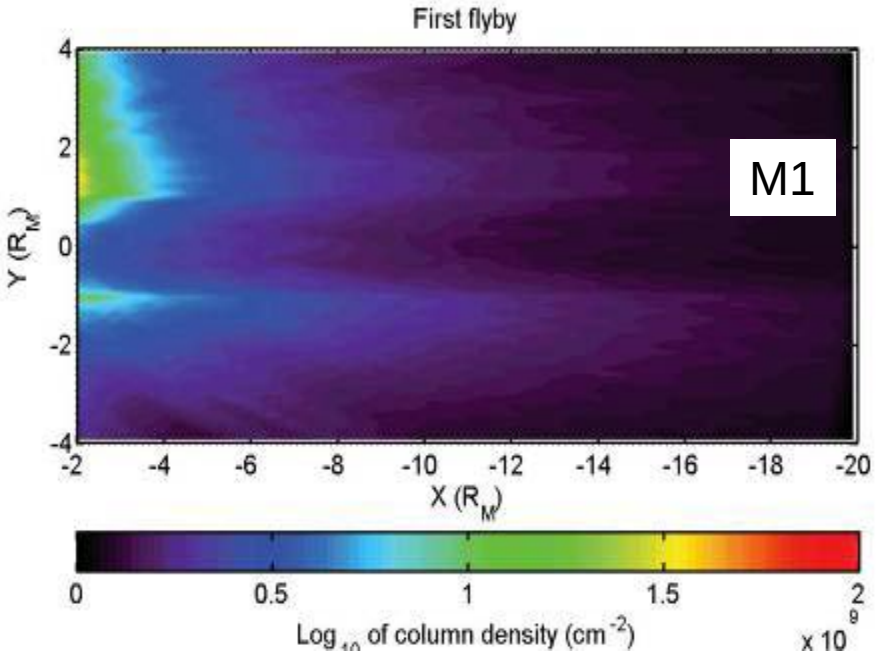


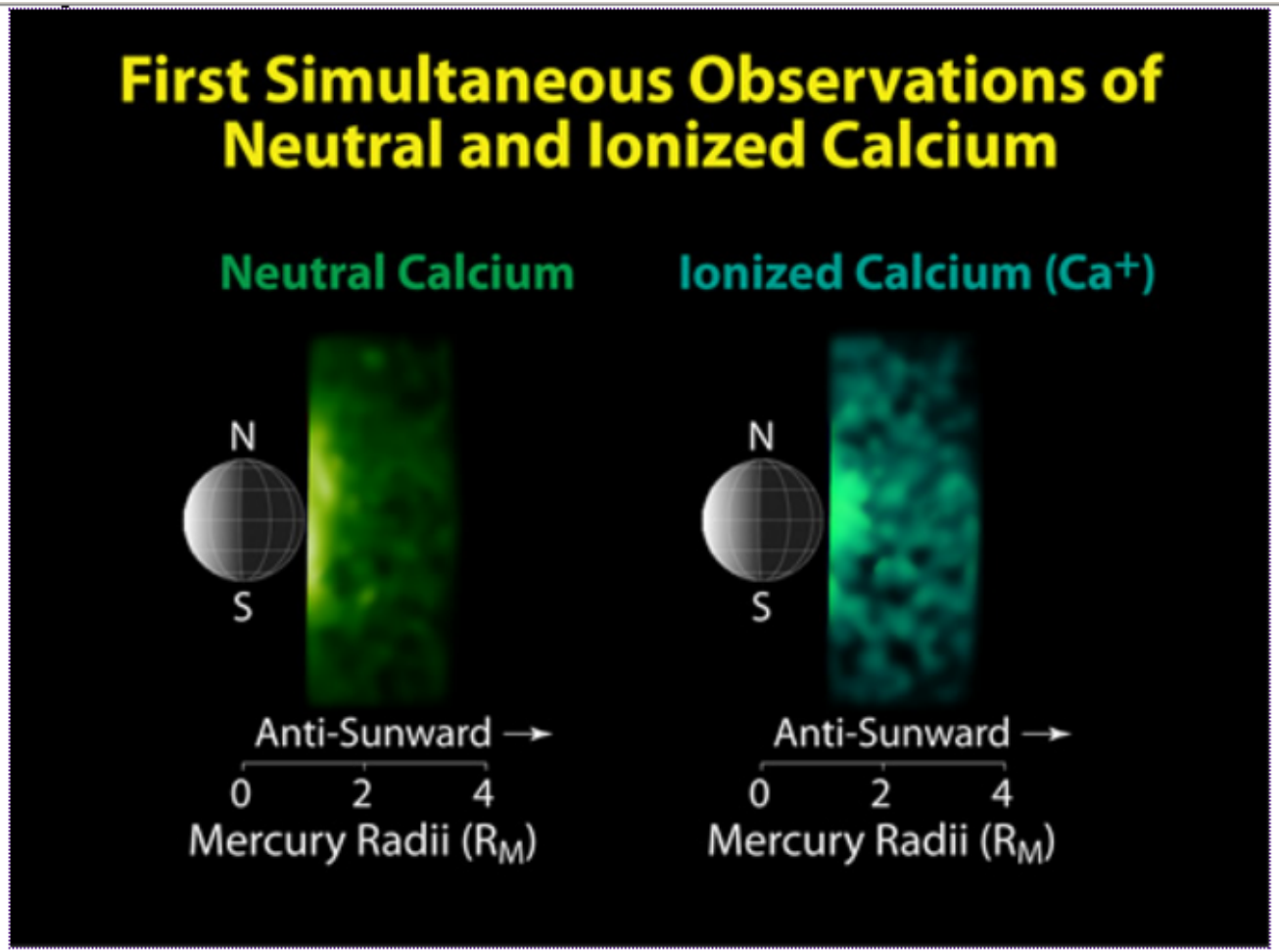
McClintock et al, 2009





McClintock et al, 2008

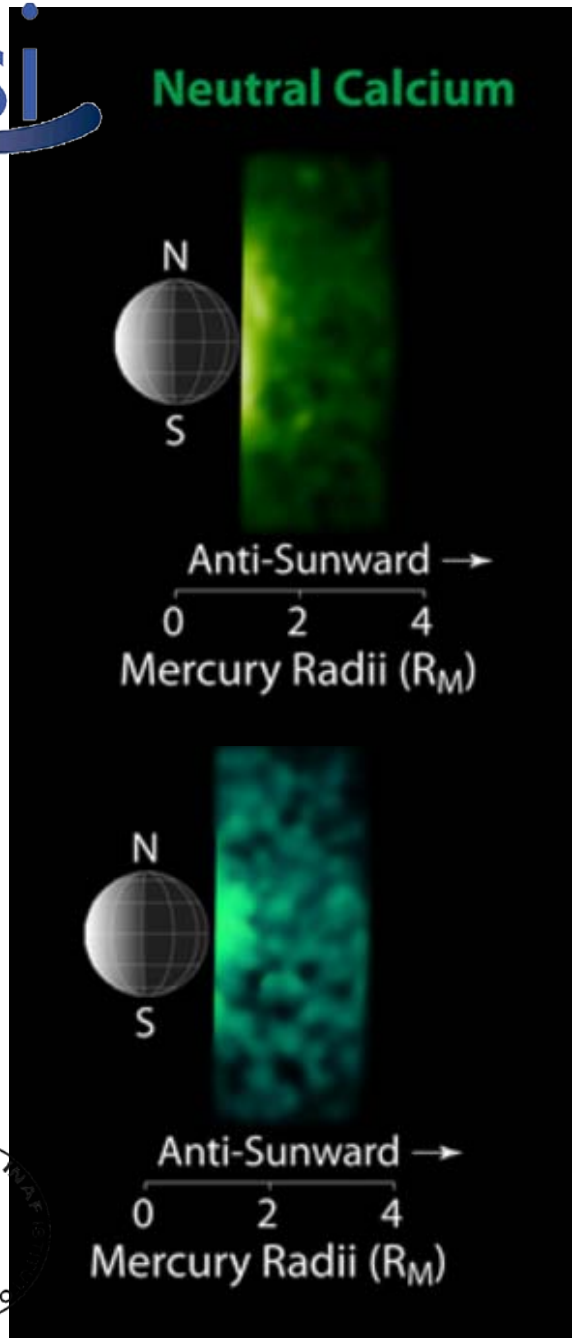


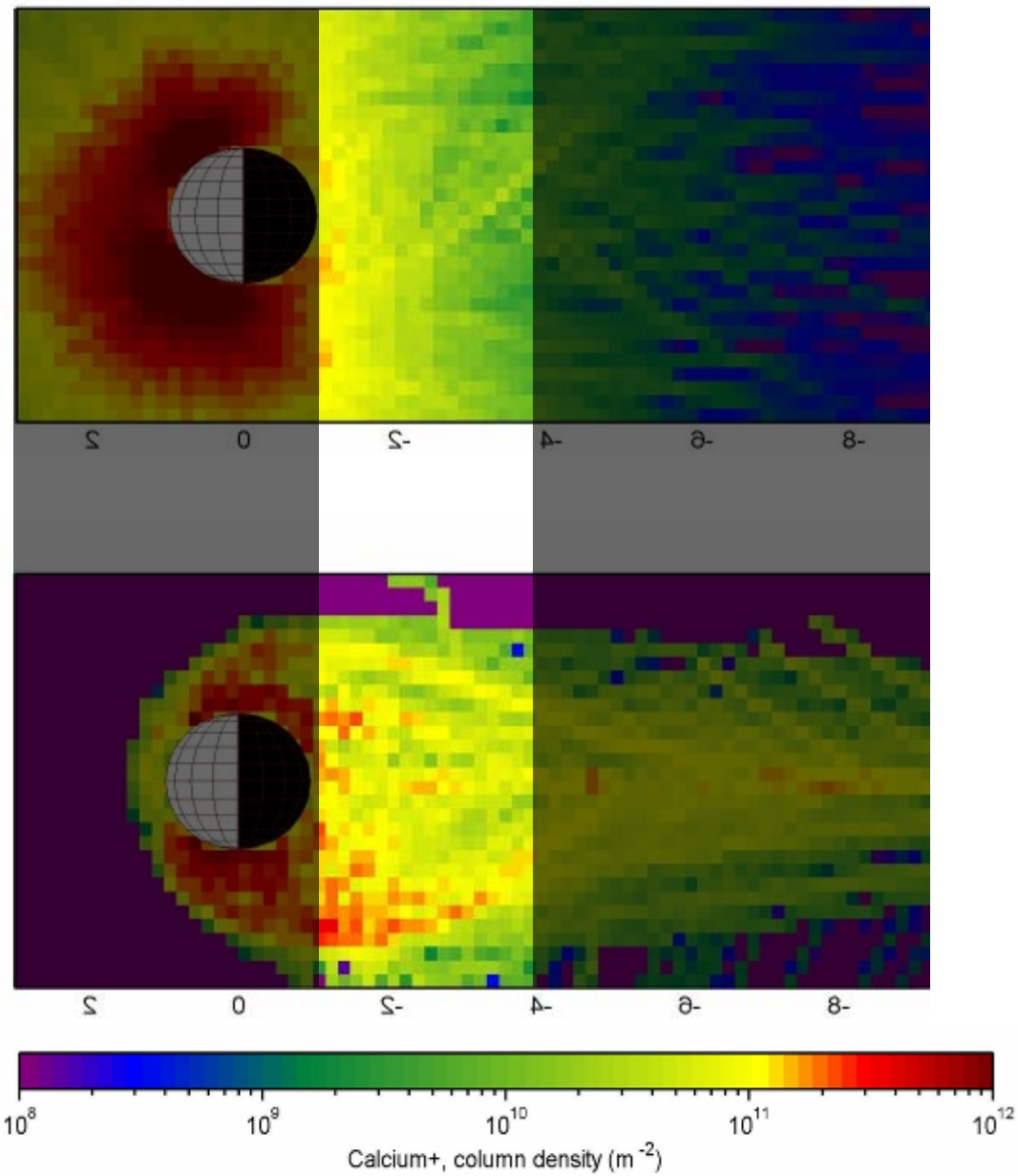


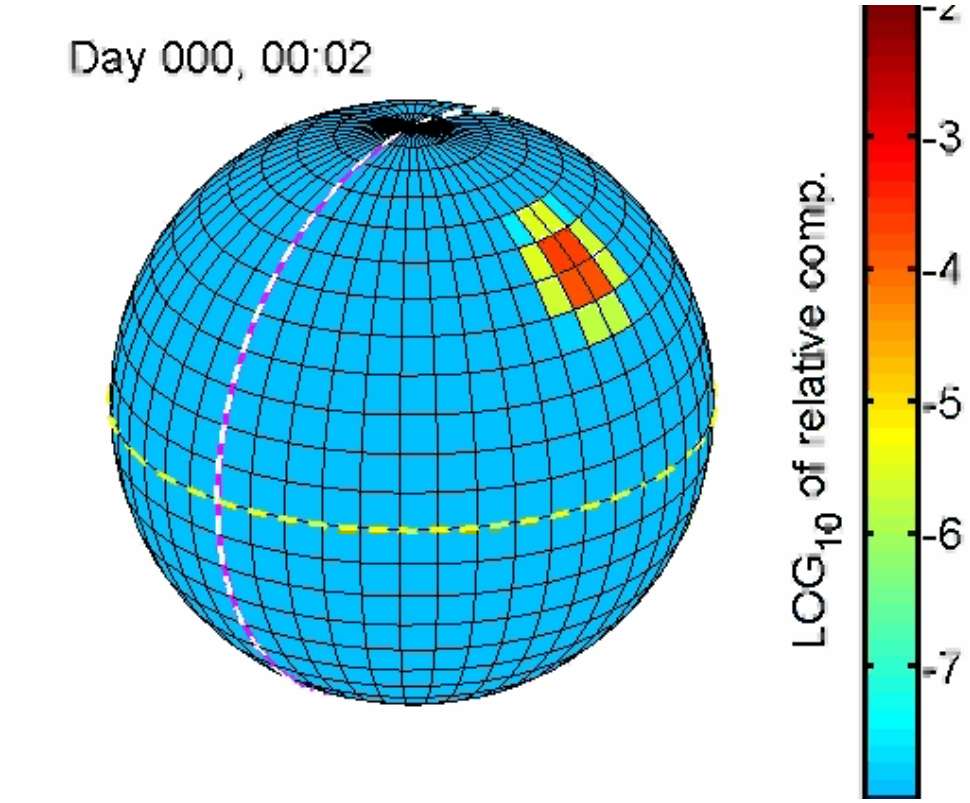
First observations of emission from ionized calcium in Mercury's tail region compared with simultaneous observations of neutral calcium. Neutral calcium is rapidly converted to ionized calcium by sunlight, explaining the generally rapid decrease of neutral calcium away from the planet. The high degree of correlation between the two observed distributions reflects the rapid conversion of neutrals to ions and demonstrates that ionized calcium represents a significant fraction of the overall calcium abundance. Simultaneous measurement of the abundances of calcium neutrals and ions is therefore necessary to determine accurately the total calcium abundance in Mercury's exosphere. This situation is in contrast to that for sodium and magnesium, which are ionized much more slowly. The significantly longer lifetime for neutral magnesium may explain why its abundance is more widely distributed in the tail region than calcium (Image 2.4).

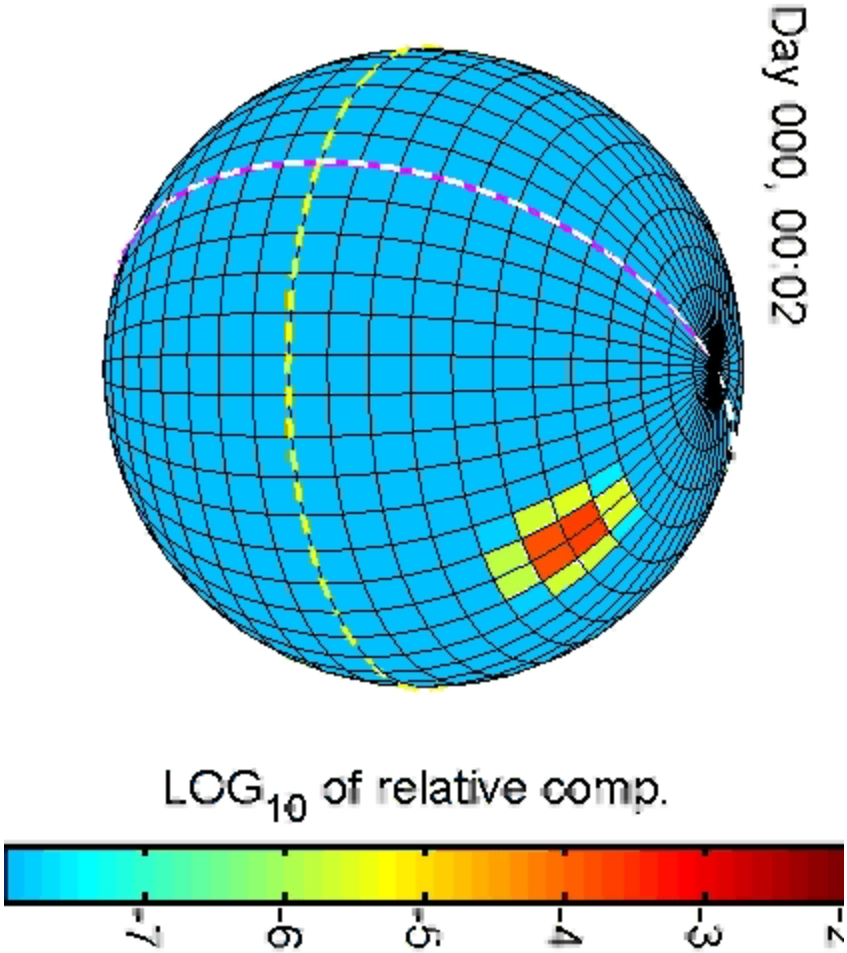
http://messenger.jhuapl.edu/news_room/presscon_multi6.html

Sputtered Ca, Ca+: MESSENGER and model

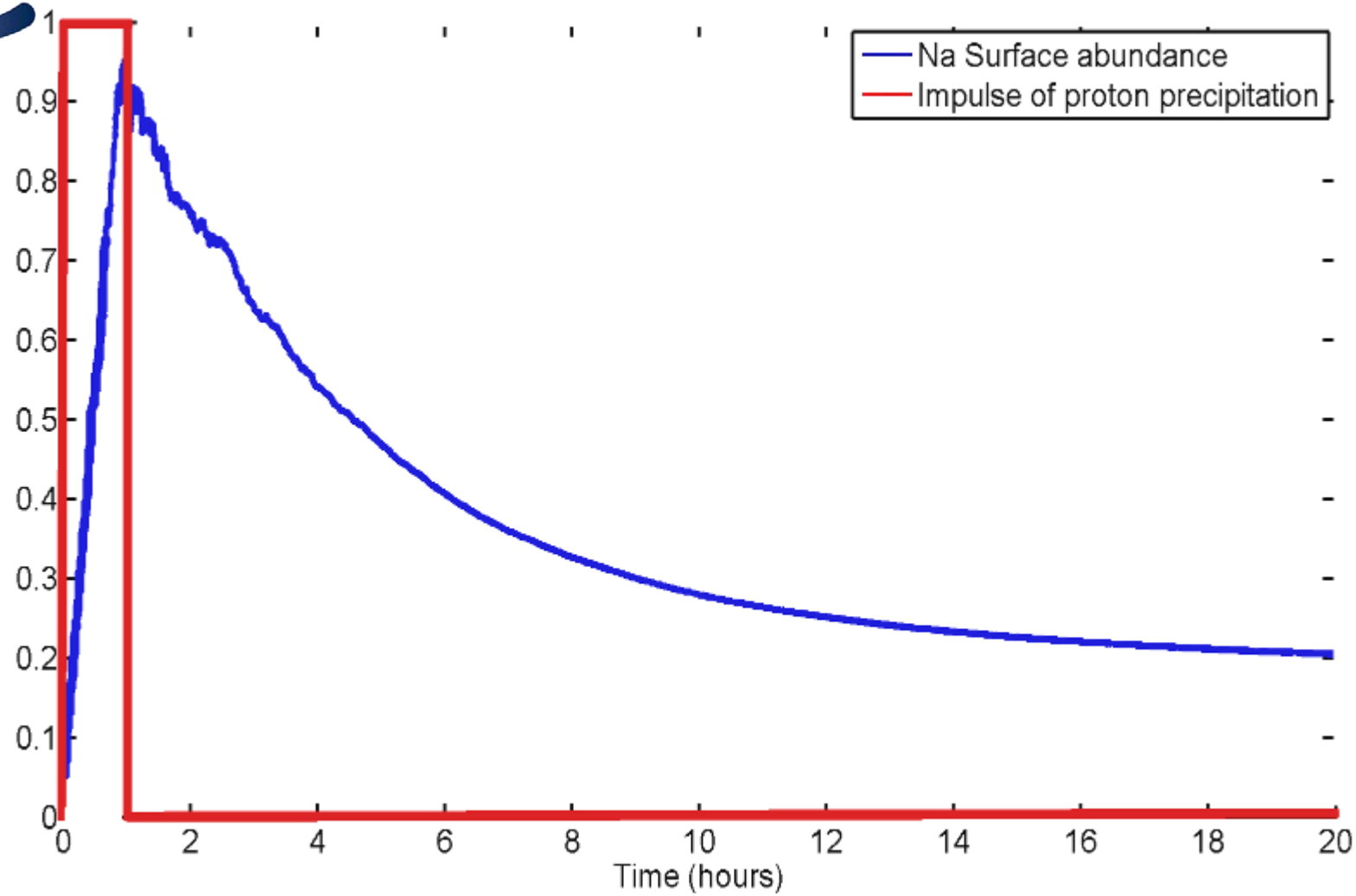





Day 000, 00:02
LOG10 of relative comp.
-2
-3
-4
-5
-6
-7

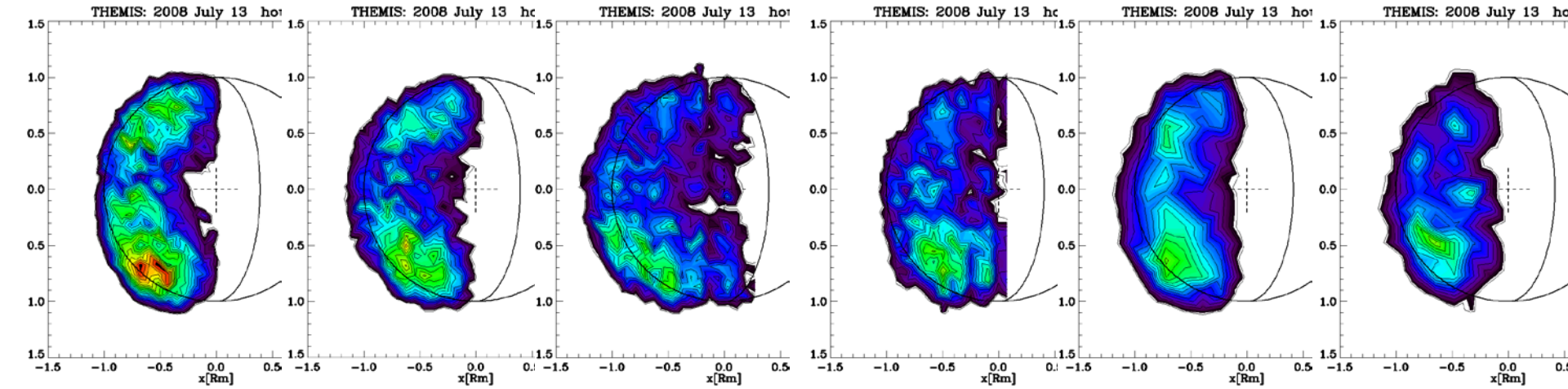

Day 000, 00:02
LOG10 of relative comp.
-2
-3
-4
-5
-6
-7

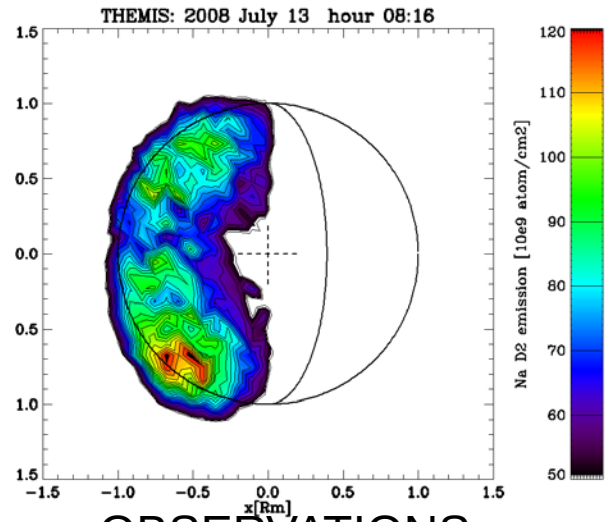
Time scale of sodium



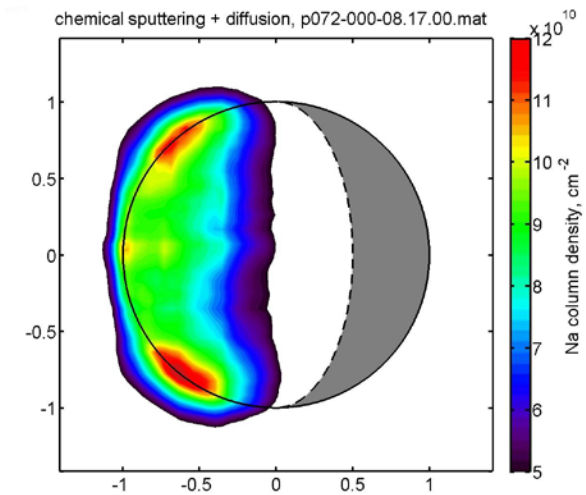
- The Na lifetime is approximately independent on the H+ flux
- For a (example) 1-hour precipitation, the lifetime after the H+ precipitation ceases is several hours

08:17 09:33 10:50 13:38 16:56 17:39

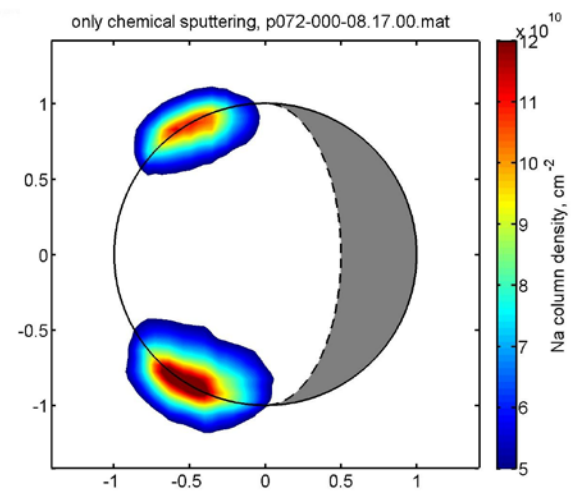




OBSERVATIONS

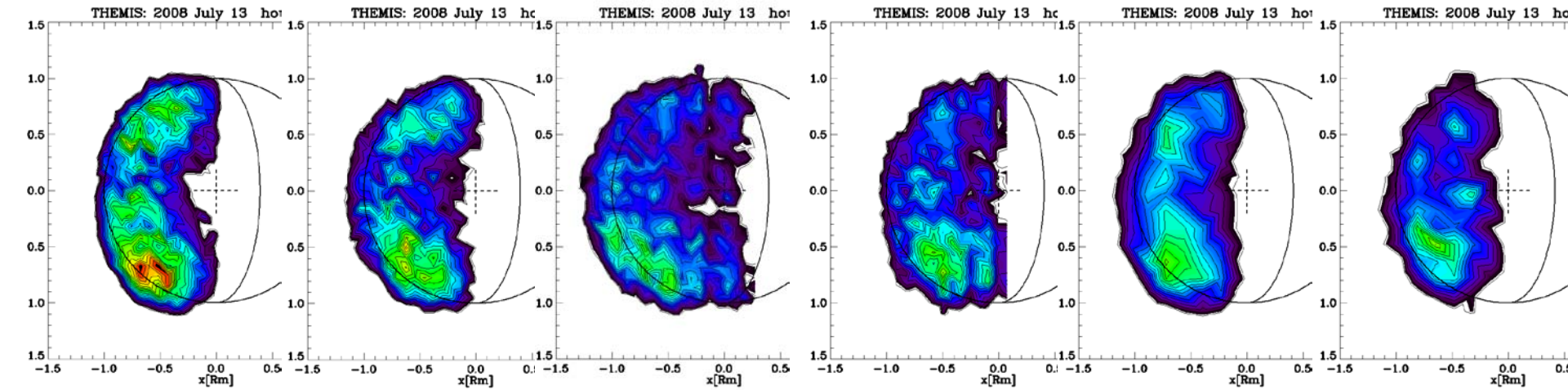


MODEL, C.S.+DIFF
seeing=1 Rm

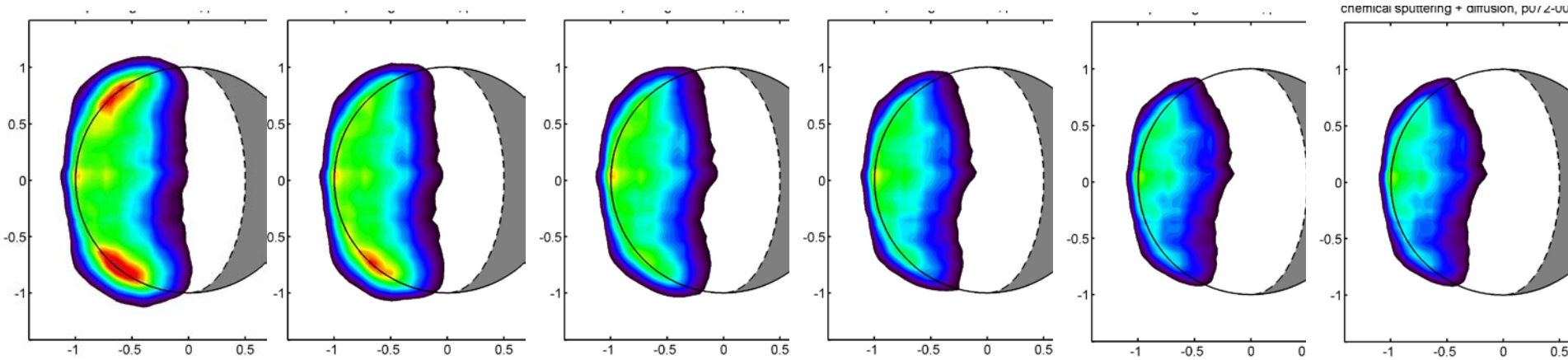


MODEL, ONLY C.S.
seeing=1 Rm

08:17 09:33 10:50 13:38 16:56 17:39



OBSERVATIONS



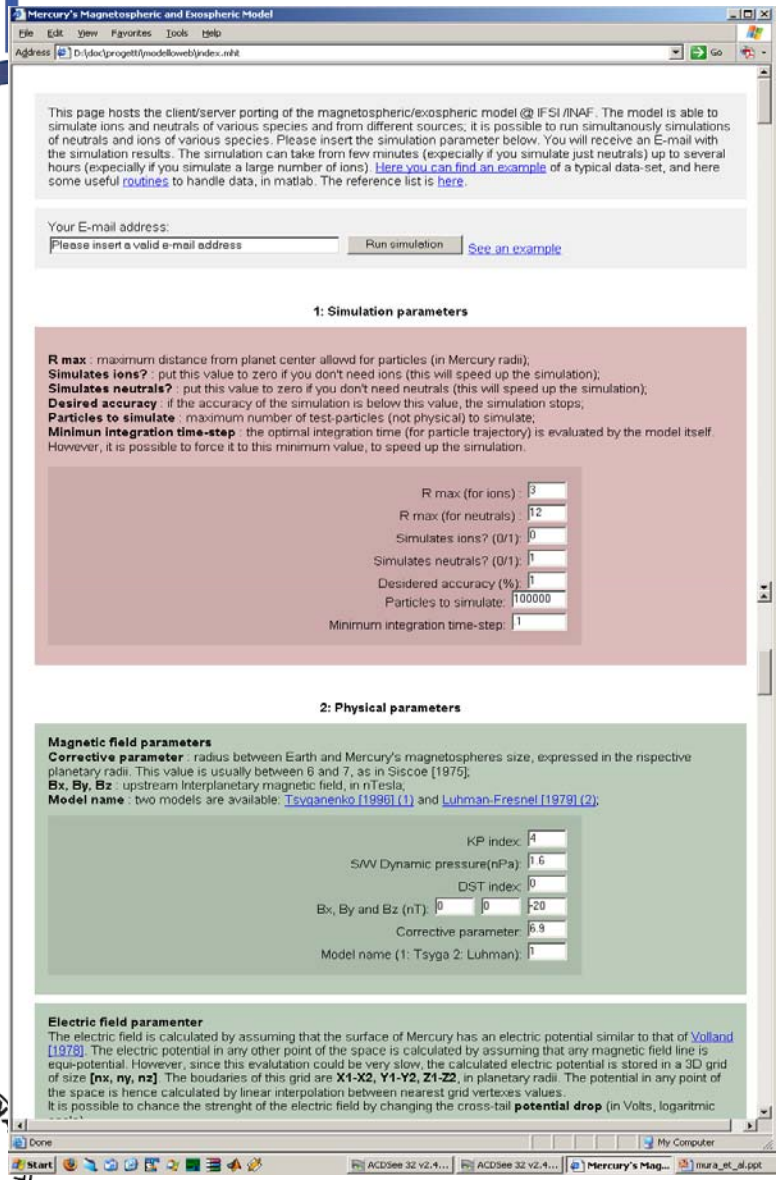
MODEL

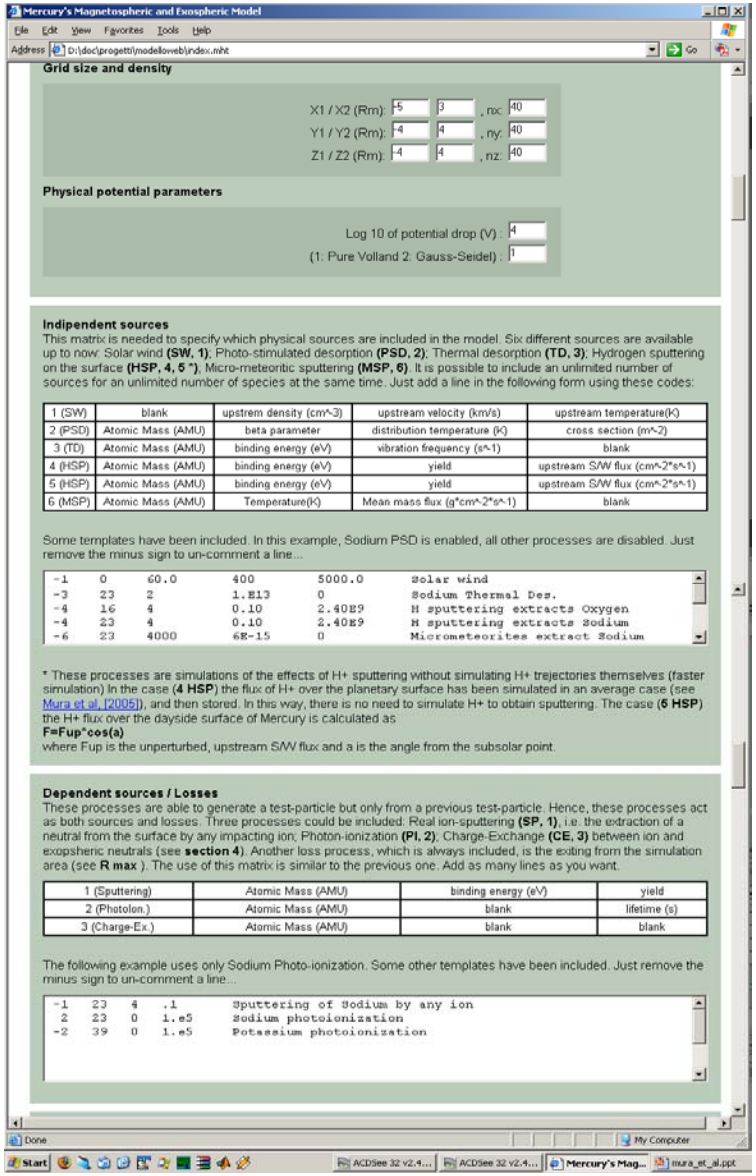
CONCLUSION

- Chemical sputtering and/or proton-enhanced diffusion can explain most of the ground-based or MESSENGER (1st FB) observation ot the Na exosphere of Mercury
- To find general good agreement between data and simulation, U=0,086 eV (resulting in T=2000 or more), ε=5% can be taken.
- A diffusion-limited flux of about 10^7 cm^{-2} s^{-1} is compatible with the observation during the transit, and necessary to explain the observations of Na at the dayside.
- A time-evolving MonteCarlo model with planet rotation is able to explain the dawn-dusk asymmetry as seen during transit.
- Thermal desorption and Photon-stimulated desorption move the Na in areas far from the H+ precipitation: no need of complex, accurate H+ flux model for this simulations
- The timescale for proton precipitation-induced enrichment and depletion of Na is about 10 hours
- Proton-enhanced diffusion can also explain the relation between proton precipitation and enhanced Na release.

Thank you for your attention

Web interface





Go to: http://elena.ifsi-roma.inaf.it