Long term measurements of the plasmasheet composition: implications on ionospheric outflow

R. Maggiolo[1], M. Hamrin[2], G. Cessateur[1], J. De Keyser[1], H. Gunell[1], L. Maes[3], T. Pitkänen[2,4]

[1]Royal Belgian Institute for Space Aeronomy, Brussels Belgium
[2]Department of Physics, Umeå University, Umeå, Sweden
[3]Max Planck Institute for Solar System Research, Göttingen, Germany
[4]Institute of Space Sciences, Shandong University, Weihai, China

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Why using long term measurements in the plasmasheet to investigate ionospheric outflow?

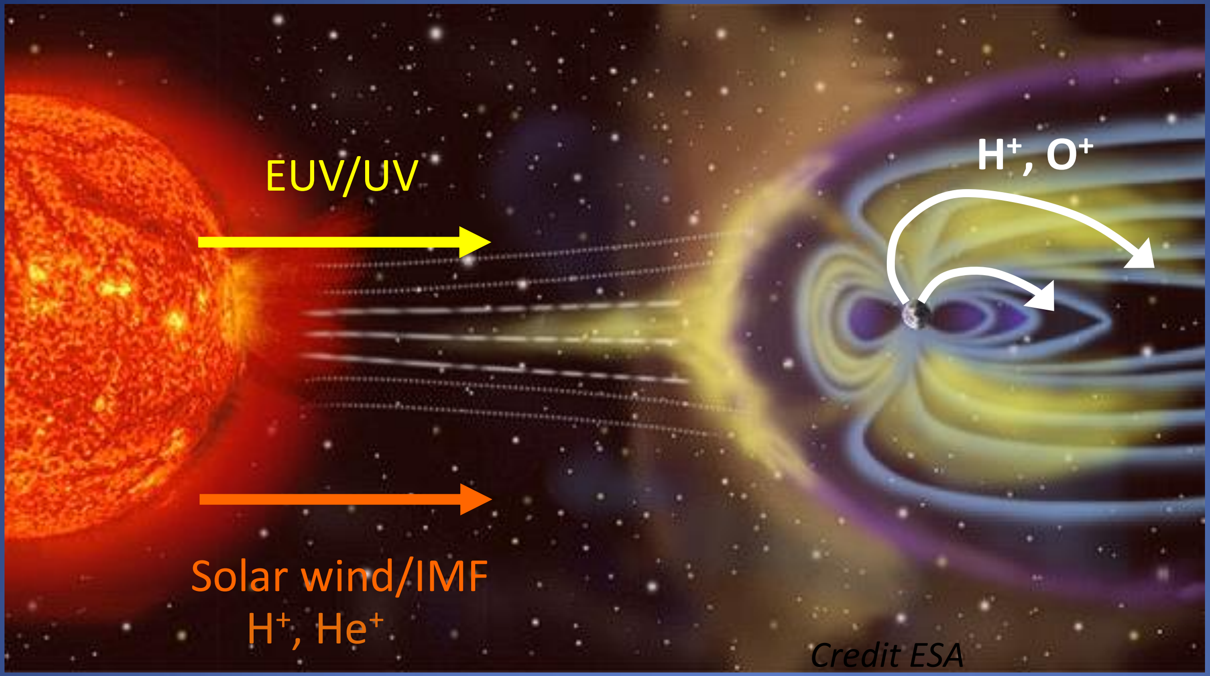
- The plasmasheet is the main reservoir of plasma in the magnetosphere. It contains a mixture of ions originating from the solar wind and the ionosphere. Among them, O^+ ions can be used as tracers of ionospheric plasma

- Measuring ion outflow can be difficult: localized sources, transient events, low energy ions…

- The plasmasheet is a large region
- The ion flux in the plasmasheet is strong and the ion energy is in the keV range: perfect for ion detectors

  $\Rightarrow$ Extended database of O^+ ion measurement in the plasmasheet

Ionospheric ions in the magnetosphere



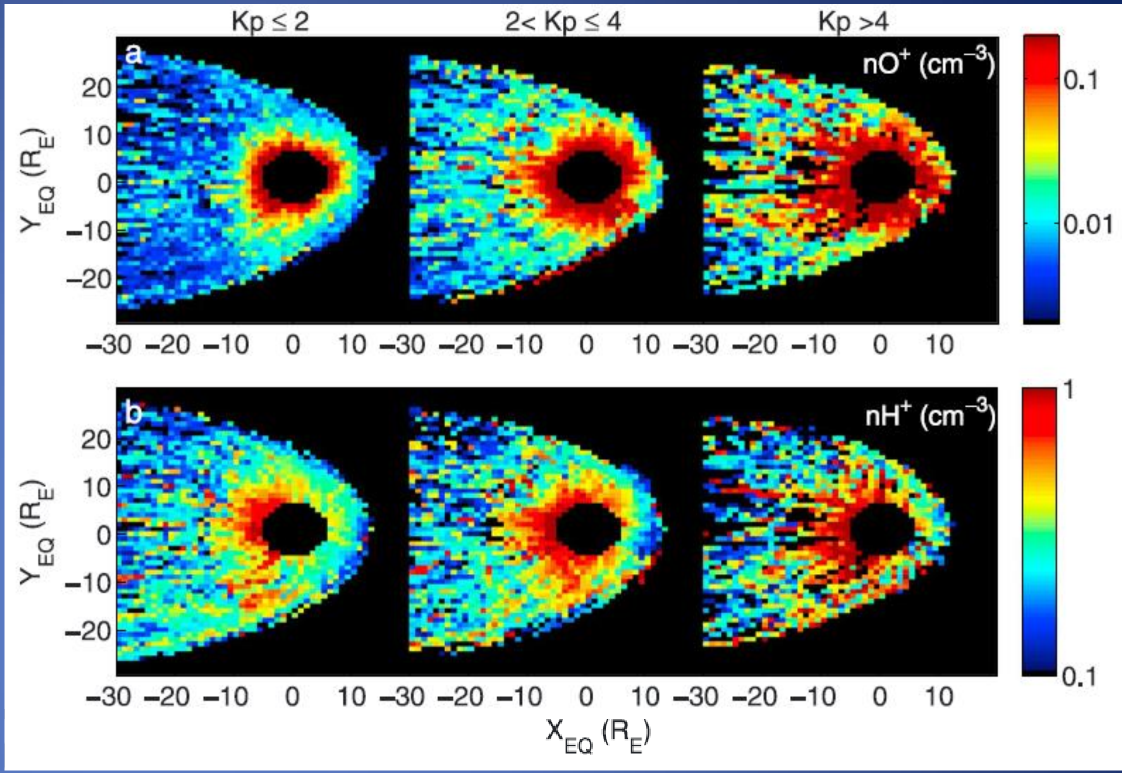
Many studies investigated the plasmasheet O+ content

- *Young et al. 1982* (GOES 1&2, geostationary orbit, 0.9-15.9 keV/e)
- *Lennartsson and Shelley 1986* (ISEE, tail 10-23 R_E, 0.1-16 keV/e)
- *Lennartsson 1989* (ISEE, tail L=3- R=23 R_E, 0.1-16 keV/e)
- *Nosé et al. 2009* (Geotail, tail 8-200 R_E, 9.4-212.1 keV/e
- *Mouikis et al. 2010* (Cluster, tail 15-19 R_E, 1-40 KeV/e)
- *Othani et al. 2011* (Geotail, tail 0-30 R_E, 5x5 R_E, 9.4-212.1 keV/e)
- *Maggiolo and Kistler 2014* (Cluster, plasmasheet 7-30 R_E, 1-40 KeV/e)
- *Kistler and Mouikis 2016* (Cluster, inner magnetosphere L<12R_E, 40 eV to 40 keV)
- …

They all show that the O^+ density in the magnetosphere increases with increasing geomagnetic activity and solar EUV/UV flux

O^+ density in the plasmasheet (*Maggiolo and Kistler 2014*)

Density maps in the equatorial plane as function of geomagnetic activity (Kp) and solar EUV/UV flux (F10.7)
1-40 keV
Projection along MF lines



Functional forms for 2 regions

Near Earth (7-8 R_E)
- nO^+ ↗ by a factor of 9 from low to high Kp

$$nO^+ = 0.016 \exp(0.0092\, F10.7 + 0.32\, Kp)\ cm^{-3}$$

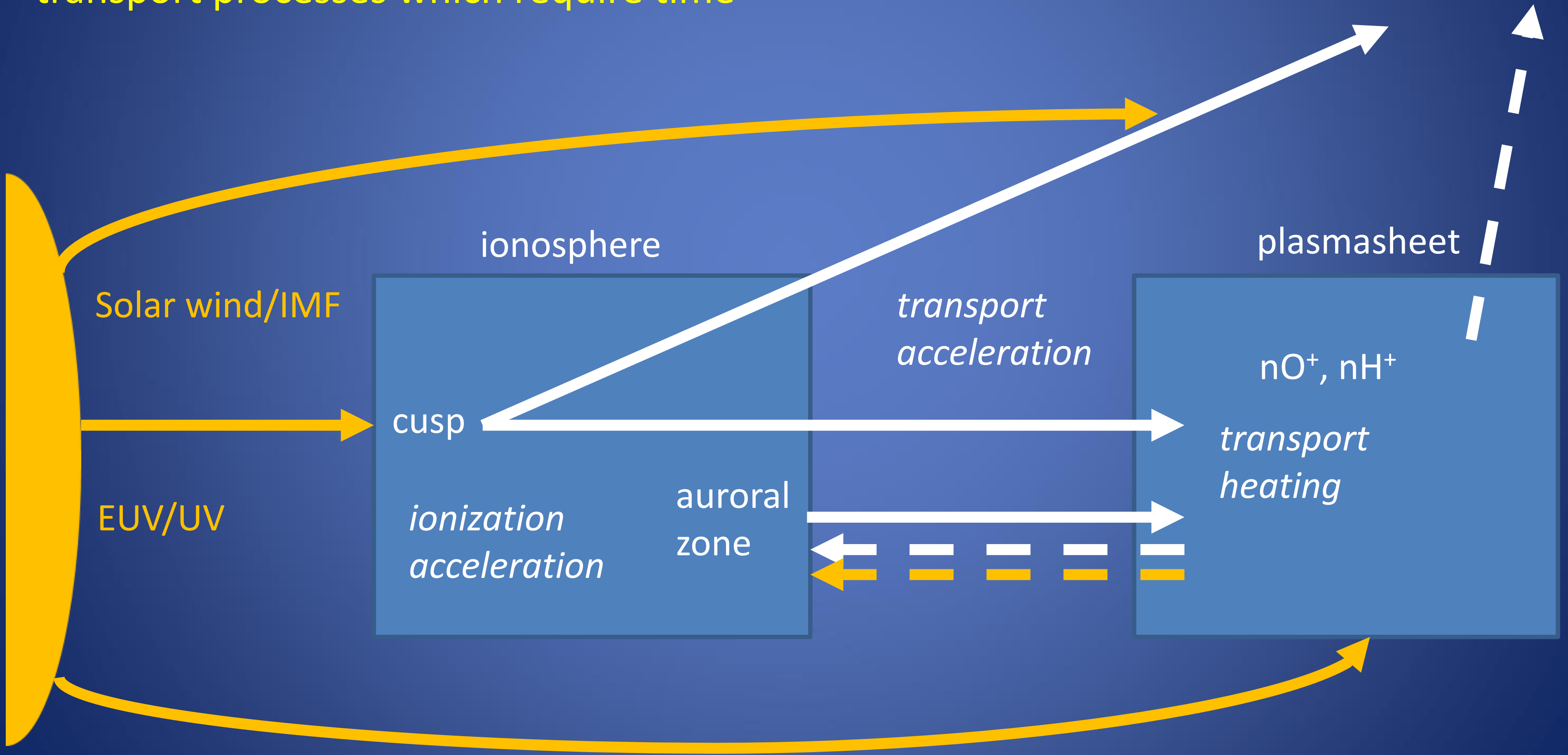
Mid tail (15-20 R_E)
- nO^+ ↗ by a factor of 20 from low to high Kp

$$nO^+ = 0.0014 \exp(0.00072\, F10.7 + 0.44\, Kp)\ cm^{-3}$$

The O^+ density is more sensitive to geomagnetic activity in the mid tail plasmasheet than in the near Earth regions

Such studies provide a static picture. For instance, the use of the 3h Kp index for geomagnetic activity doesn't provide the time response of the plasmasheet density and composition to geomagnetic activity.

The O^+ density variations in the plasmasheet results from a chain of acceleration and transport processes which require time



Can we get more information about ionospheric outflow from measurements made in the plasmasheet?

$\Rightarrow$ We investigate the delayed correlation between solar wind parameters and the O^+ and O^+/H^+ density in the plasmasheet :

Lagged correlation between $nO^+(t)$ and $SW(t-\Delta t)$ with Δt up to 24 hours to evidence the plasmasheet response time to solar wind drivers

Method applied to geomagnetic indices (Maggiolo et al. 2017).
$\Rightarrow$The interpretation of linear correlations should be made very carefully as many biases have a strong impact on the results

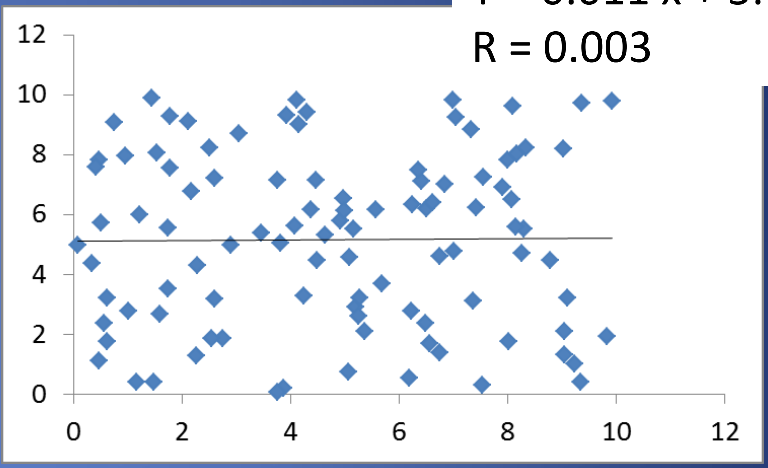
Correlation analysis

Main assumption for correlation analysis are not satisfied (Maggiolo et al. 2017):

- Data are not normally distributed (impact of outliers)

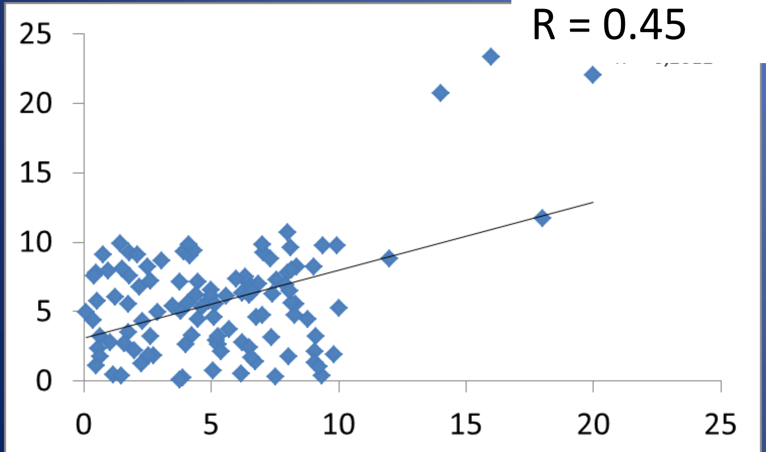
The range of variation of the parameter and outliers strongly impact results!

100 random points
$0<x<10$; $0<y<10$



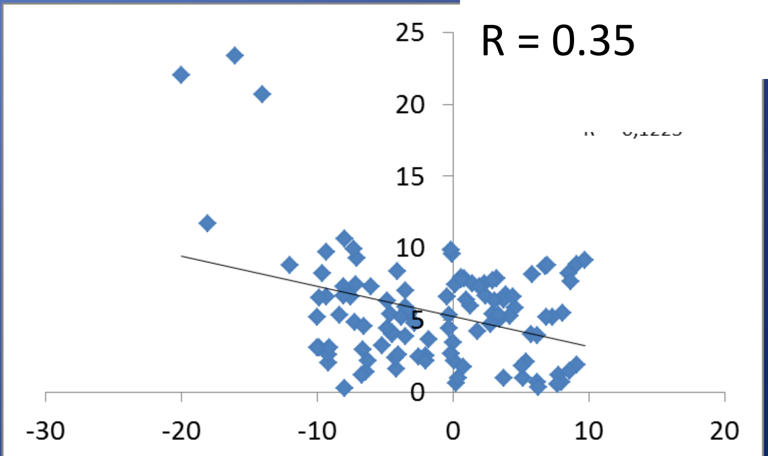
Y = 0.011 x + 5.11
R = 0.003

100 random points $0<x<10$; $0<y<10$
+ 10 points correlated
(with random error)



Y = 0.49 x + 3.09
R = 0.45

100 random points $-10<x<10$; $0<y<10$
+ 10 points correlated
(with some random error)



Y = -0.35 x + 5.28
R = 0.35

Pearson correlation

Main assumption for correlation analysis are not satisfied (Maggiolo et al. 2017):

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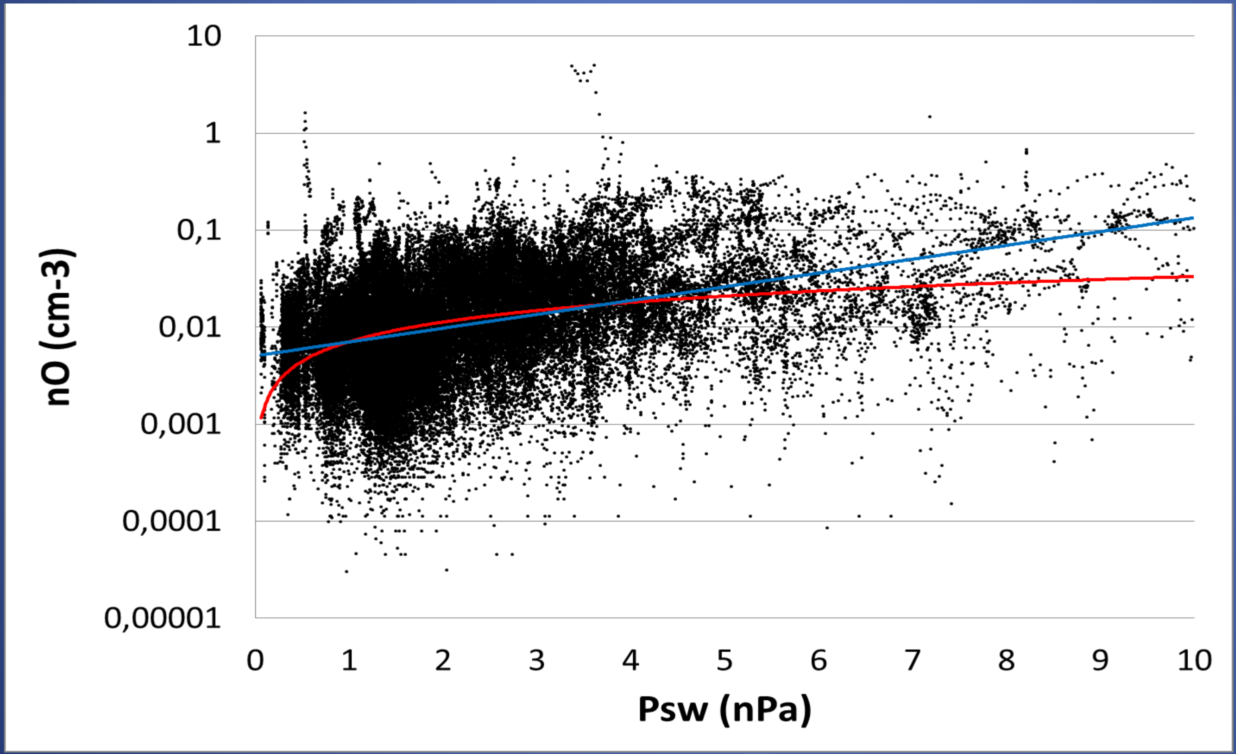
- The dependence between parameters is not necessarily linear



$nO = 0,0071.Psw^{0.67}$
$R = 0.37$
$nO = 0,0051.exp(0.33.Psw)$
$R = 0.40$

Method

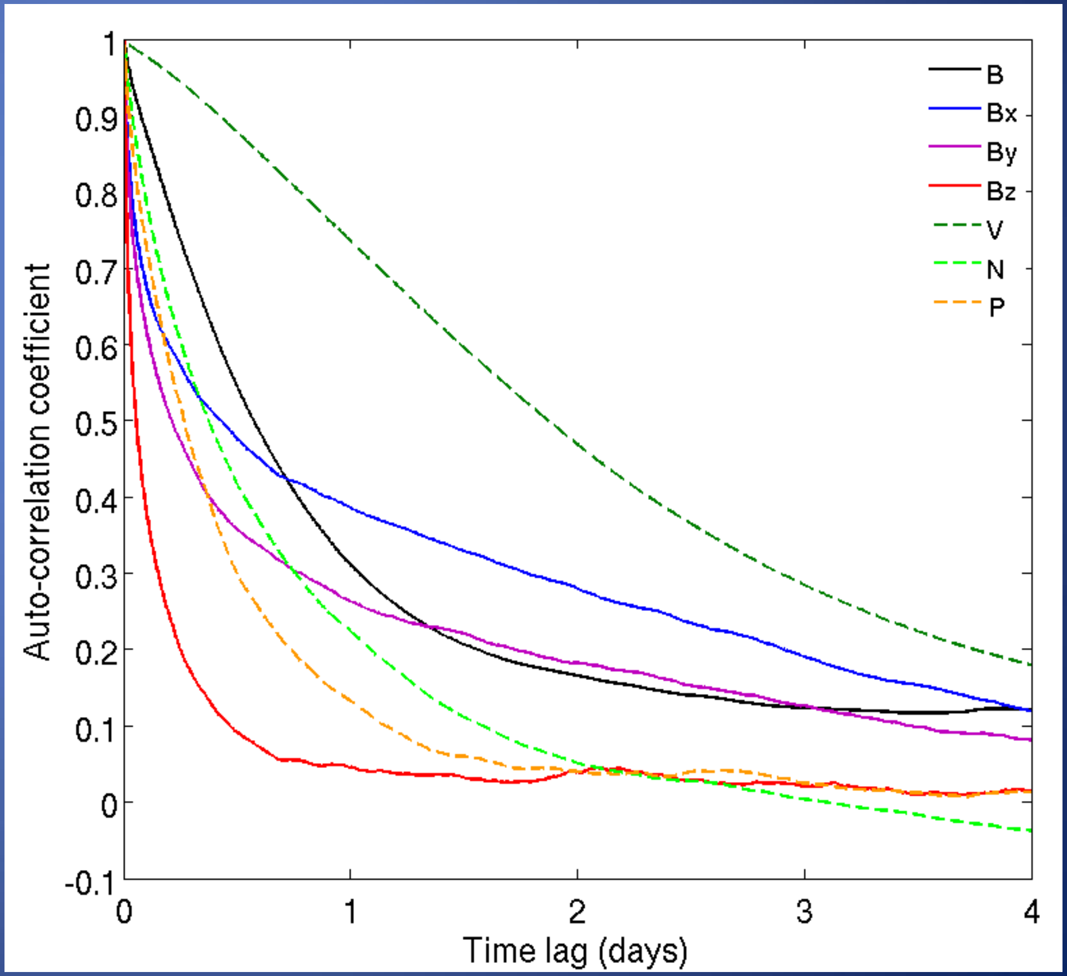
Main assumption for correlation analysis are not satisfied (Maggiolo et al. 2017):

- Data are not normally distributed (impact of outliers)
- The dependence between parameters is not necessarily linear
- The observations are not independent of each other

Autocorrelation

$\Rightarrow$ Smooth the time variation of the CC

B	14h
Bx	10h
By	5h
Bz	1.5h
V	45h
N	9h
P	6.5h



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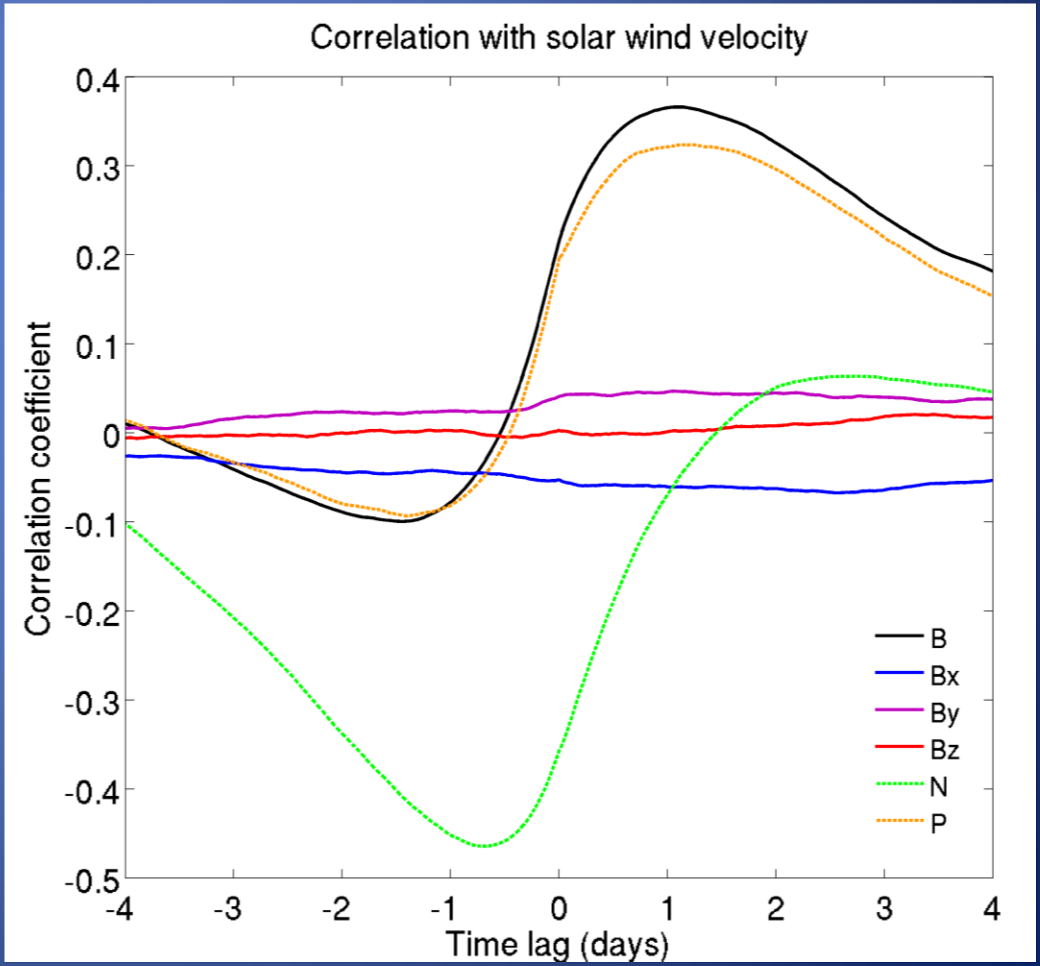

Method

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Significance of the Pearson correlation coefficient

Has to be check by testing the probability of obtaining a non-zero correlation coefficient by chance while the two variables are not correlated (t-test)

Threshold value for the CC depends on the number of data points

In this study: high number of data (from 10000 to 70000)

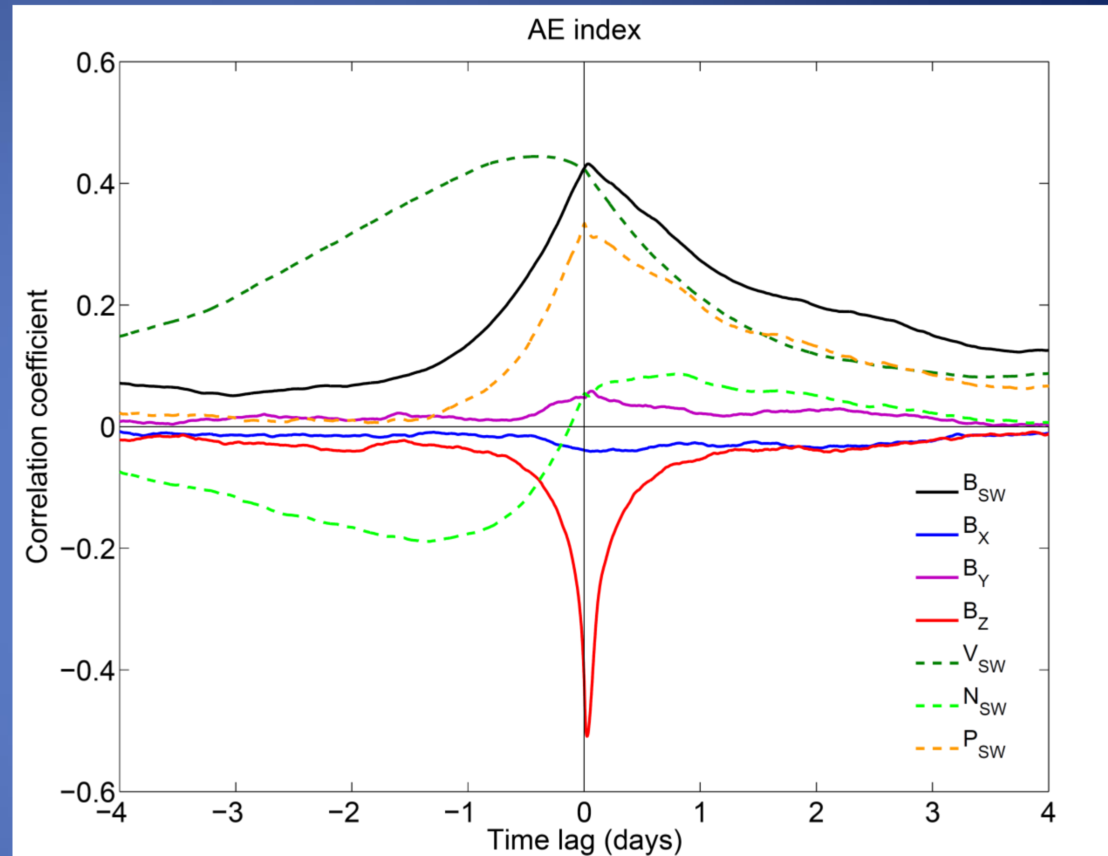
99% significance level when |CC| > 0.114

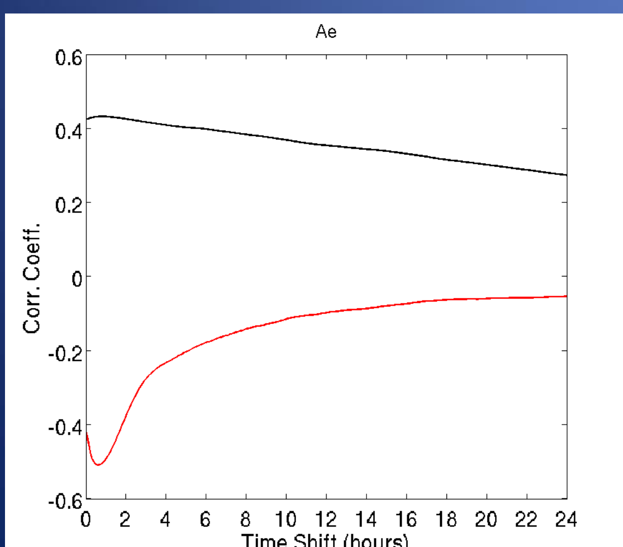
N-2	90	95	98	99	99.9
1	0.988	0.997	0.9995	0.9999	0.99999
10	0.487	0.576	0.658	0.708	0.823
40	0.257	0.304	0.358	0.393	0.490
120	0150	0.178	0.210	0.232	0.294
>1000	0.073	0.087	0.103	**0.114**	0.146

The lagged correlation has been applied to SW parameters and geomagnetic indices *(Maggiolo et al. 2017)*

Correlation peak:

AE (B_Z): 35 minutes
AE (B): 50 minutes

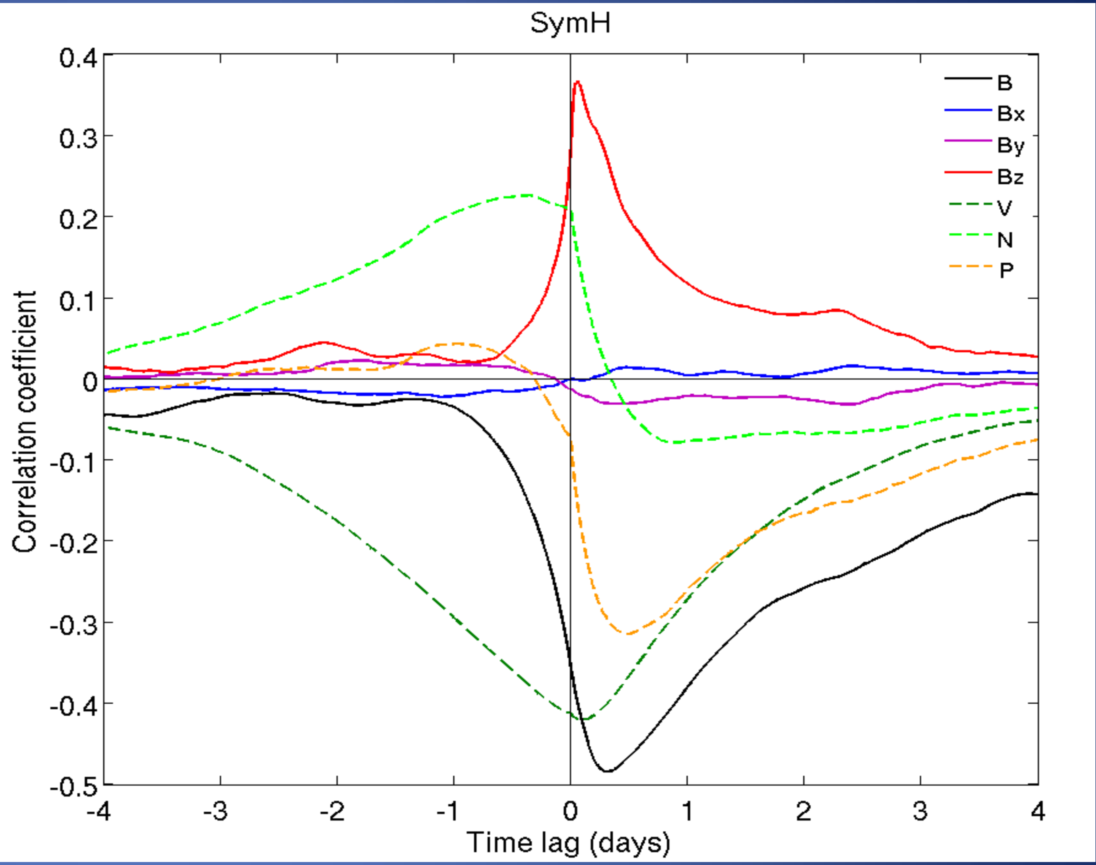


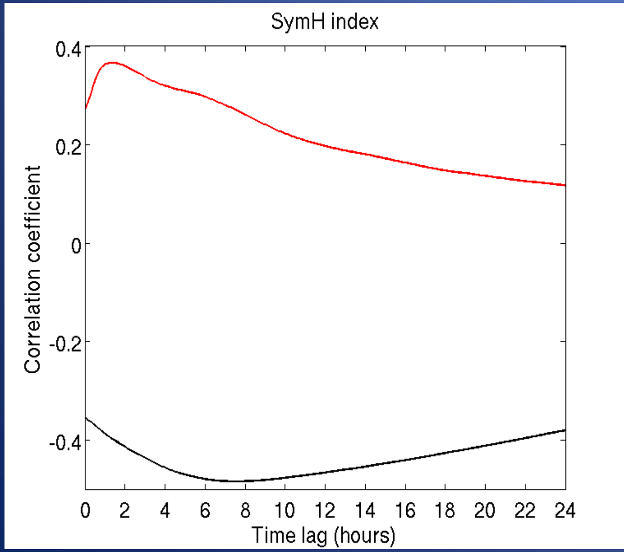


The lagged correlation has been applied to SW parameters and geomagnetic indices *(Maggiolo et al. 2017)*

Correlation peak:

SymH (B_Z): 80 minutes
SymH (B): 455 minutes

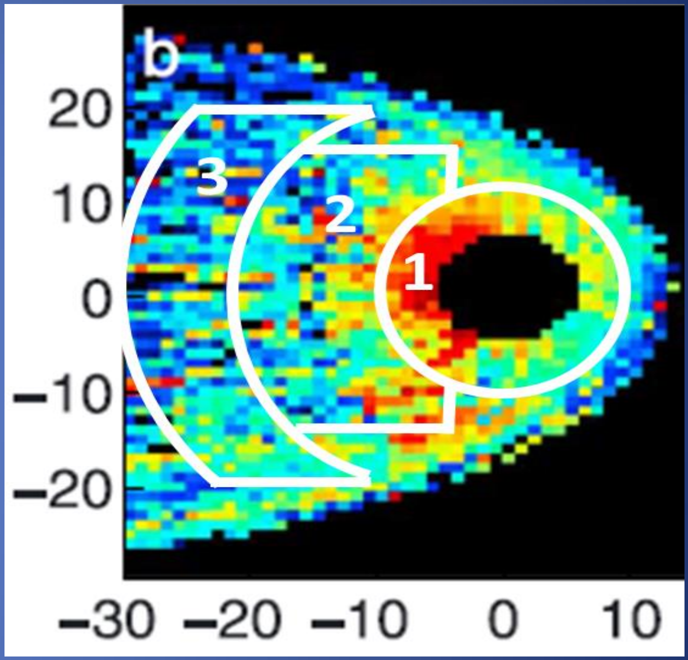




O^+ density in the plasmasheet

•**Data**

•Solar wind parameters from OMNI (shifted @ 1 AU)
•Plasmasheet density from Cluster CODIF from 2001-2005 between 1-40 keV
(database from *Maggiolo and Kistler. 2014*)



Solar wind parameters
B, Bx, By, Bz, P, N ,V

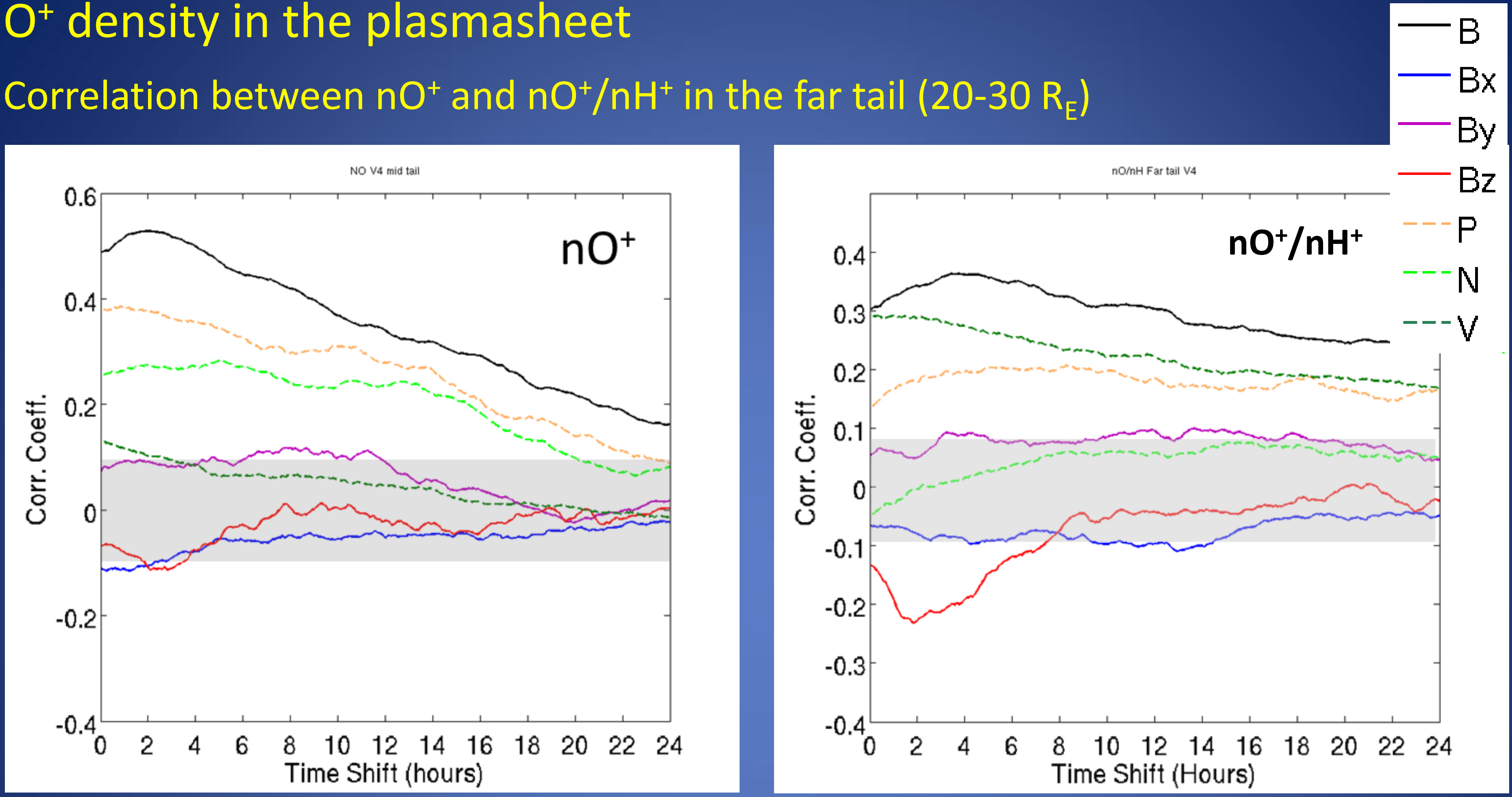
Three regions
1- Near Earth, 6<R<10
2- Mid tail, 10<R<20, -15<Y<15, X<-5
3- Far tail, 20<R<30,-20<Y<20

Exponential dependence of the density on SW parameters
Exp ($nO^+(t)$) and $P_{SW}(t-\Delta t)$ with Δ t up to 1 day

Large data set (from 10000 to 70000 data points)
99% significance level when |CC| > 0.1

O^+ density in the plasmasheet

Correlation between nO^+ and nO^+/nH^+ in the far tail (20-30 R_E)



nO^+: Strong correlation with B, P and N for long time shift (up to one day)

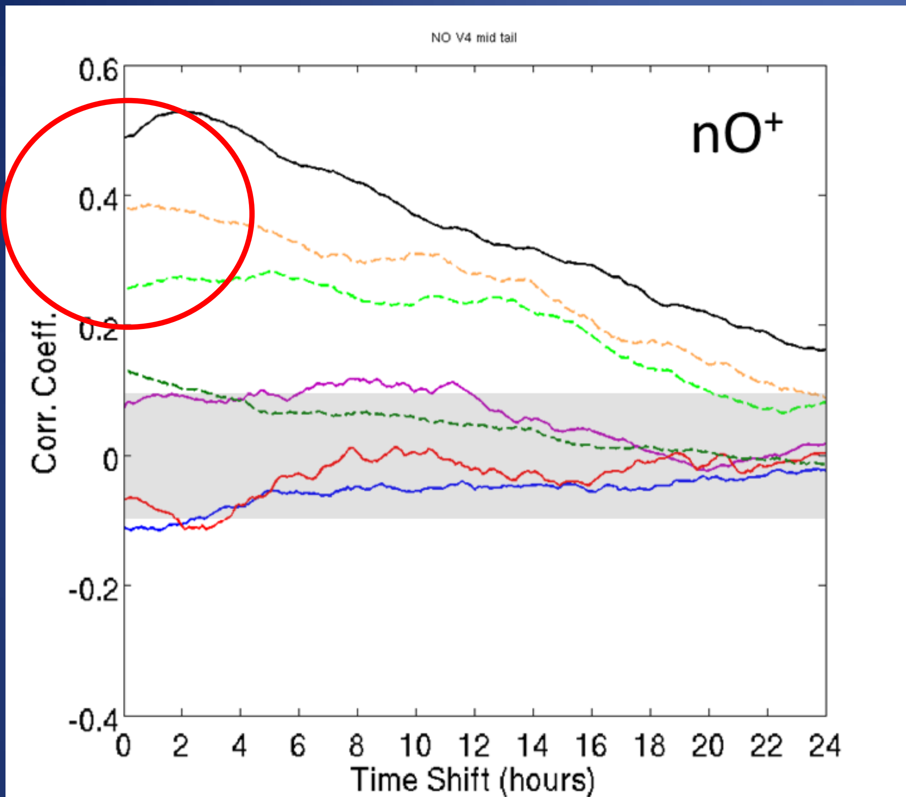
nO^+/nH^+: Strong correlation with B, V and P for long time shift (up to one day)

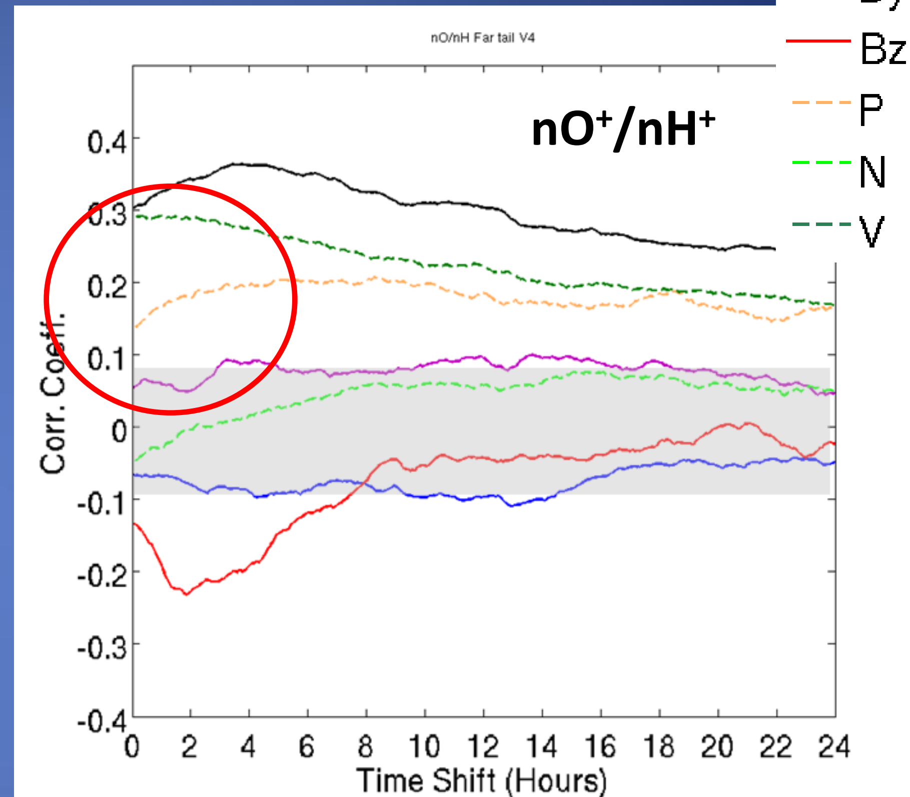
Correlation (weak but significant) with IMF B_Z corresponding to an increase of nO^+ and nO^+/nH^+ for $B_Z<0$

Correlation with B_Z and B peaks for time shifts ~1-5 hours

O^+ density in the plasmasheet

Correlation between nO^+ and nO^+/nH^+ in the far tail (20-30 R_E)





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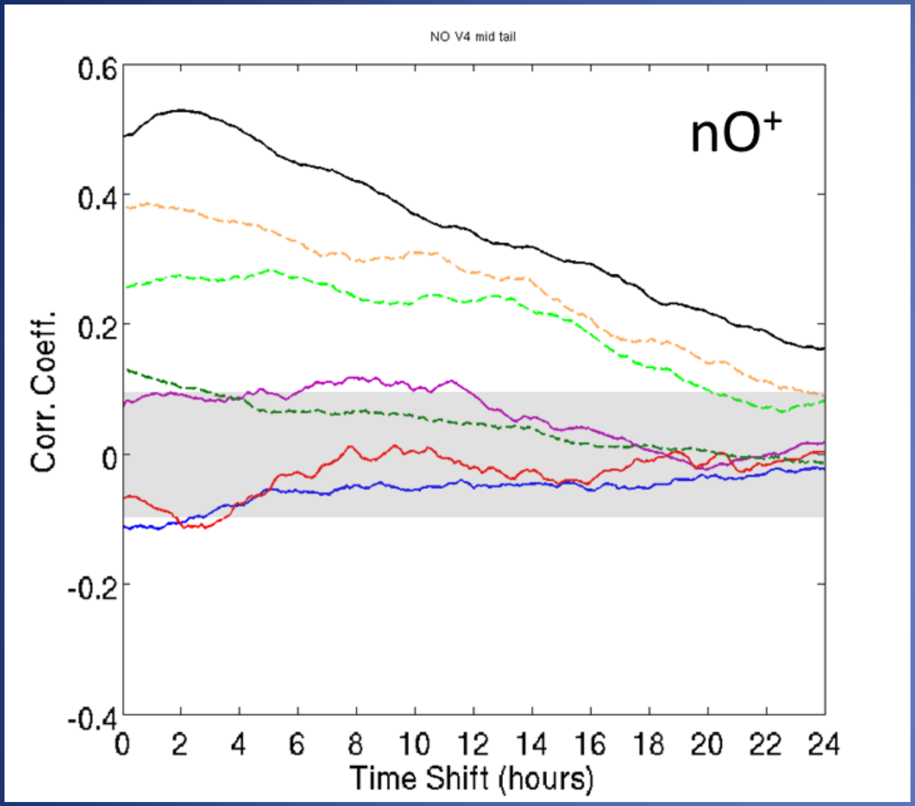
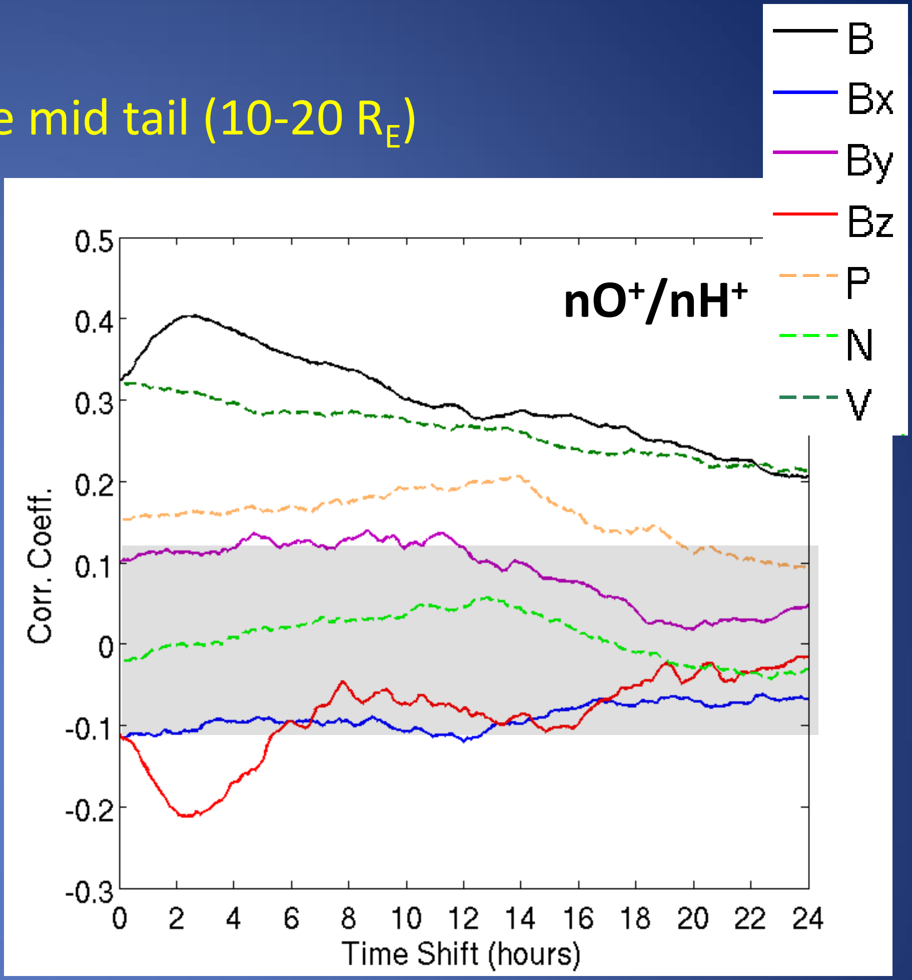
Correlation with B_Z and B peaks for time shifts ~1-5 hours

O^+ density in the plasmasheet

Correlation between nO^+ and nO^+/nH^+ in the mid tail (10-20 R_E)





Very similar to far tail

nO^+: Strong correlation with B, P and N for long time shift (up to one day)

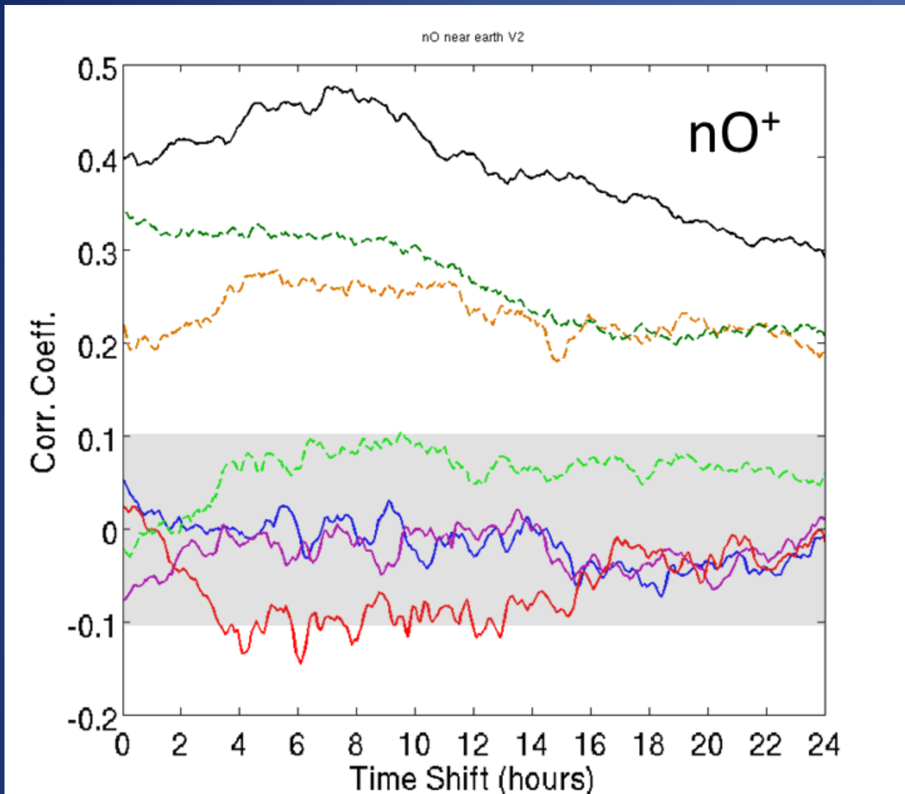
nO^+/nH^+: Strong correlation with B, V and P for long time shift (up to one day)

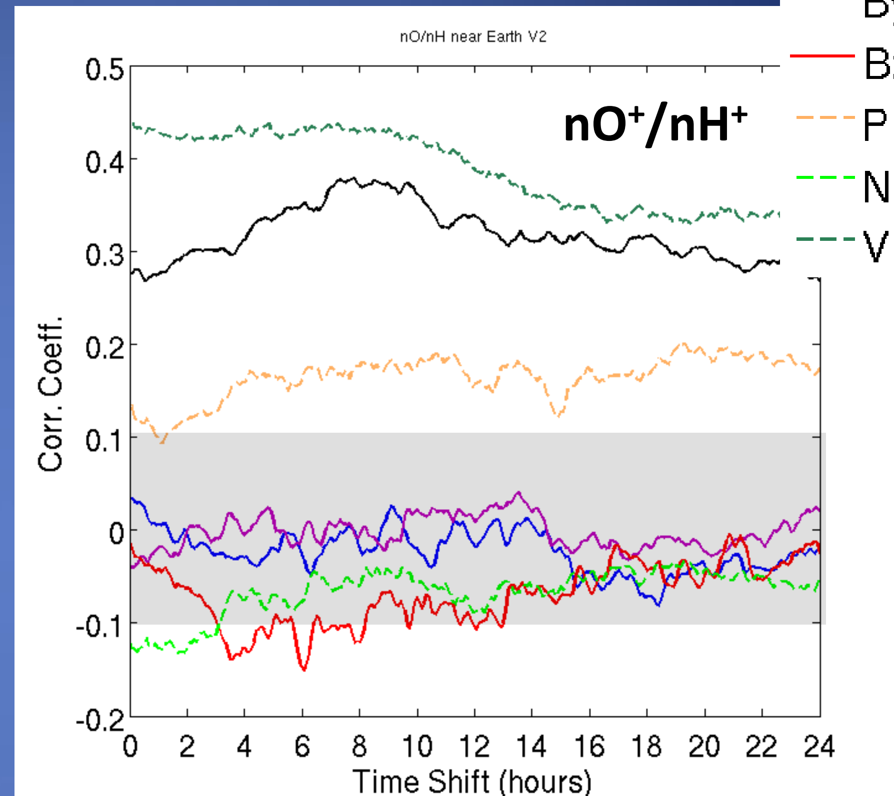
Correlation (weak but significant) with IMF B_Z corresponding to an increase of nO^+ and nO^+/nH^+ for $B_Z<0$

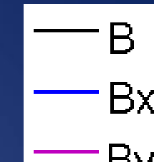
Correlation with B_Z and B peaks for time shifts ~1-5 hours

O^+ density in the plasmasheet

Correlation between nO^+ and nO^+/nH^+ in the near Earth (6-10 R_E)







Lower correlation coefficients, Longer response time

nO^+: Strong correlation with B, V and P for long time shift (> 1 day)

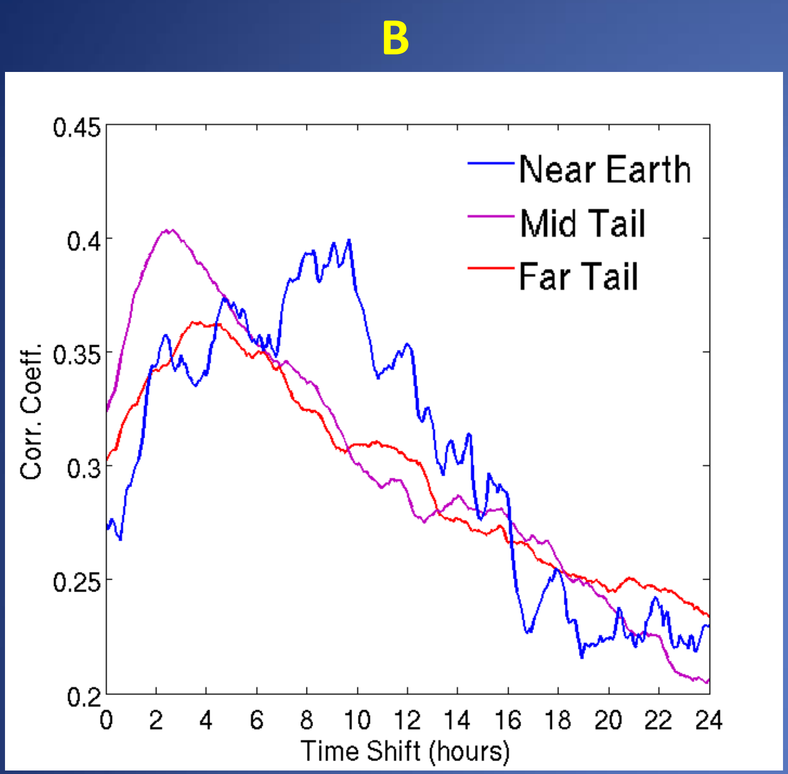
nO^+/nH^+: Strong correlation with V, B and P for long time shift (> 1 day)

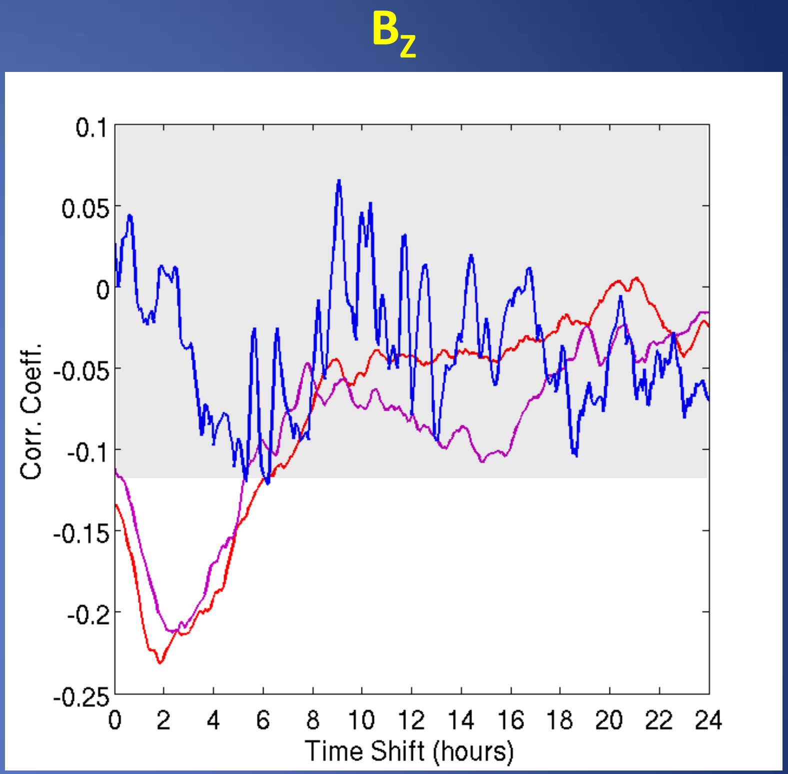
Correlation (weak but significant) with IMF B_Z corresponding to an increase of nO^+ and nO^+/nH^+ for $B_Z<0$

Correlation with B_Z and B peaks for time shifts ~3-12 hours

O^+ density in the plasmasheet

Correlation with nO^+/nH^+





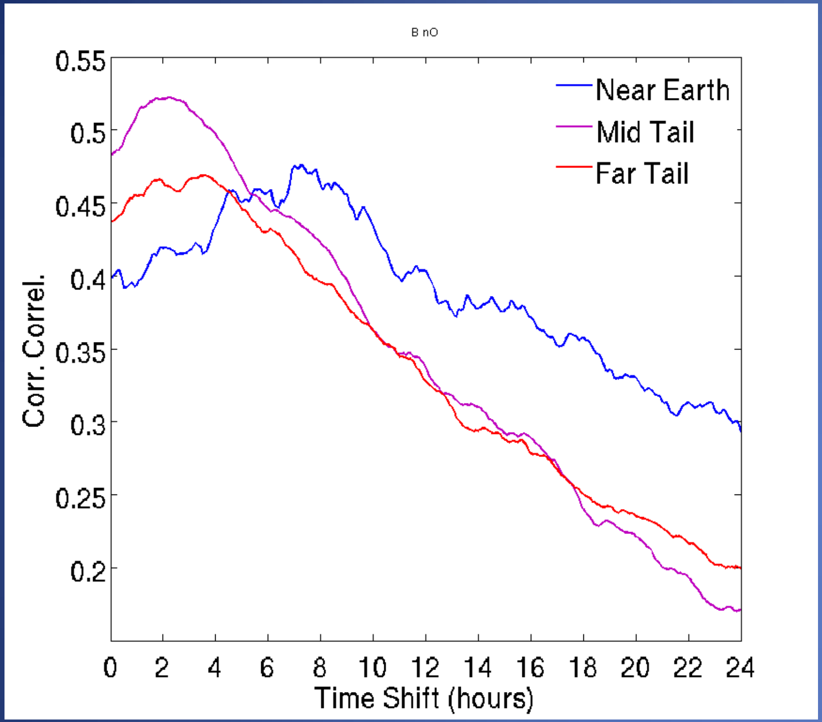
Quick response of nO^+ to IMF B_Z in the mid and far tail

Delayed response in the inner magnetosphere but last longer

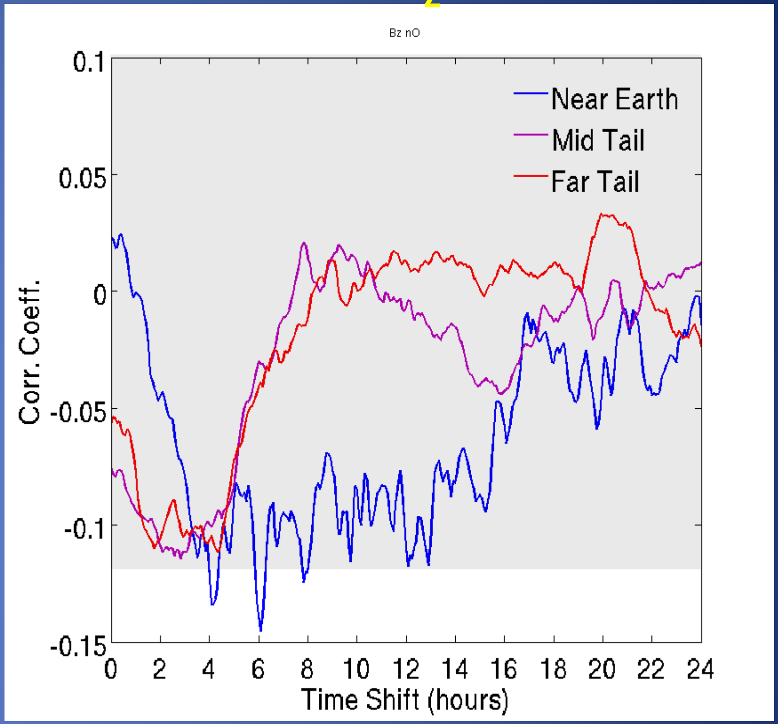
Results: O^+ density in the plasmasheet

Correlation with nO^+

B



B_Z



Quick response of nO^+ to IMF B_Z in the mid and far tail
Delayed response in the inner magnetosphere but last longer

Results: O^+ density in the plasmasheet

- Parameters which are best correlated with O^+ density in the plasmasheet:
  B, P, V, N and B_Z

- Better correlation with B compared to B_Z
  - Artefact due to the fact that B is always positive?
  - Strong impact of the magnitude of IMF B_Z?

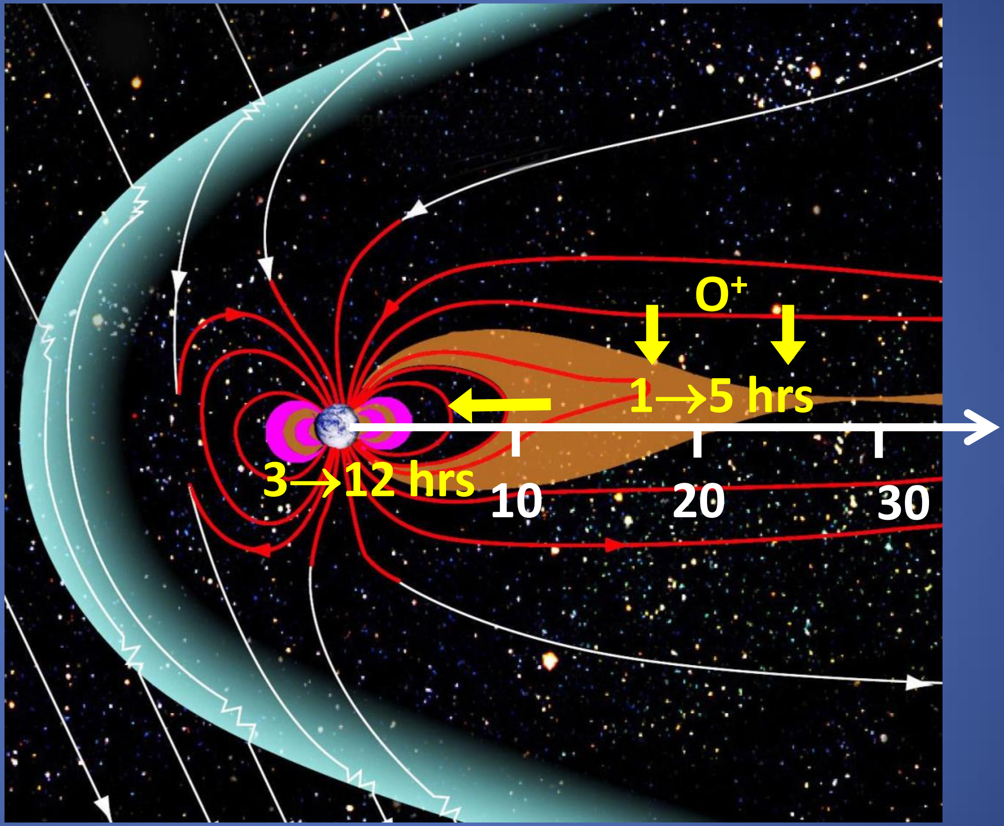
- Long correlation time, statistically significant up to $\Delta t > 1$ day.
- Quick response of the O^+ density in the mid/far tail (1-5 hours), presumably due to the direct injection of ions in this region
- Slower response of the O^+ density in the inner plasmasheet (3-12 hours), presumably due to the fact that O^+ ions in this region are convected from the mid/far tail and have longer residence time

- The response time must be taken into account when correlation the plasmasheet composition to solar wind or activity indices.

"The O^+ density is more sensitive to geomagnetic activity in the mid tail plasmasheet than in the near Earth regions" really? or is it just delayed?

Results: O^+ density in the plasmasheet

These result are consistent with an injection of ionospheric ions in the mid-far tail followed by an earthward drift to the inner magnetosphere where ionospheric ions have a longer residence time.



Can we get information about the ionospheric source and outflow processes from these results?

Can we get information about the ionospheric source and outflow processes from these results?
Not straightforward…

The O^+ density in the plasmasheet results from the integrated effect of source and loss processes

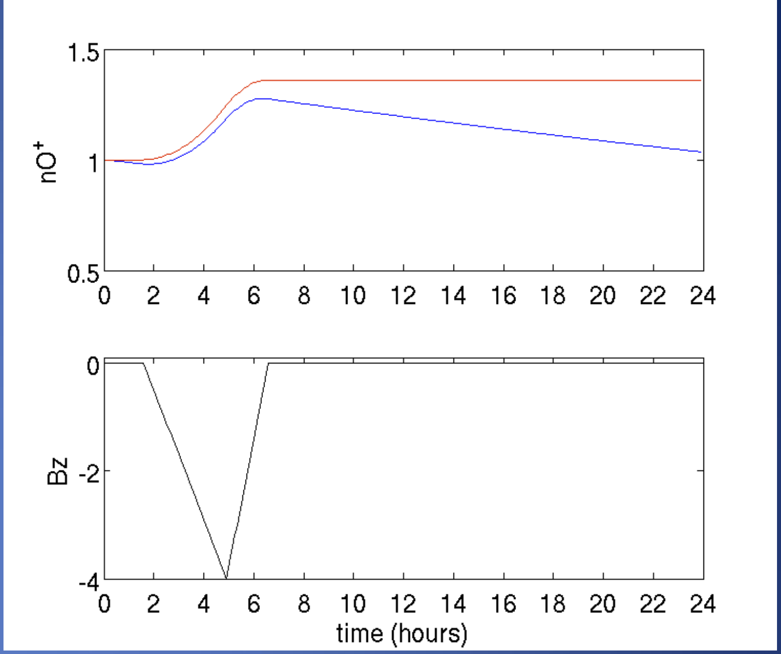
$$\frac{d(nO^+)}{dt} = S - L$$

$$nO^+(t) = \int S(t)dt - L(t)dt$$

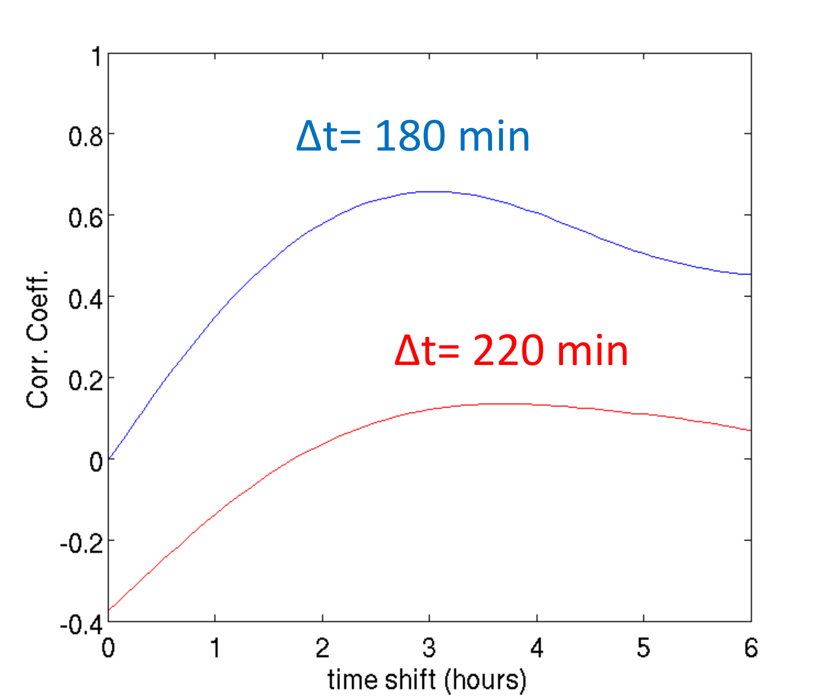
$\Rightarrow$ While we have a good dataset in the plasmasheet, we don't have direct information on outflow processes

$$S(t) = K_S . B_Z, L(t) = K_L$$

$$S(t) = K_S . B_Z, L(t) = 0$$



Instantaneous response of the source to IMF B_Z BUT the delayed correlation indicates a peak of the CC with a significant delay



Correlation between S(t) and $|B_Z|$

The response of the ionospheric source is likely faster than the location of the peak of the CC

$\Rightarrow$ The ionospheric source responds quickly to the solar wind/IMF

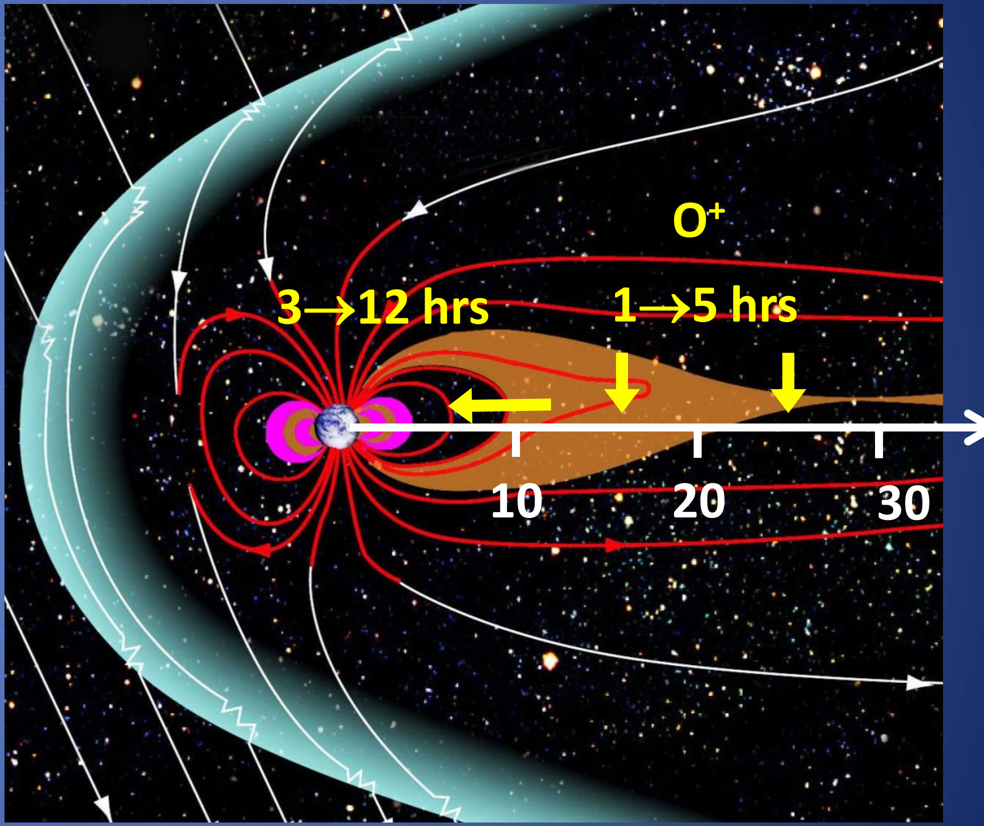
Ionospheric source

Cusp

A modulation of this source would impact the plasmasheet composition with a delay consistent with our observations (TOF ~ 1 hour or less)

An increase of the inflow of keV O^+ transiting in the lobes would mostly affect the mid-far tail plasmasheet where these energetic ions enter the plasmasheet (e.g. Cladis and Frank 1992, Peroomian et al. 2006)

Consistent with Cluster case studies of during storm periods (Kistler et al. 2010)



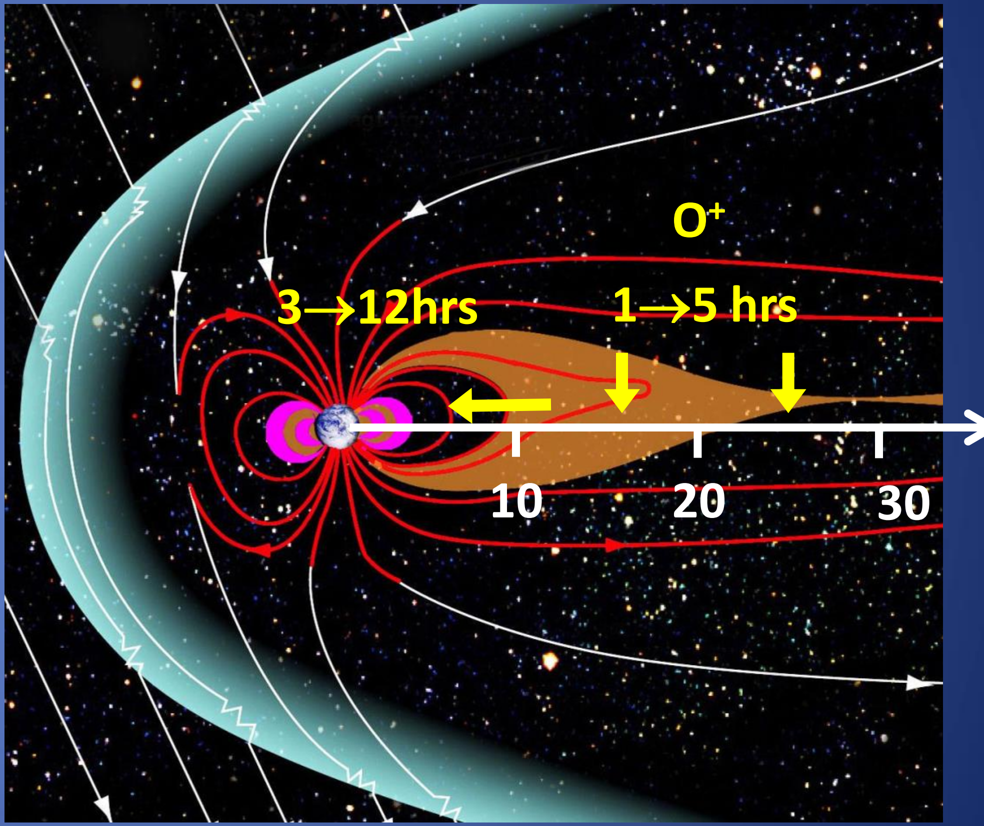
Ionospheric source

Nightside auroral zone

An increase of this source during substorm would result in an increase of the O+ density in the plasmasheet with a delay of ~1 hour (~40 min. B_Z →substorm + ~20 min. TOF)

Where do auroral outflow reach the plasmasheet?

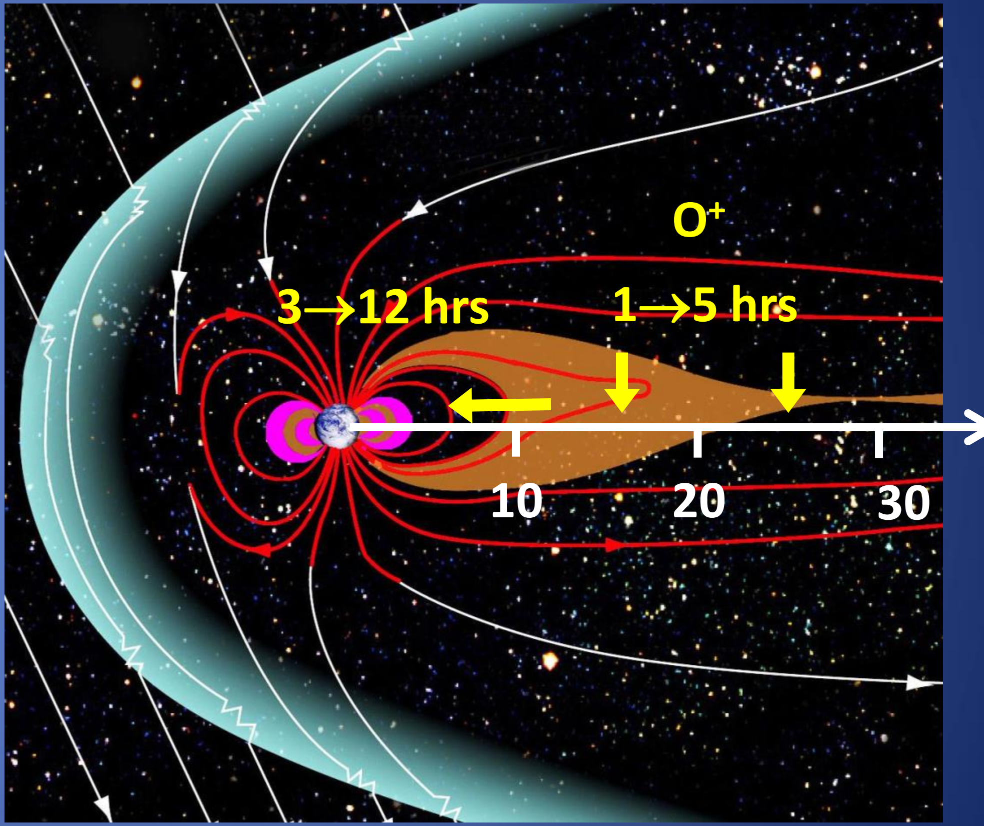
- 12 R_E (Delcourt et al. 1989, model)
- 20R_E (Sauvaud et al. 2004, observations)



Ionospheric source

Polar wind

- Low E ions escaping from the polar cap likely contain a significant fraction of O^+ ions (e.g. Abe et al. 2004, Maes et al. 2015…)
- Polar wind ions can reach the mid and far plasmasheet (e.g. yau et al. 2012)
- While these low energy ions have a long transport time, an increase of convection during active periods may lead to a rapid injection of low-energy ions in transit in the lobe region (Peterson et al. 2009)



Conclusion

The response time has to be taken into account
Linear correlation analysis in space physics has to be interpreted carefully. In particular the magnitude of the CC.

The O^+ density in the mid/far plasmasheet responds quickly to solar wind/IMF
The response in the near Earth regions is slower
$\Rightarrow$ Injection of ionospheric ions in the mid/far plasmasheet followed by transport toward the Earth

Difficult to separate the contribution of the various ionospheric source and of transport processes
- Is linear correlation a pertaining tool?
- May be more relevant to directly correlate ion outflow to solar wind/IMF parameters