

low-energy ion-neutral interactions as post-Cluster White Paper theme

M. Yamauchi¹, I. Dandouras², J. De Keyser³, O. Marghitu⁴, G. Parks⁵, and White Paper team

(1) IRF, Kiruna (2) IRAP, Toulouse (3) BIRA-IASB, Brussels (4) ISS, Bucharest (5) UCB/SSL, Berkeley

1. Low-energy plasma-neutral gas interaction in space

1.1. Present-day knowledge

1.2. Limitations

1.3. Observation-model discrepancy

ex.1 Earth: neutral behavior in the upper thermosphere and exosphere

ex.2 Venus and Titan: super-rotation and fast ion flow

ex.3 Cold environments such as interstellar space: formation of organic matter

ex.4 Comet: unexpected structures in plasma-neutral gas mixed plasma

ex.5 Meteor: air burst

ex.6 Past climate change: solar influences

1.4. Science questions related to the plasma-neutral gas interactions

2. Measurement strategy

2.1. Required measurements for ions and neutral species

2.2. Required measurements of the background plasma

2.3. Required measurements for external energy source

2.4. Summary of relevant measurements ([Table 2](#))

2.5. Destinations of relevant missions ([Table 1](#))

3. Terrestrial mission case ([Fig. 1](#), [Table 3](#))

3.1. Observation strategy using multi-spacecraft

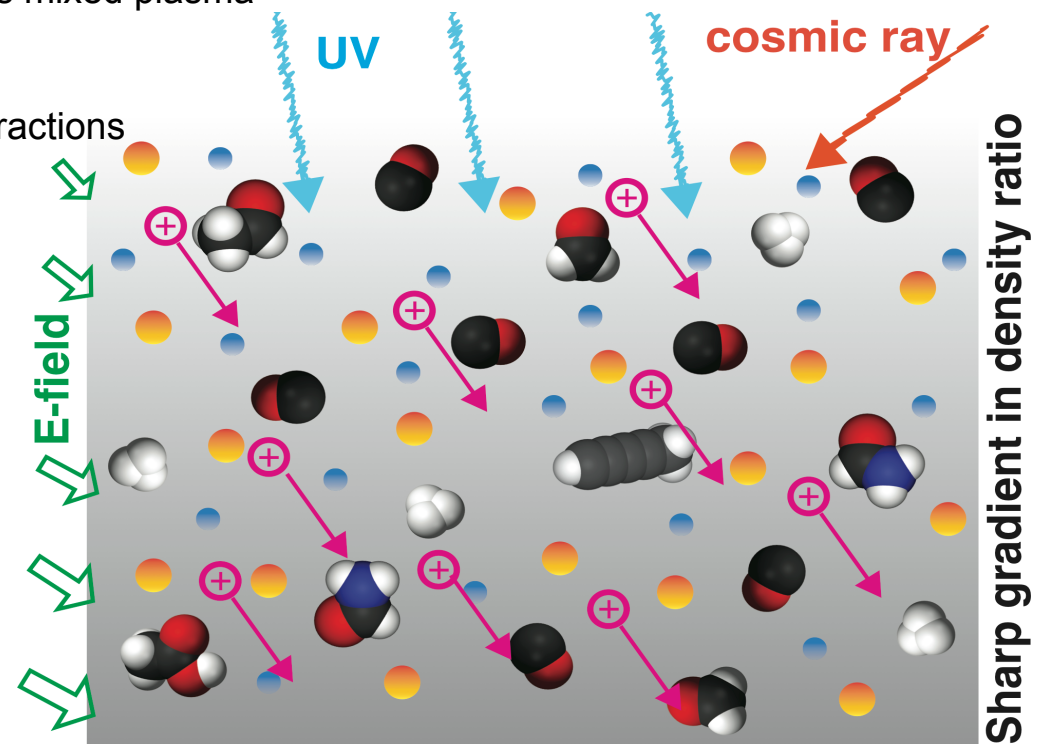
3.2. Payload

3.3. Support from the ground-based observations

3.4. Science Closure ([Table 4](#))

3.5. Requirement for the spacecraft

4. Summary of Technological challenges



Beyond simplified approximations

Recent space observations in mixtures of ions and neutral suggest that the present knowledge on plasma-neutral gas interactions is far from complete

Due to this lack of knowledge, it is difficult to describe neutral behaviors in a tenuous plasma (upper thermosphere and exosphere, comet, interstellar medium): $\Rightarrow$ Theme (A)

(A) How and by how much do plasma-neutral gas interactions influence the re-distribution of externally provided energy to the composing species? (physical aspect of the energy re-distribution)

(A1) Impact of ion-neutral energy exchange on long-term evolution of planet, comet, ring, etc.

(A2) Structures and variability of the upper thermosphere and exosphere

(A3) Energy cascade in partially ionized plasma with large gradients or layered structures

(A4) Role of ion-neutral momentum transfer in the super-rotation and cold ion flows

Organic matters in space are found in low-density and low-temperature environments, where neutral-neutral interactions is less efficient than neutral-ion interactions: $\Rightarrow$ Theme (B)

(B) How and by how much did plasma-neutral gas interactions contribute the growth of heavy complex molecules toward biomolecules? (chemical aspect of the energy re-distribution)

(B1) Plasma conditions that enhance the chemical reaction?

(B2) Formation of catalytic plasma structure in tenuous environments

Possible parameters that influence the interaction are: **(1) Temperature; (2) Density, composition, and ionization ratio; (3) Gravity; (4) External free energy** (radiation, cosmic ray, large-scale E & B field); and **(5) Existence of catalysts** (surfaces of the dust grains, cloud, non-mixing layers). Among them, (1)-(3) are difficult to achieve inside ground laboratory experiment and need in-situ observations.

Mission destination	(1) T	(2) n	(3) g	A1	A2	A3	A4	B1	B2	mission size ^{*2}
Interstellar/Oort cloud	very low	very low	very low	x	-	x	(x)	x	(x)	LL or L
Ice Giant atmosphere	very low	medium	high	x	x	x	x	(x)	(x)	LL
plumes (Enceladus, Io, Europe)	low	medium	medium	x	x	x	(x)	x	(x)	L or LL
Titan around exobase	low	medium	high	x	x	x	(x)	x	x	L or LL
comet rendezvous	wide^{*1}	wide^{*1}	low	x	x	x	x	x	x	L
deep inside gas giant	medium	high	very high	(x)	-	(x)	-	(x)	-	L
artificial comet	medium	high	medium	x	-	x	(x)	(x)	(x)	< M
Earth around exobase	high	medium	high	x	x	x	x	x	x	M
Venus around exobase	high	medium	high	x	x	x	x	x	x	M
planetary L2 comp.	(mixed)	low	very low	x	(x)		(x)	-	-	< M

*1 It ranges from very low to high along the orbit.

*2 LL: Need to collaborate with other agency (for cost or RTG).

Table 1: Where to go

What must be measured?	priority* ¹	Earth* ²	in-situ method	remote method* ³
Neutral/Ion density (major species)	1	n/a	mature	mature
Neutral/Ion mass spectrometer to high m:	2	1	mature	mature
Neutral temperature (average)	1	n/a	under development	(too heavy)
Ion temperature (average)	2	3	mature	(too heavy)
Neutral temperature (major species)	2	1	under development	(too heavy)
Electron temperature and density	2	1	mature	Earth only
Neutral bulk velocity (average)	2	n/a	need improvement	only limited case
Ion bulk velocity (average)	2	3	need improvement	Earth only
Neutral velocity distribution (major species)	1	1	under development	only limited case
Ion energy spectra (major species) < 10 eV	2	3	need improvement	-
Energetic neutral energy spectra >10 eV	2	1	need improvement	-
Ion energy spectra (major species) >10 eV	2	1	mature	-
Electron energy spectra	2	1	mature	-
Energetic particles (> 10 keV)	3	1	mature	-
Cosmic ray (> 100 MeV)	3	3	(too heavy)	Earth only
DC B-field	1	1	mature	Earth only
DC E-field	2	1	mature	Earth only
Electric current	3	3	mature	Earth only
EM waves < 10 kHz	3	3	mature	-

*1: **1: always mandatory, 2: mandatory depends on mission, 3: optional**

*2: Priority for Terrestrial mission. **1: mandatory, 3: optional**

*3: Either from the spacecraft and from ground (mainly for Earth).

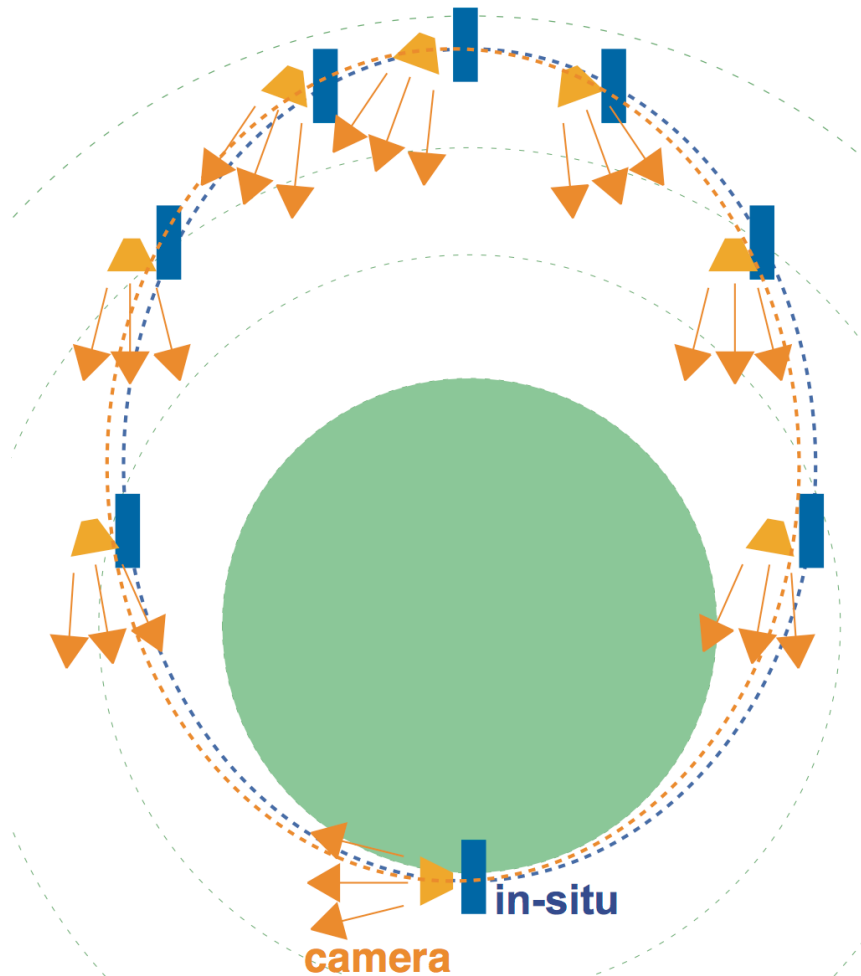
Table 2: what to measure

Fig. 1/Table 3: Terrestrial mission case (can copy for Venus/Mars)

Main (in-situ): payload 100-120 kg

Sub or despan platform (remote): payload 10-15 kg

Sub (in-situ) x 1 or 2 for multi-point: payload 5-10 kg



in-situ resolution: $\Delta h_{SC}/dt < 80 \text{ km}/20 \text{ sec}$

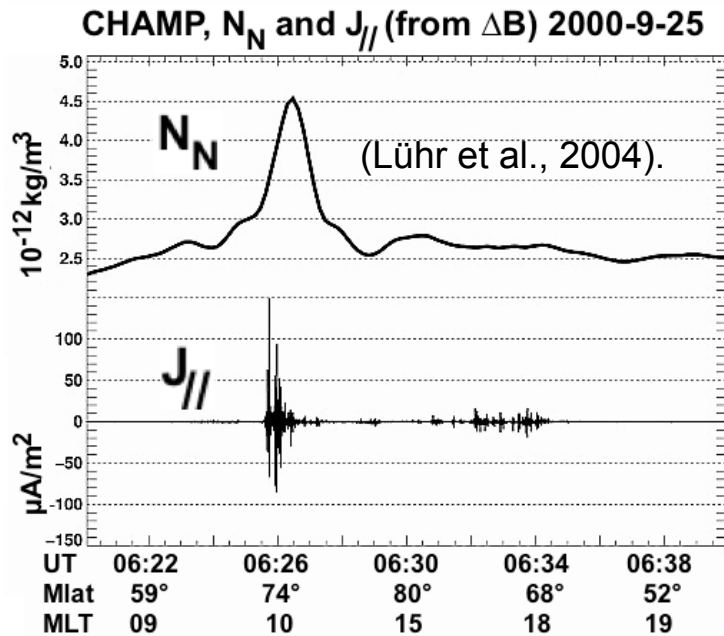
imager resolution: $\Delta h_{SC}/dt < 100 \text{ km}/\text{min}$

mandatory measurements	in-situ instruments
Neutral/Ion composition:	mass spectrometer (+ optical)
Tn (major species)	under development
Te and Ne	Langmuir probe
f(Vn) for N ₂ and O	under development
Ion (major species) >10 eV	ion spectrometer
Electron	electron spectrometer
DC B (5m boom)	magnetometer
DC E (20 boom)	antenna
keep SC potential < 1V	potential control
important measurement	
Ti (average)	Langmuir robe
Vi (average)	ion driftmeter
Vn (average)	accelerometer
Ion (major species) < 10 eV	cold ion spectrometer
ENA >10 eV	ENA
Energetic (> 10 keV)	solid-state detector
Cosmic ray (> 100 MeV)	wide angle telescope
Electric current	magnetometers
EM waves < 10 kHz	induction coil.

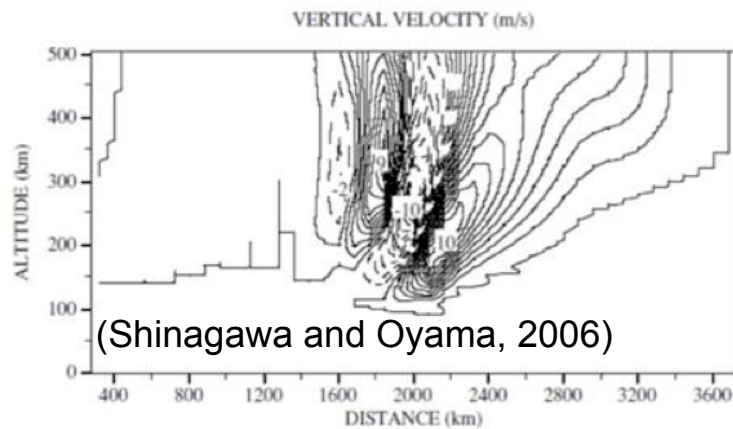
Table 4: Science closure for Earth mission case

Science question	How can observations answer?
(A) re-distribution of incoming energy through ion-neutral interaction	By covering the energy distribution and macroscopic parameters (n , v , T) of both the background neutrals and ions, energy transfer can be measured on the distribution function level, e.g., whether a double-peak distribution is formed or not when the velocity is different between ions and neutrals under low collision frequency.
(A1) effect on long-term evolution	Measurement for (A) also tells the neutral heating and its variation, allowing us to calculate neutral-driven escape
(A2) thermosphere/exosphere	By combining remote measurements with (A), we can separate spatial-temporal structures including the layered structures and its variability
(A3) energy cascade in gradient	By adding extra measurement points using small sub-satellites to the above (A), we can evaluate the effect of the gradient
(A4) ion-neutral moment transfer	Measurement for (A) directly answers this
(B1) condition for chemical reaction	The high-mass resolution composition data can tell the chemical products and the full plasma measurements tells the corresponding plasma condition
(B2) catalytic plasma structure	Combining measurements for (B1) and (A2), we can compare the layered structure and chemical reaction, to evaluate level of catalytic role of the structure

ex.1 Earth: Ionosphere-Thermosphere/exosphere interaction



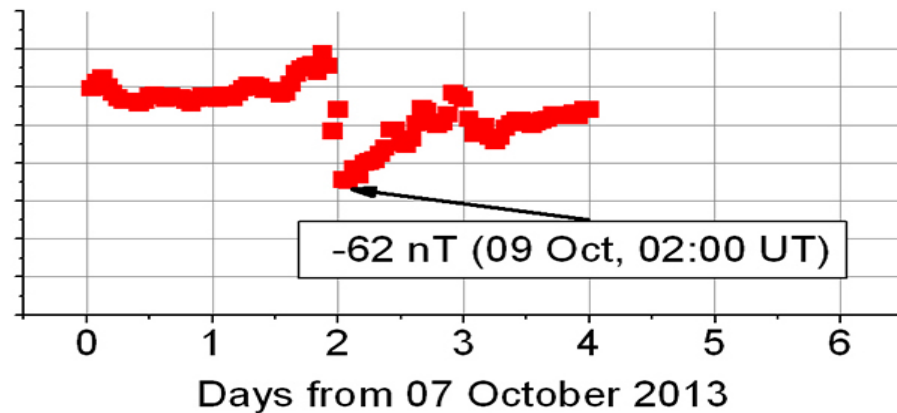
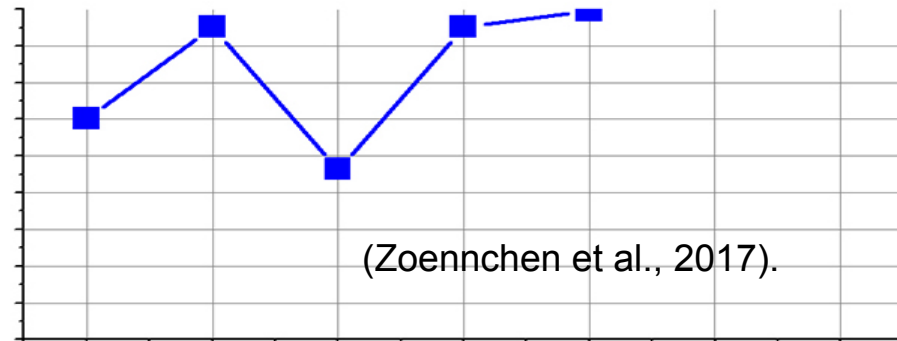
Observed density bump and fine-scale field-aligned at above 400 km altitude



Simulation of neutral wind in narrow channel does not re-produce observation

- (a) No modern measurement with composition > 300 km
- (b) Observations depart from of the models (left)
- (c) Anomaly particularly during magnetic storm.

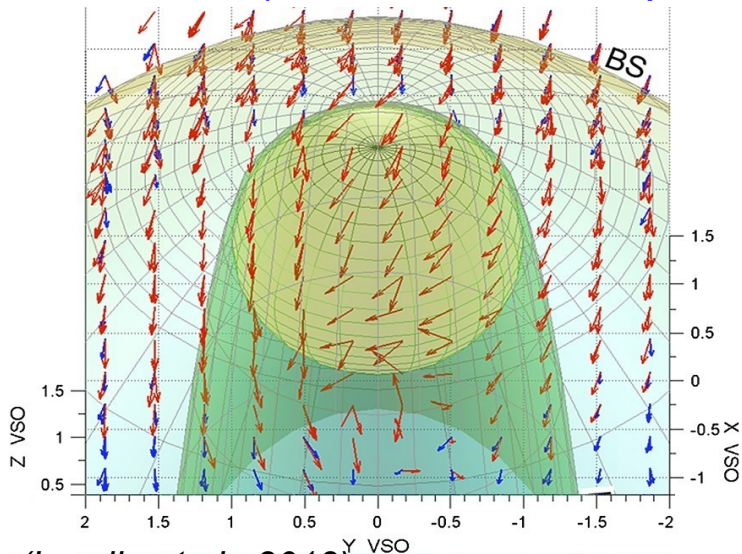
Storm 8 - day(0): 07 October 2013



Relative variation in the column density of exospheric H (represented by total solar Ly-alpha flux in %) suddenly increases (decrease in Ly-alpha flux) when a large geomagnetic storm took place

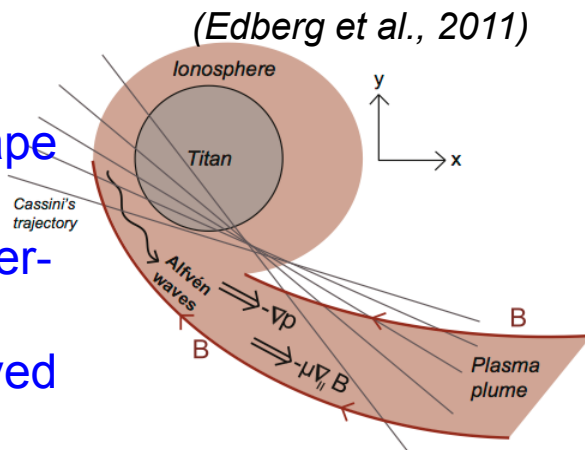
ex.2 Venus/Titan: super-rotation & cold ion outflow

(a) Ion convection in the super-rotation direction by VEX suggests that ions (10 times faster) drives neutral super-rotation.



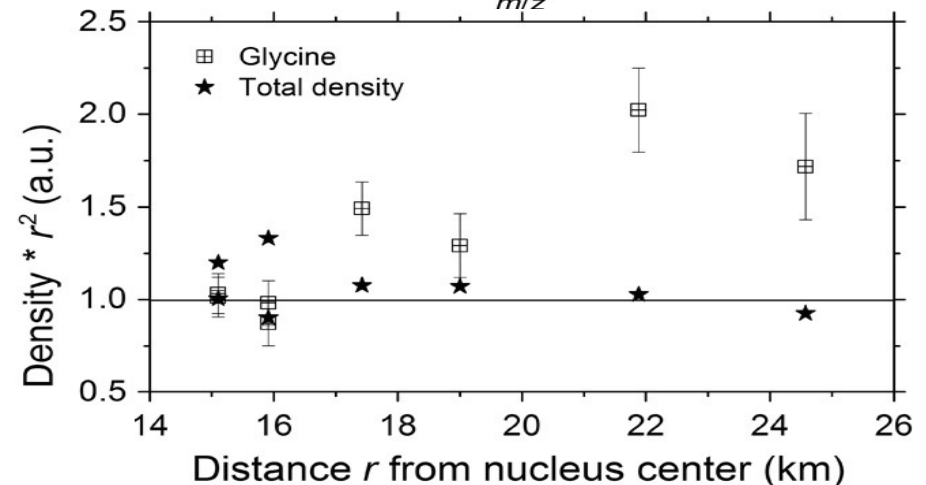
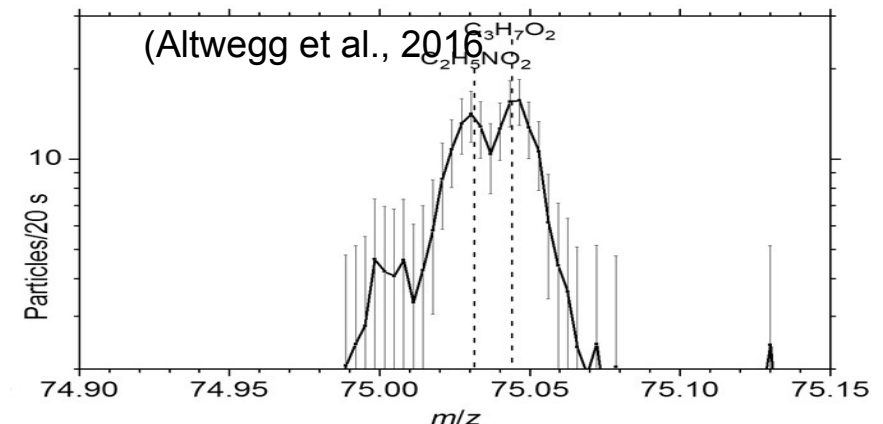
(Lundin et al., 2013)

(b) Massive escape of cold ions & atmospheric super-rotation for Titan remain as unsolved problems



ex.3 Formation of organic matters in cold environments

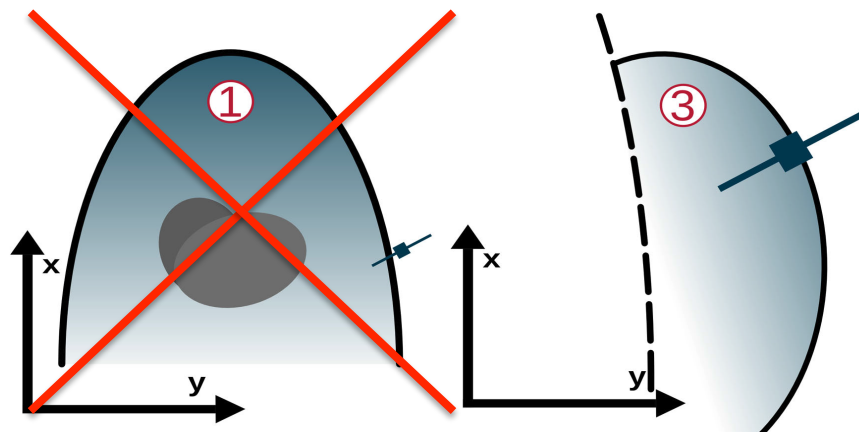
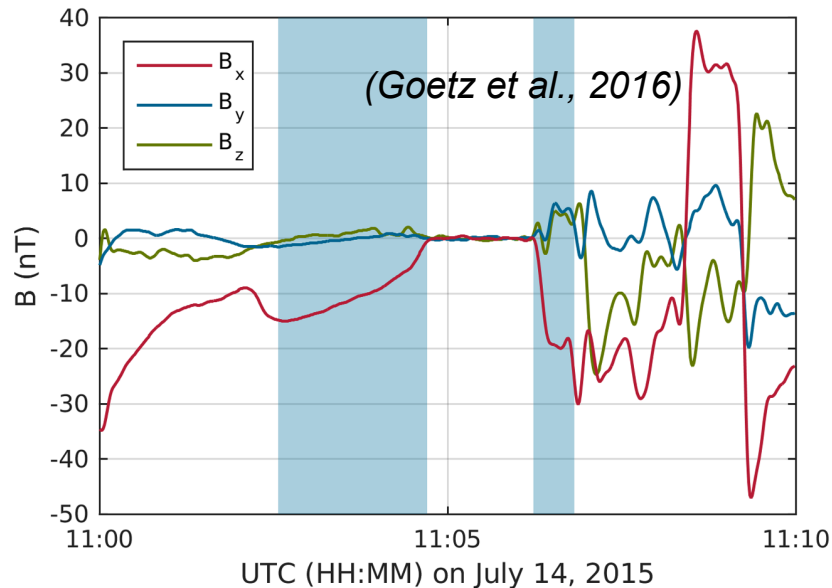
Complex carbonates and even amino acids are found in comet (Rosetta) and interstellar medium + Catalytic structure like stratospheric clouds under cold environment enhances chemical reactions $\Rightarrow$ roles of cold environment ?



Rosetta observations of volatile Glycine ($C_2H_5NO_2$)).

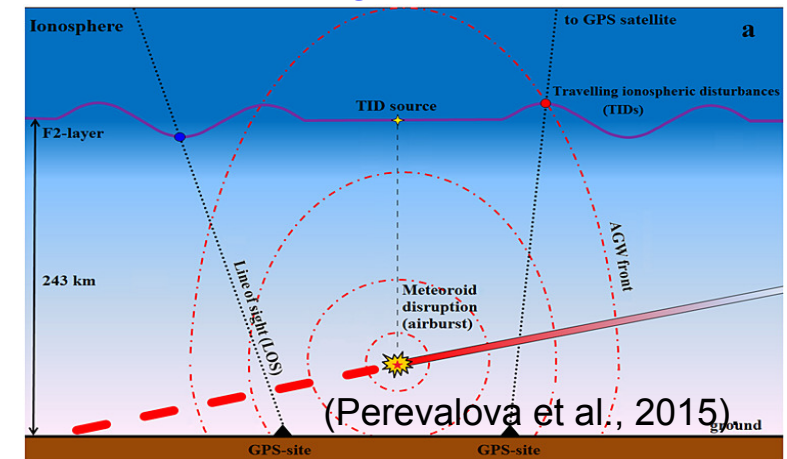
ex.4 Comet: unexpected structures

Magnetic cavity (probably bubble-like rippling of the boundary) is difficult to explain with ions and electrons only, and influence of neutrals in forming the magnetic cavity is suspected.



ex.5 Meteor: air burst

Chelyabinsk meteoroid airburst affected the ionosphere. Airburst/shock energy that involves plasma was larger than expected



ex.6 Climate: solar influences

Sun was the main driver until 1980's. $\Rightarrow$ How did plasma/B-field influence the neutral atmosphere?

