Comet 67P - a mass loading laboratory

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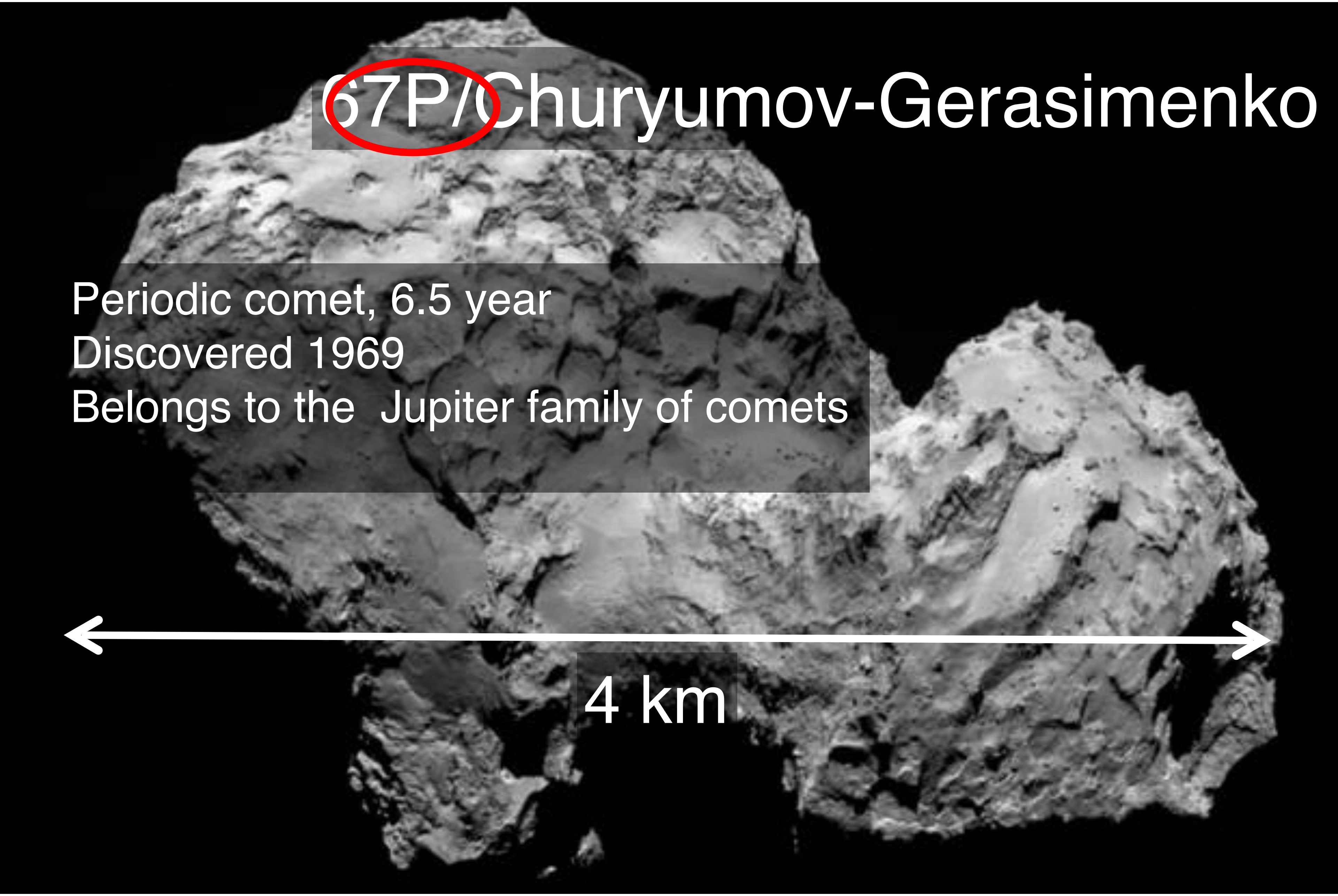
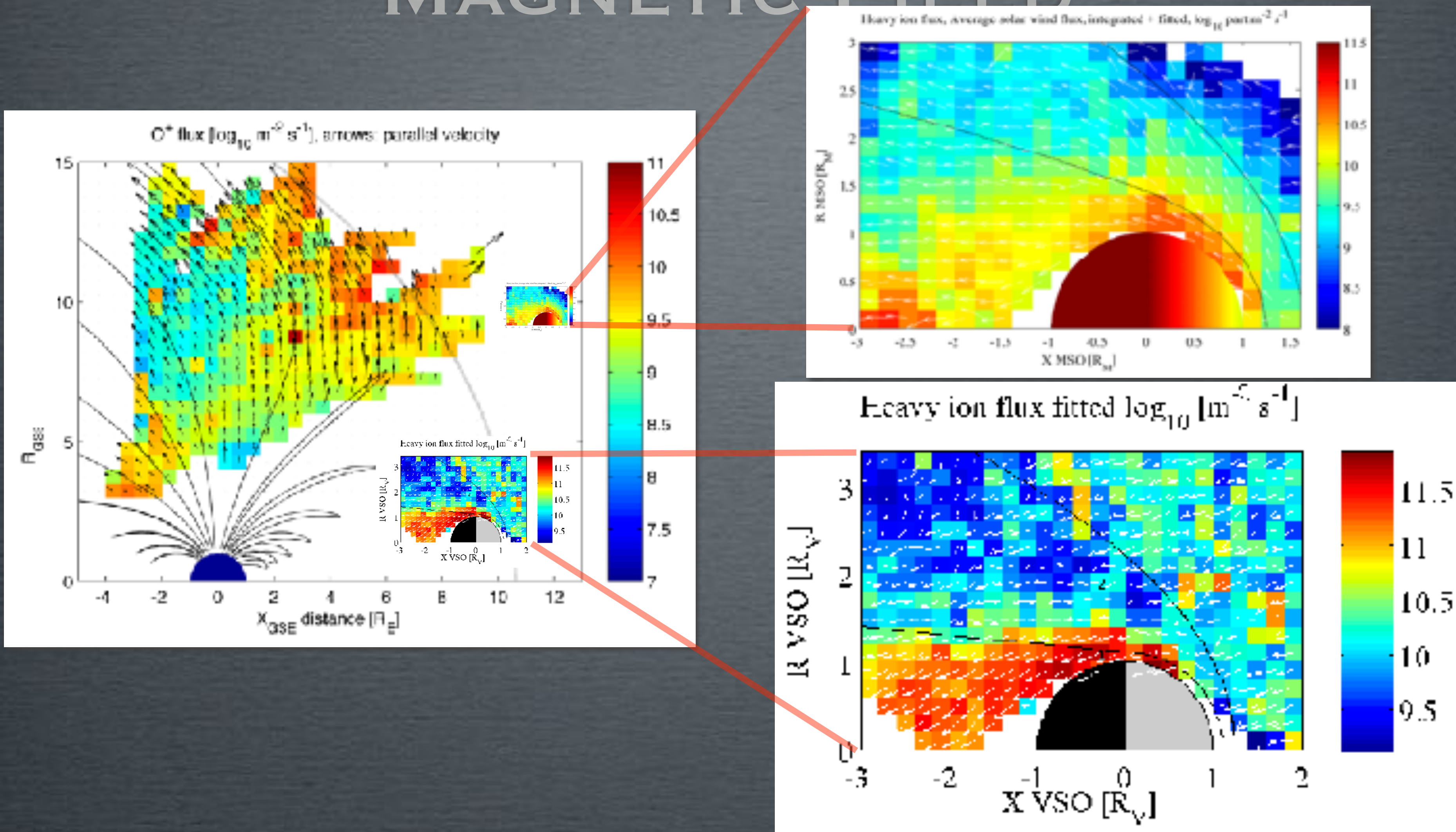
All Is Lost

A. I. Eriksson


67P/Churyumov-Gerasimenko
Periodic comet, 6.5 year
Discovered 1969
Belongs to the Jupiter family of comets
4 km

Emergence of boundaries

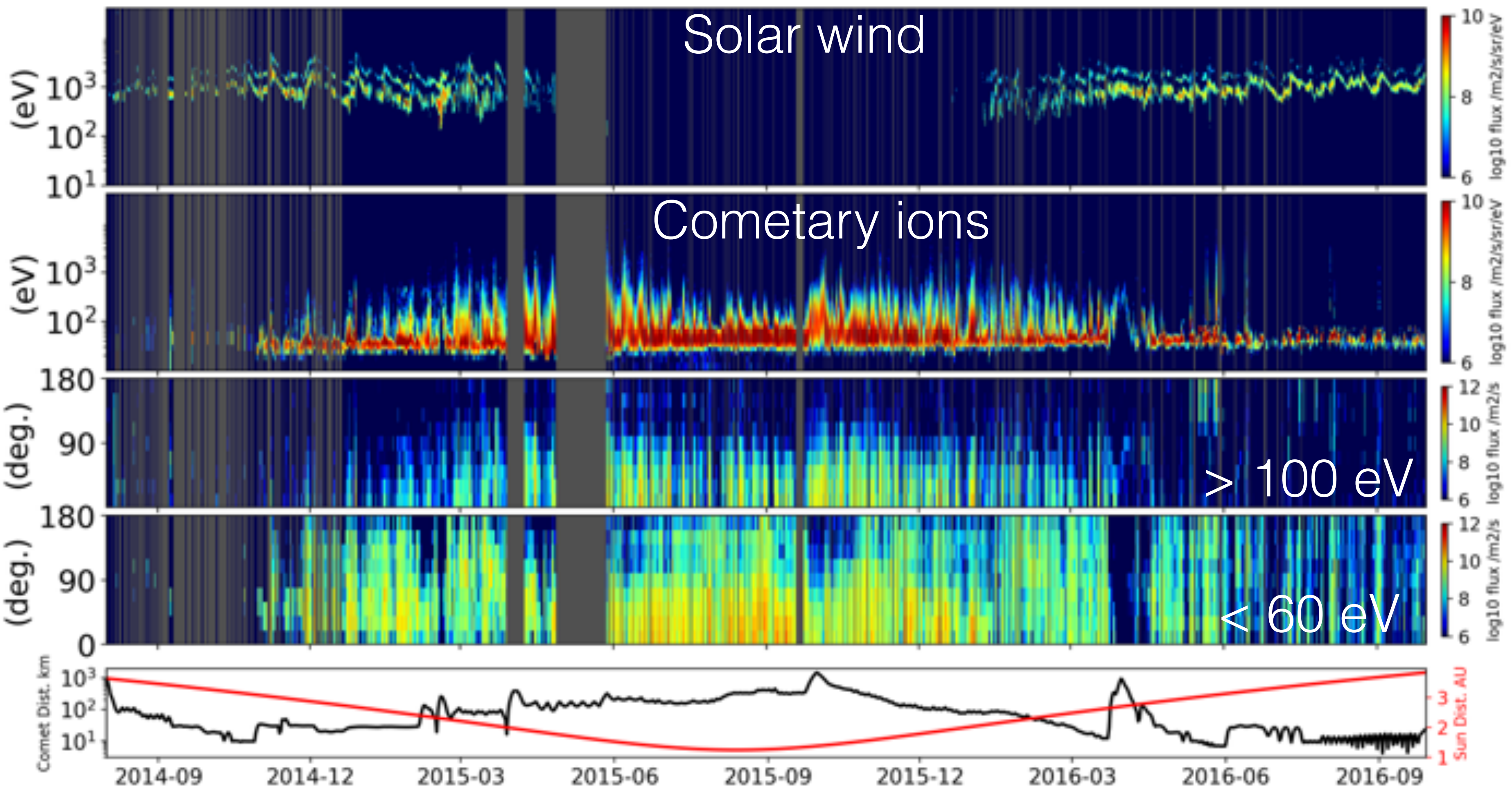
Role of a Planetary Magnetic Field



A Changing Paradigm?

Ion Environment of comet 67P

Nilsson et al., MNRAS, 2017



Cone angle of cometary ions, 0° anti-sunward

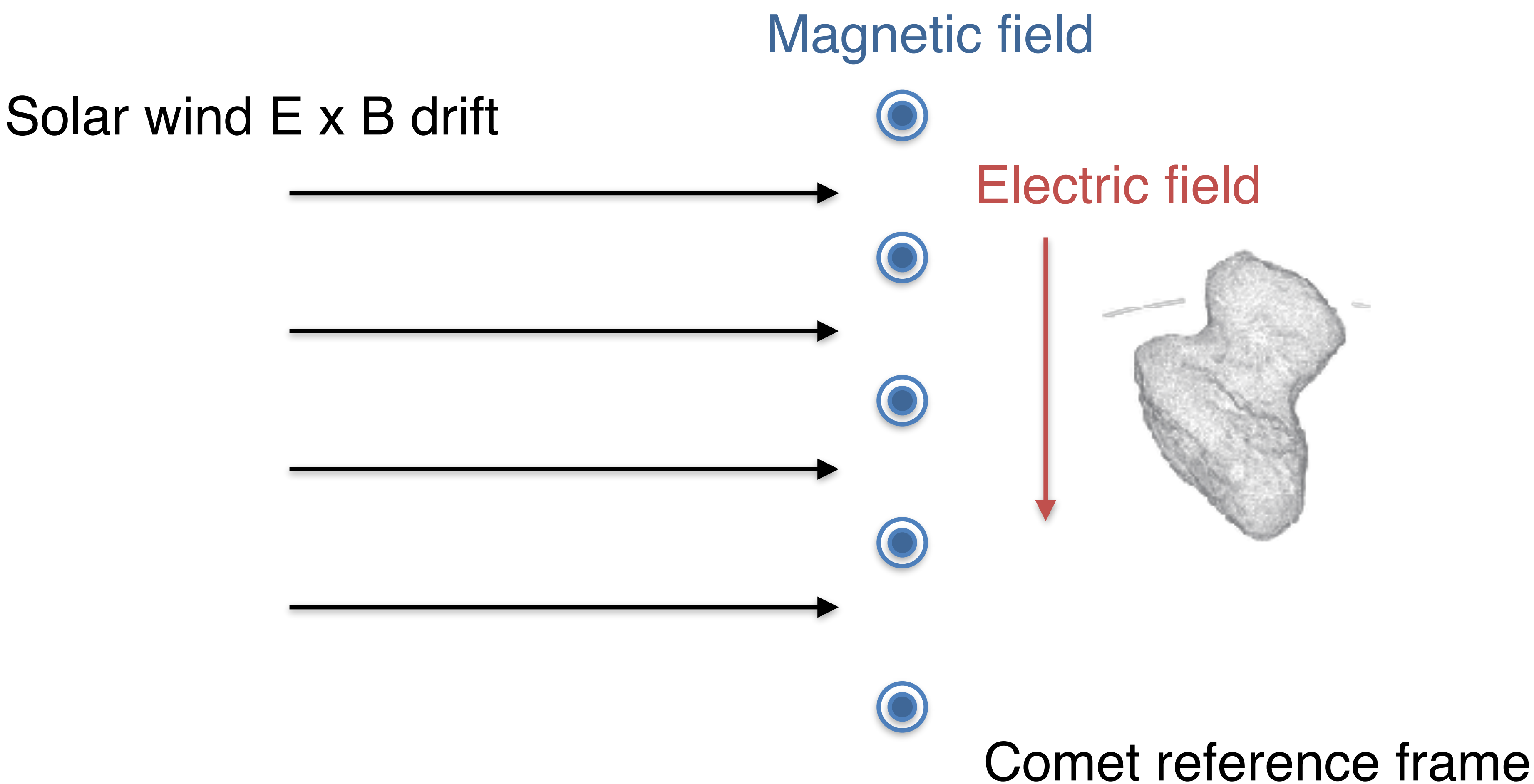
Before the boundaries form

The role of mass-loading

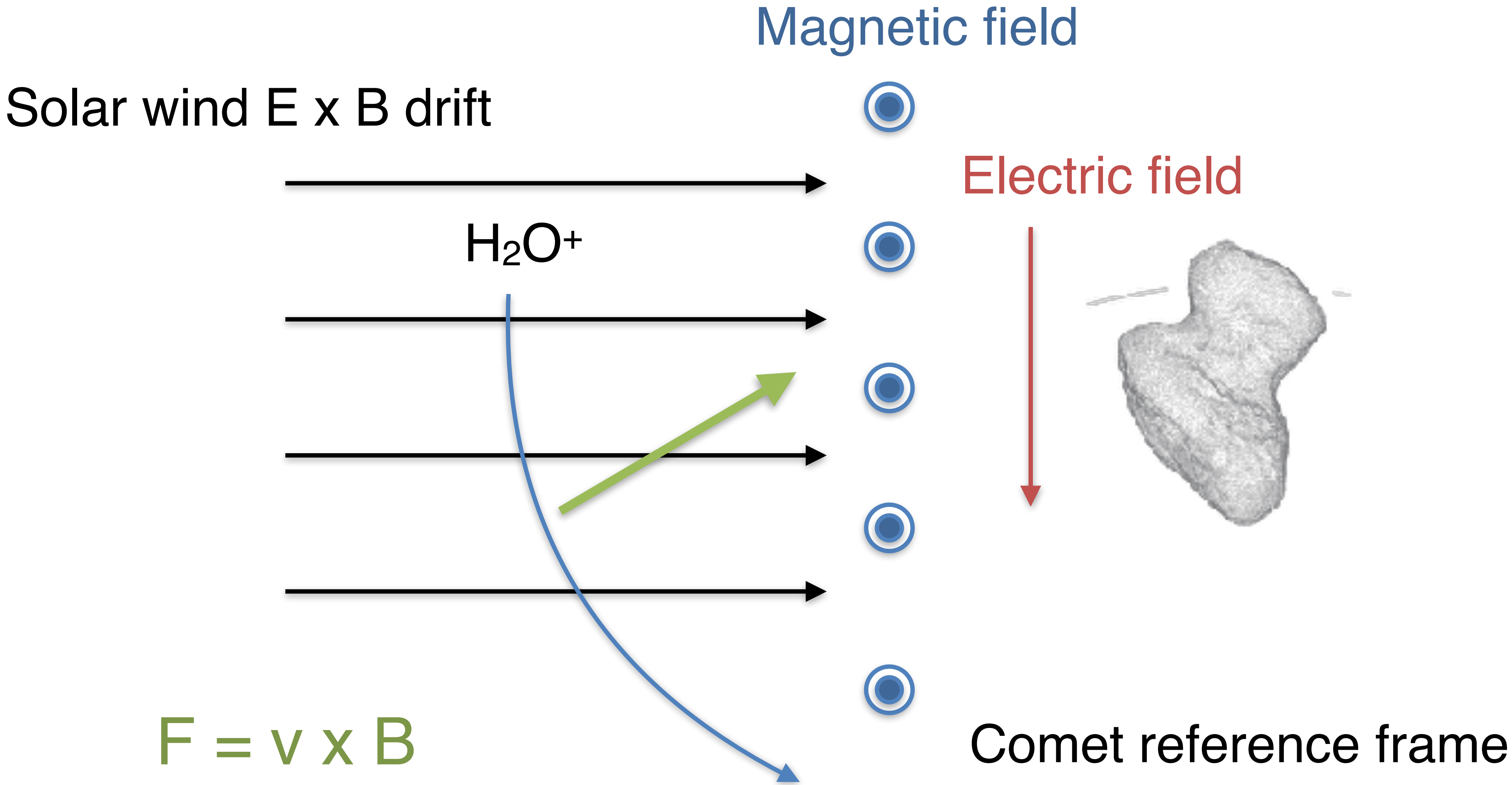
Why is mass loading important?

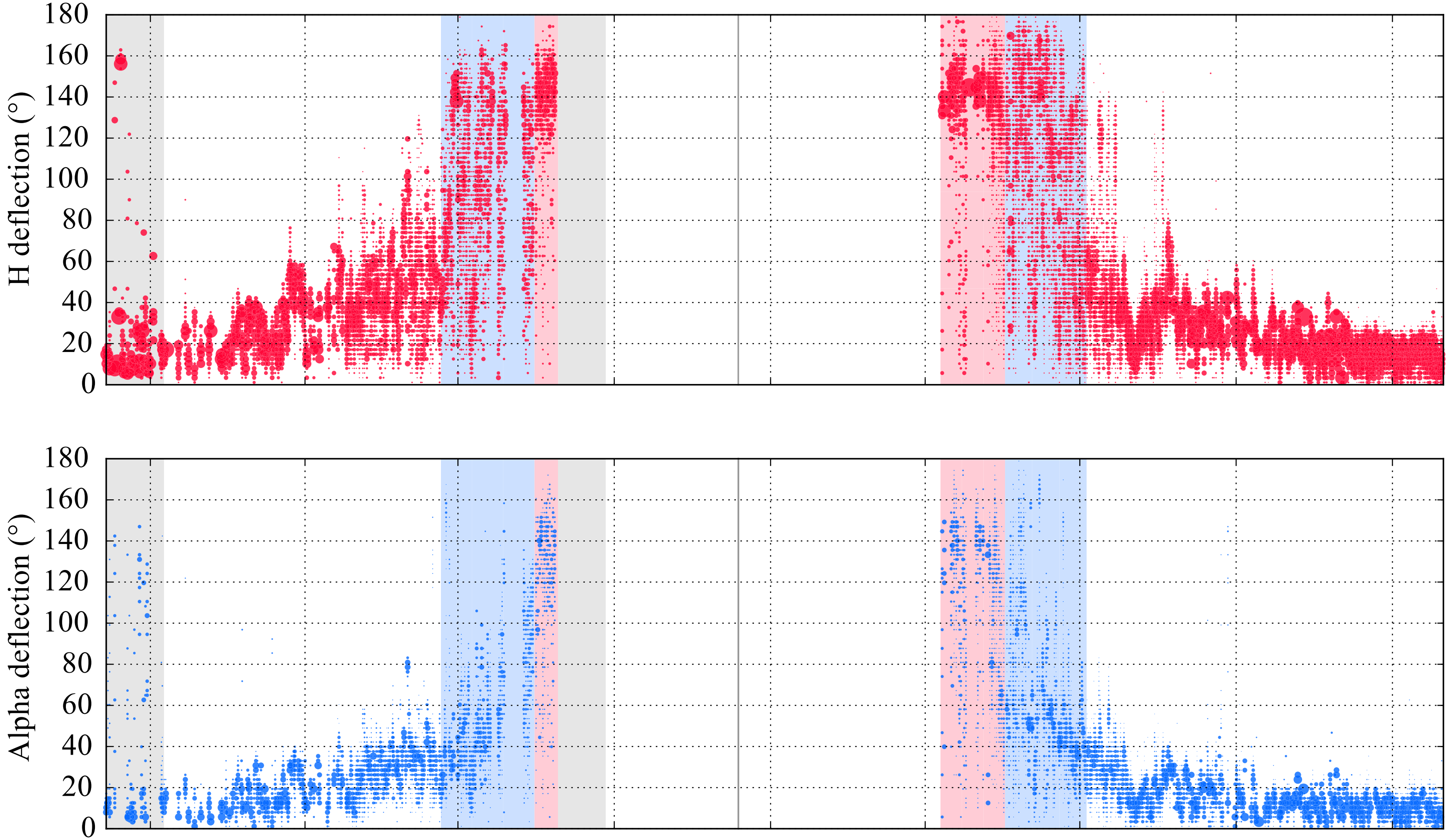
- Direct interaction between solar wind and atmosphere
- May happen for a hot atmosphere with a large scale height
- Young Earth - strong EUV heated the upper atmosphere
- Strong stellar wind may overcome pressure of ionopause / magnetopause

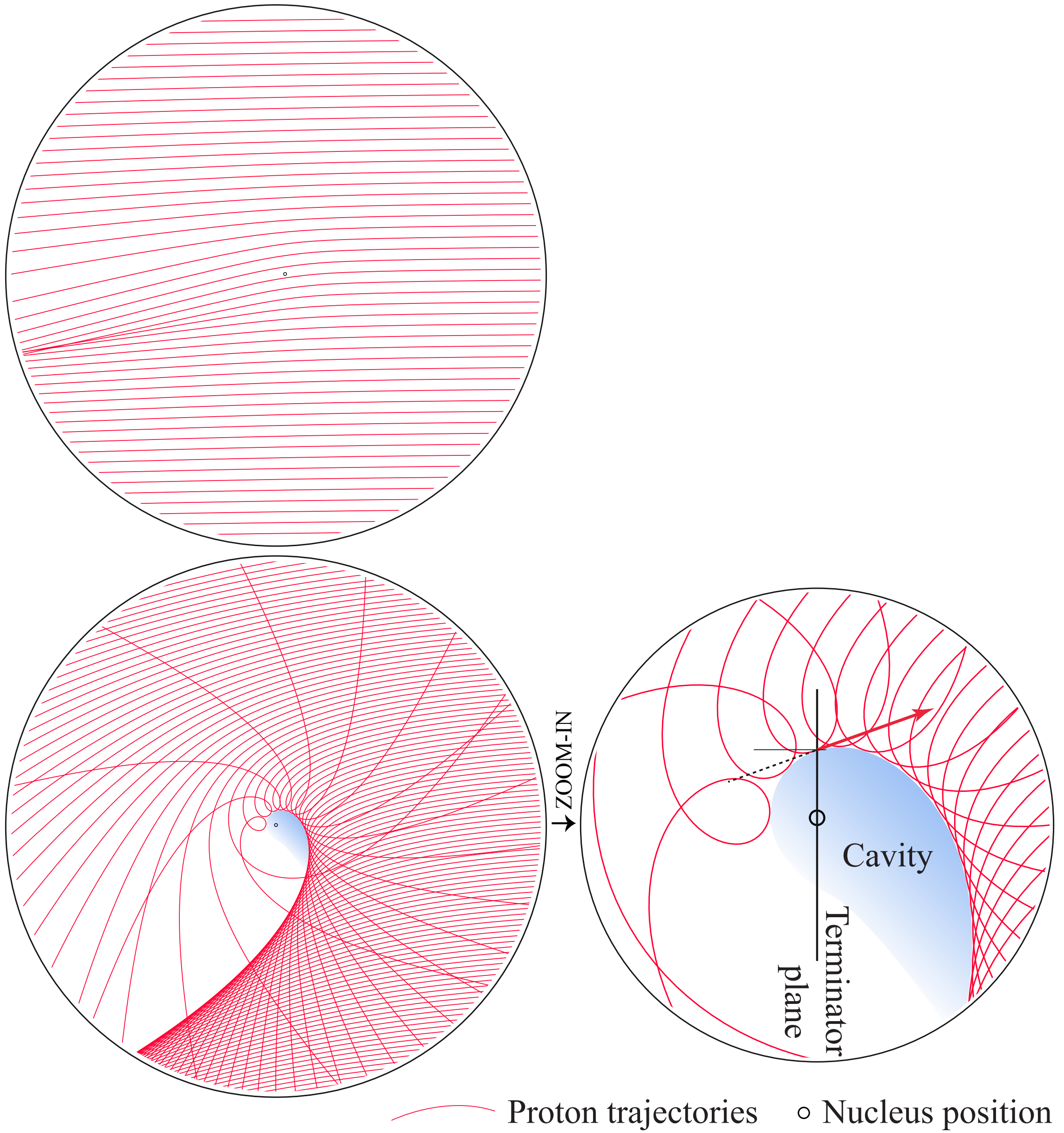
Lets look at some of the physics!



What happens to a new born ion?




180
160
140
120
100
80
60
40
20
0
H deflection (°)
Alpha deflection (°)


ZOOM-IN
Cavity
Terminator plane
Proton trajectories
Nucleus position

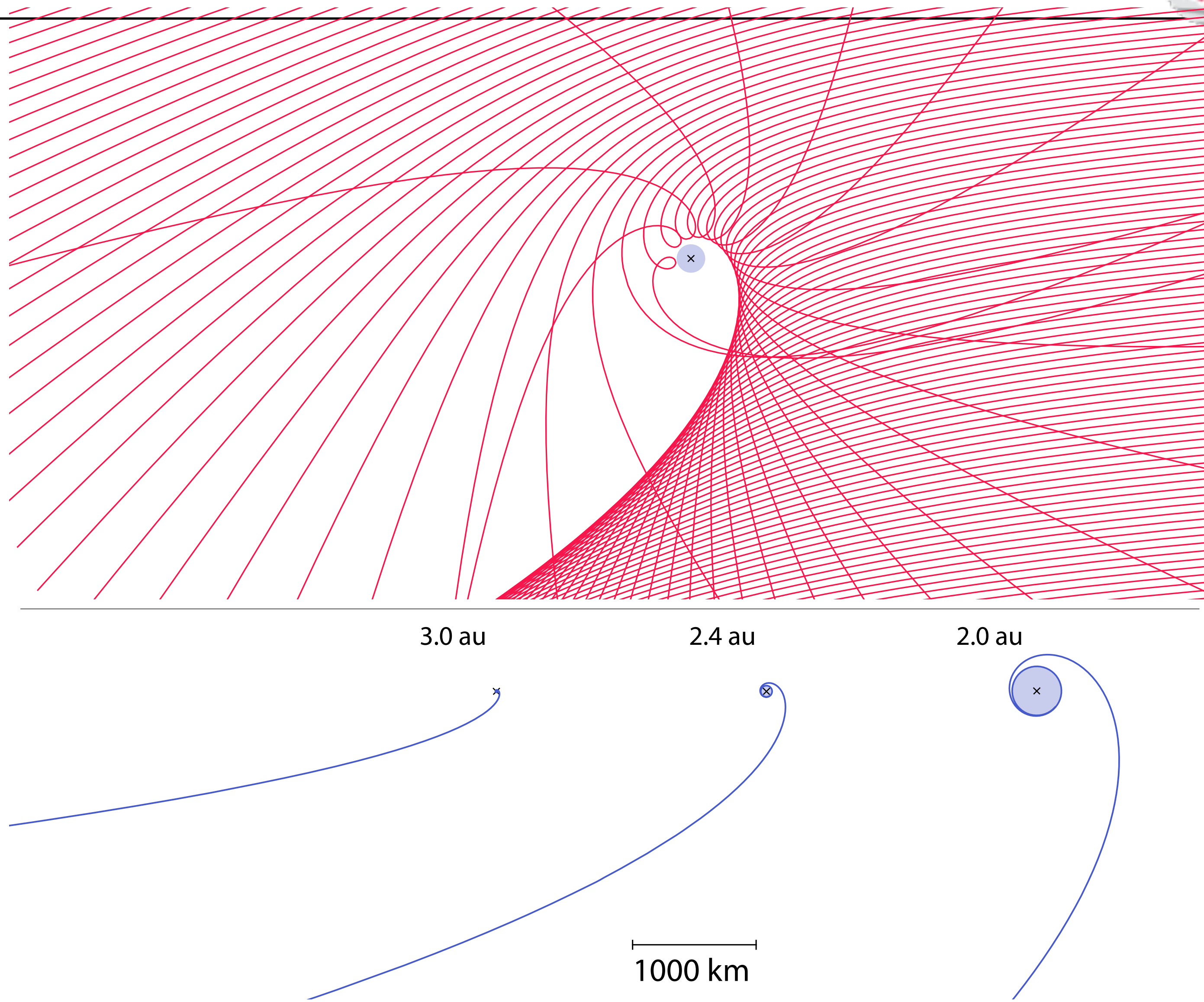
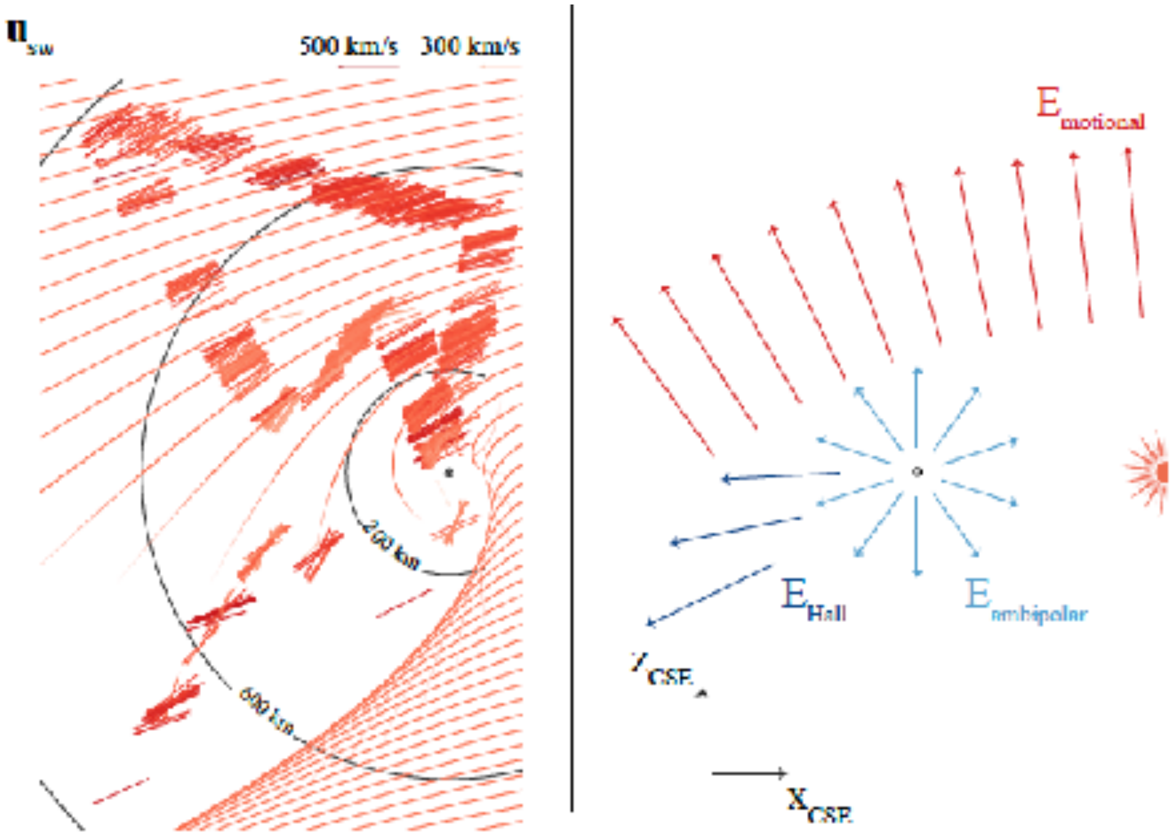
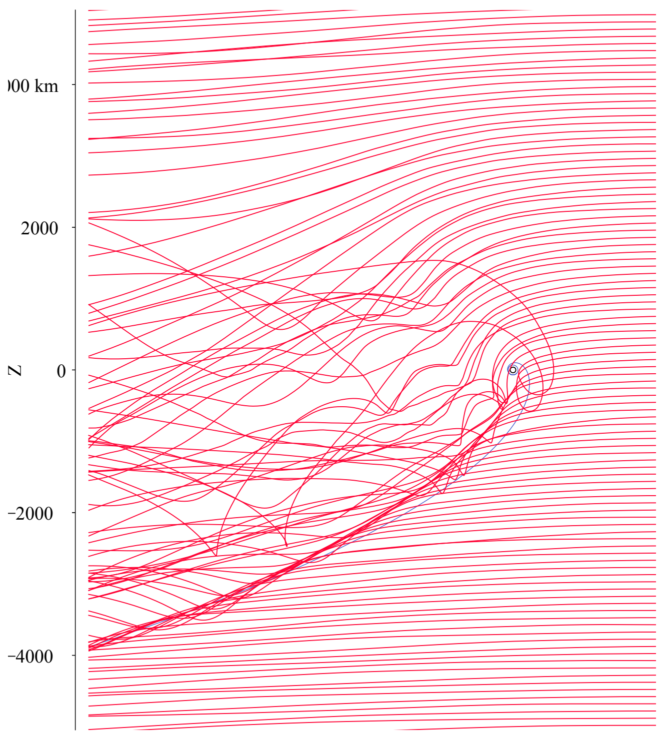


Fig. 4. Top row: examples of solar proton trajectories, dimensionless, initially flowing from the right to the left. No particle can enter in the cavity, the central disk of radius $r_{\mathrm{cav}} \approx 0.28\, r_E$. Bottom row: the shape of the caustic created by particles coming from infinity, using the same spatial scale for three different heliocentric distances, as developed by Saillenfest et al. (2018). The corresponding values of r_E are, from left to right: 27, 165 and 714 km. Near the origin, the caustic wraps around the cavity. The nucleus position is displayed by a black cross in all plots.

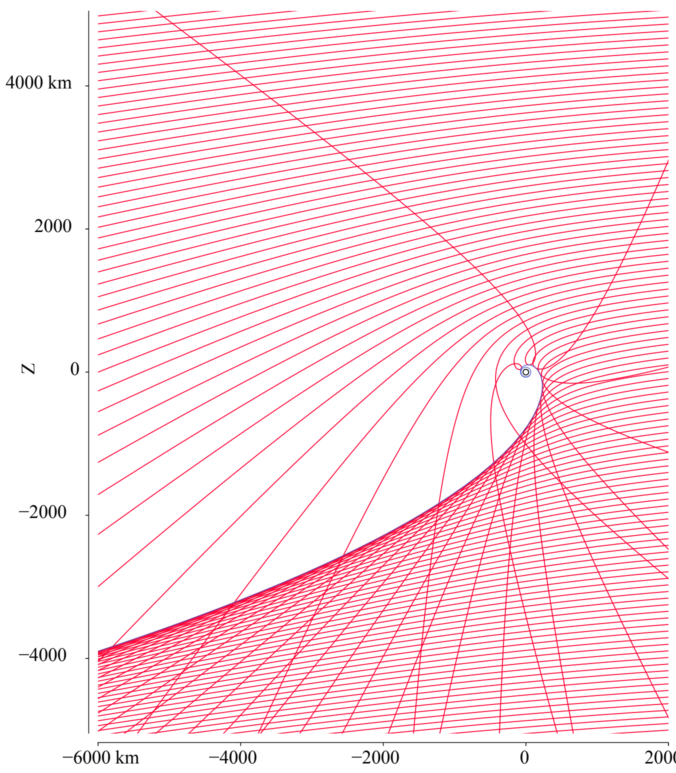


u_sw
500 km/s
300 km/s
200 km
600 km
E_motional
E_Hall
E_ambipolar
Z_CSE
X_CSE

Flash hybrid code



Simple model



Our first boundary, a solar wind cavity

Next was a diamagnetic cavity

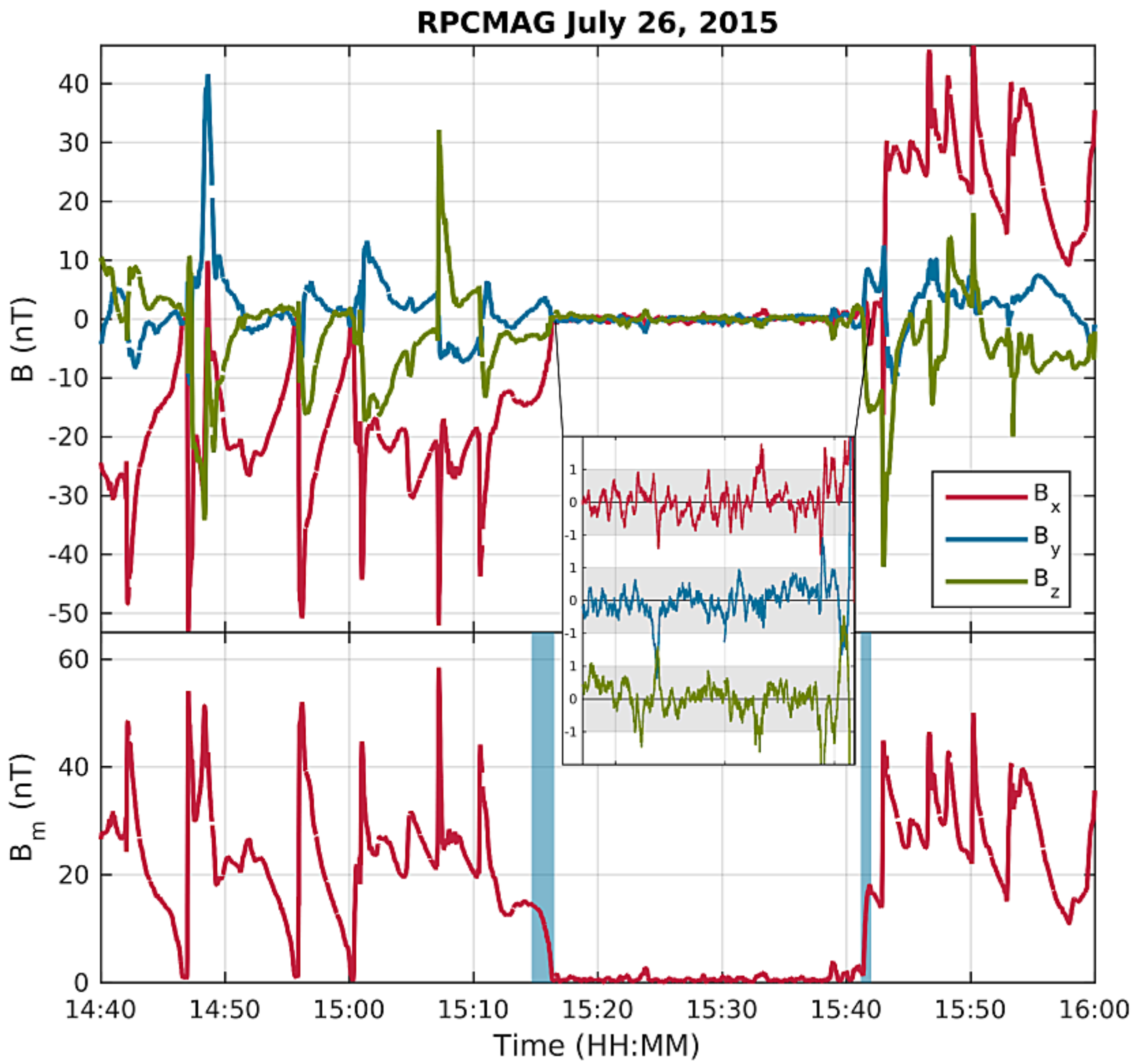
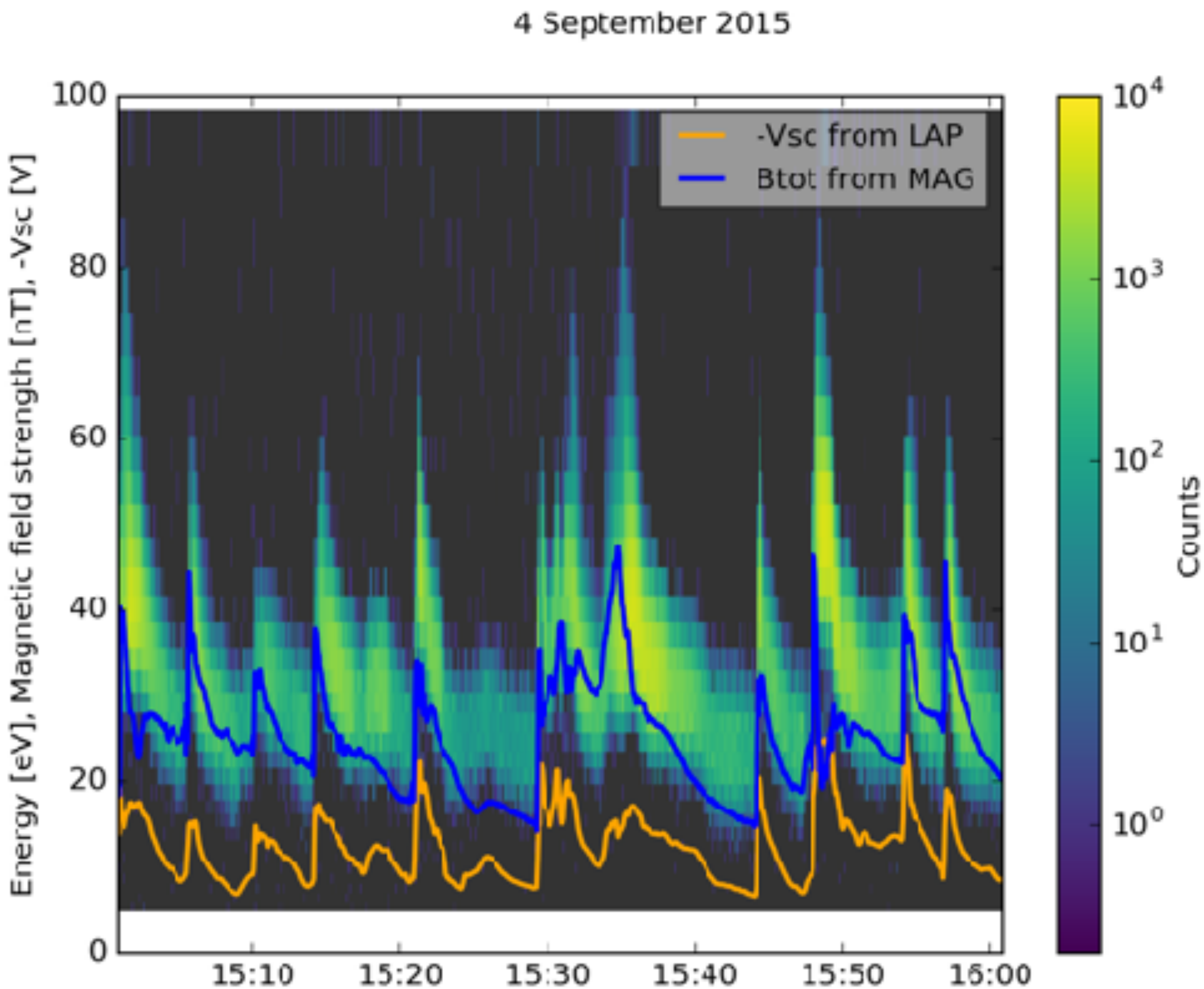


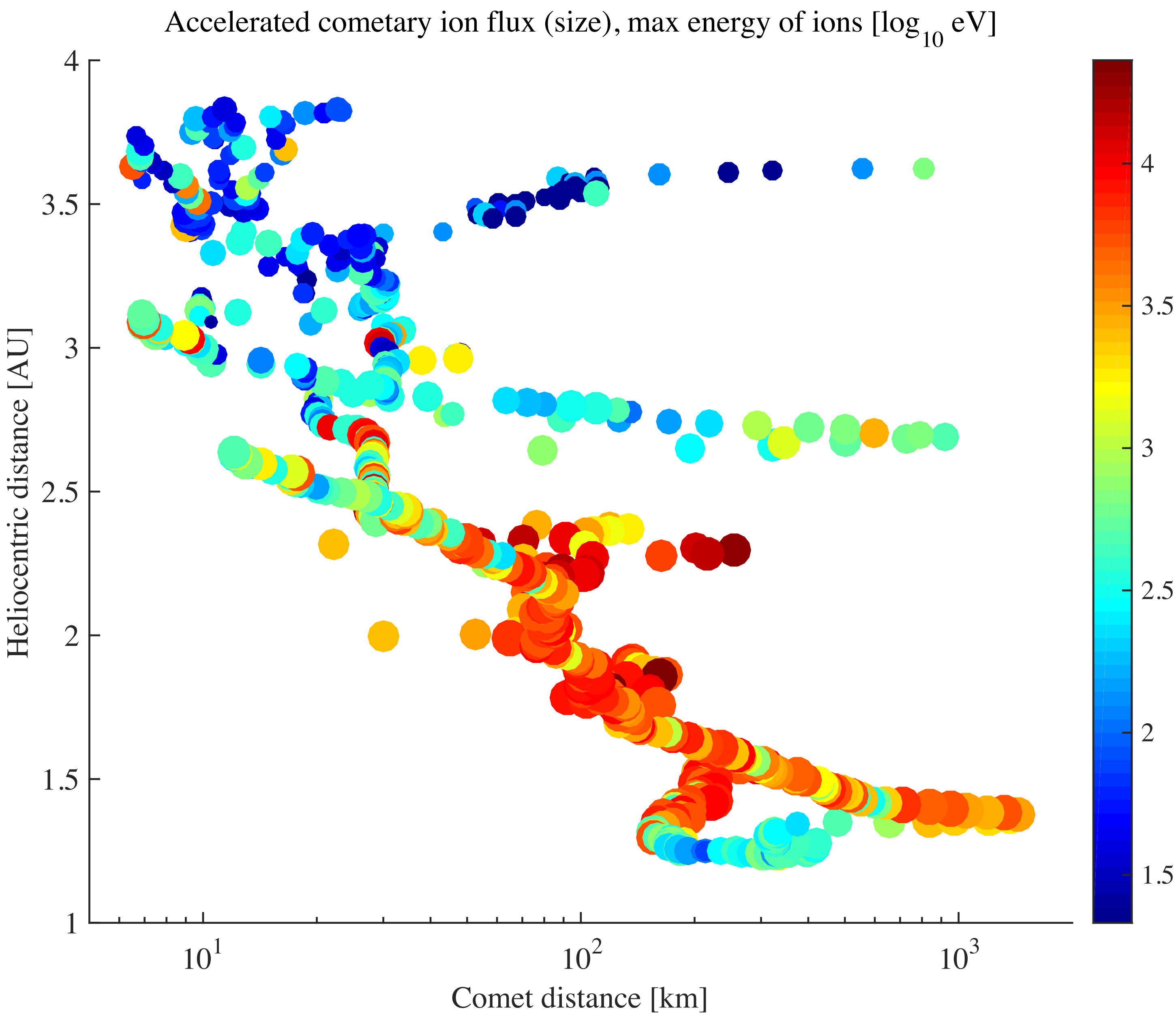
Fig. 1. Magnetic field data on July 26, 2015 from 14:40:00 UT to 16:00:00 UT. The *top panel* shows the three vector components, which have been corrected by subtracting a constant offset determined by the remaining magnetic field data in the cavity. The magnetic field magnitude shown in the *bottom panel* has been calculated from the corrected data. The cavity is visible between 15:16:00 UT and 15:41:00 UT, and the shaded areas mark the transition regions. The inset shows a more detailed picture of the three magnetic field components in the diamagnetic cavity.



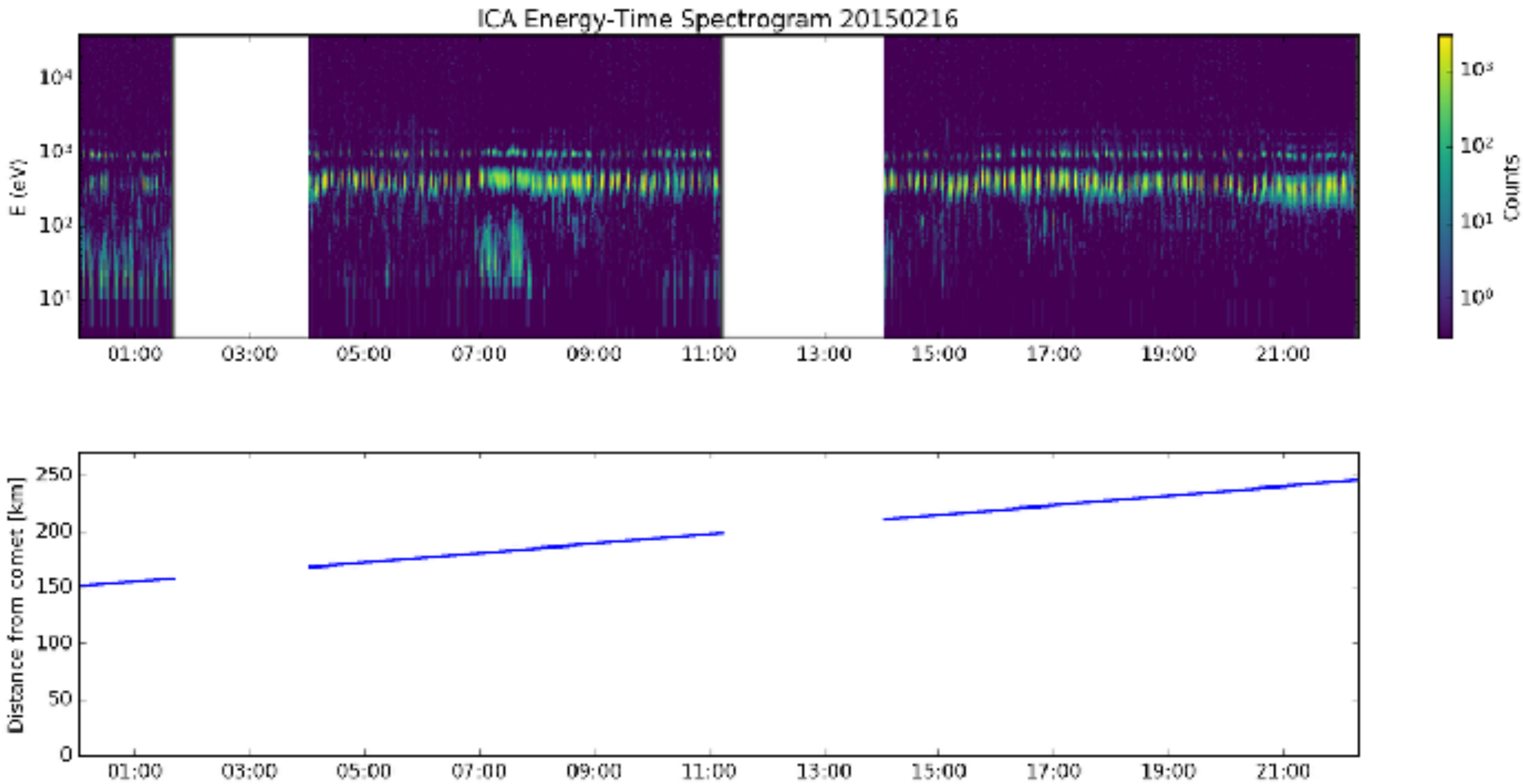
Stenberg Wieser et al, MNRAS, 2017

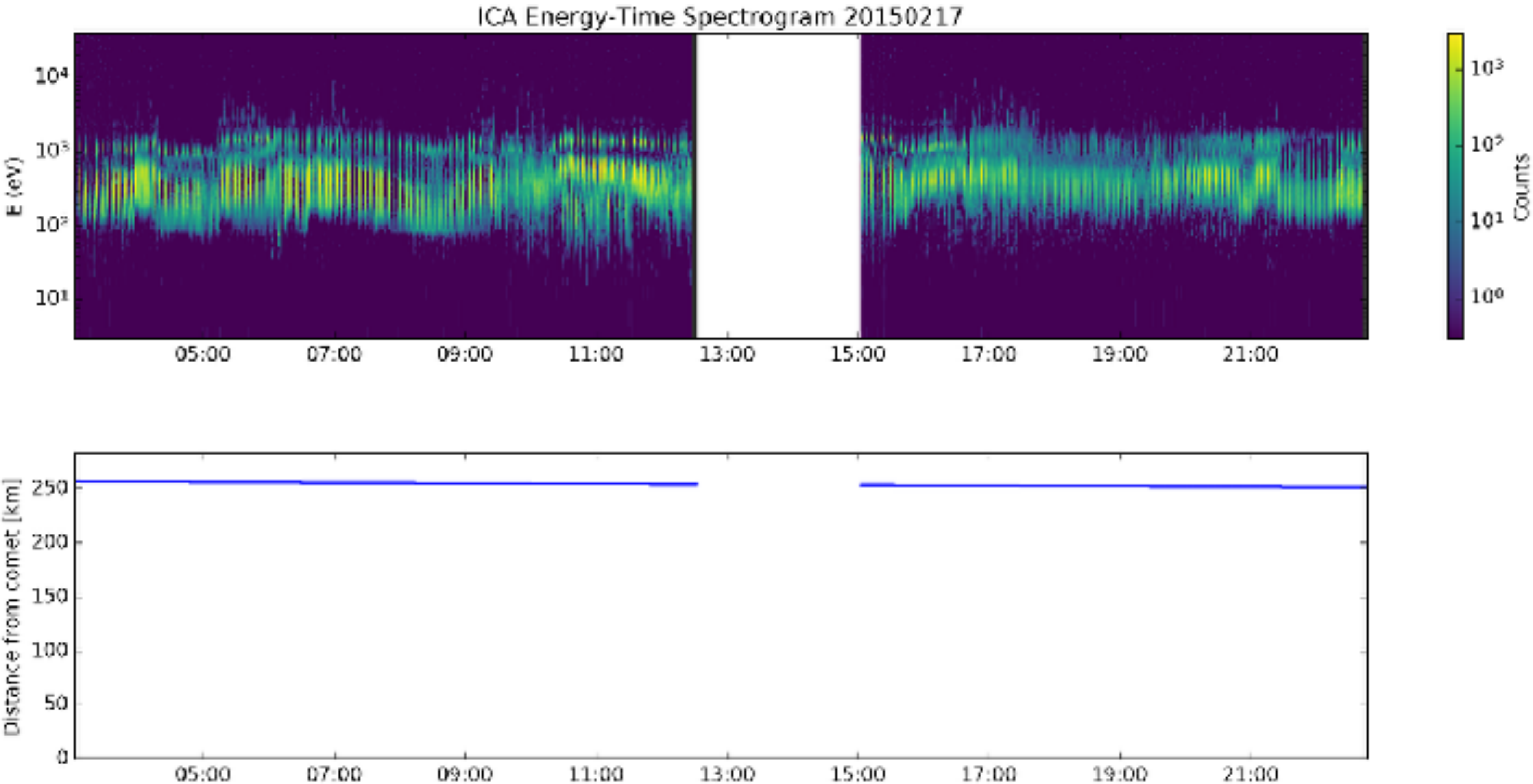
What about shocks?

There are shocks in the solar wind
independent
of the presence of a comet
How do we tell?



Accelerated cometary ion flux (size), max energy of ions [log10 eV]
Heliocentric distance [AU]
4
3.5
3
2.5
2
1.5
1
10^1
10^2
10^3
Comet distance [km]
4
3.5
3
2.5
2
1.5

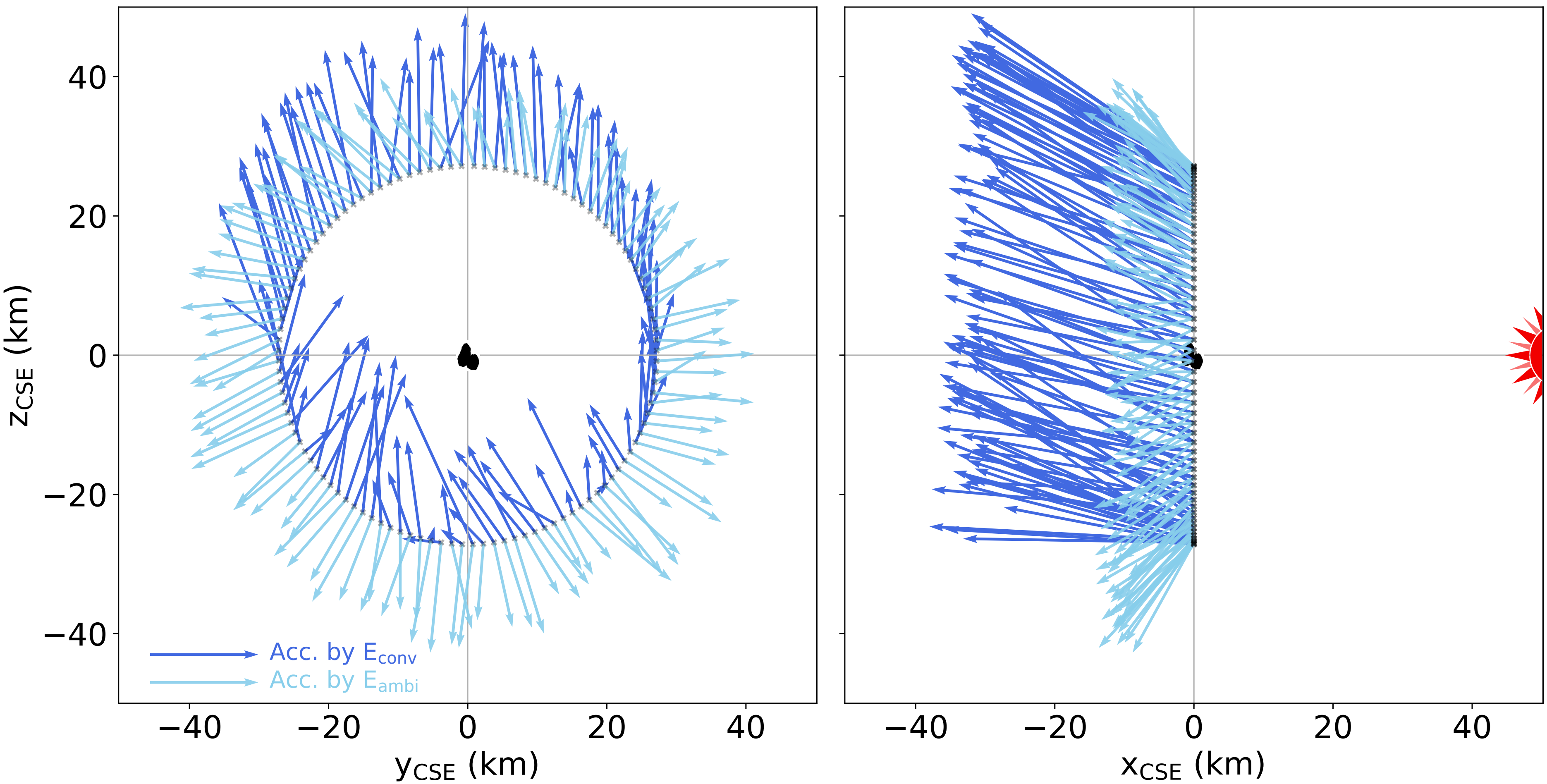

ICA Energy-Time Spectrogram 20150216
E (eV)
Counts
Distance from comet [km]
01:00
03:00
05:00
07:00
09:00
11:00
13:00
15:00
17:00
19:00
21:00
0
50
100
150
200
250


ICA Energy-Time Spectrogram 20150217
E (eV)
Counts
Distance from comet [km]
05:00
07:00
09:00
11:00
13:00
15:00
17:00
19:00
21:00

No solar wind ions, no solar wind magnetic field,

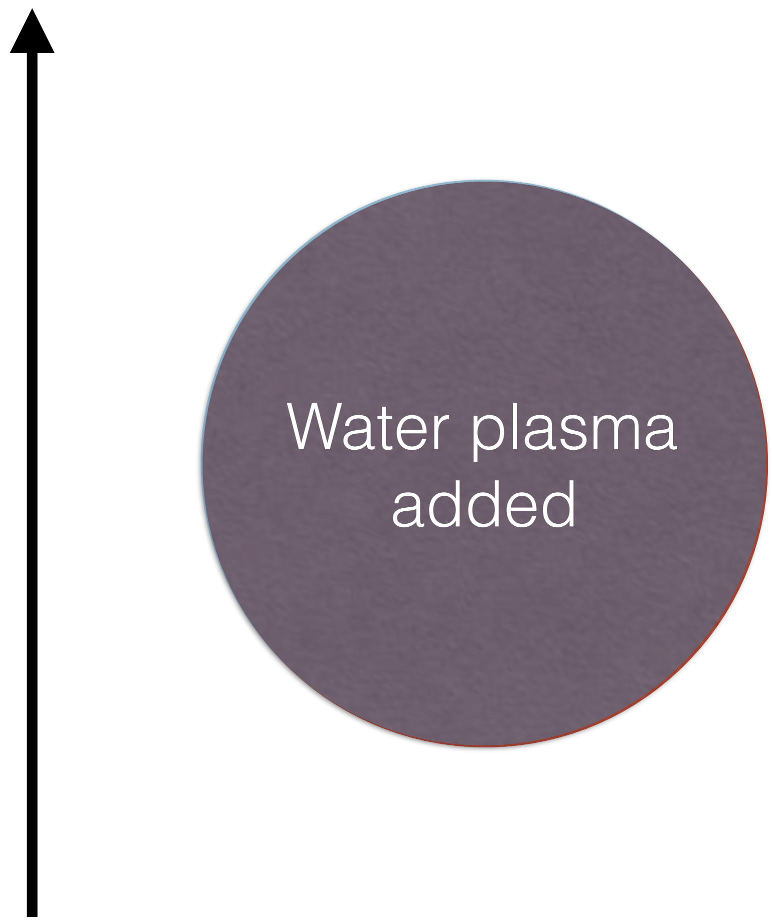
What about the solar wind electric field?

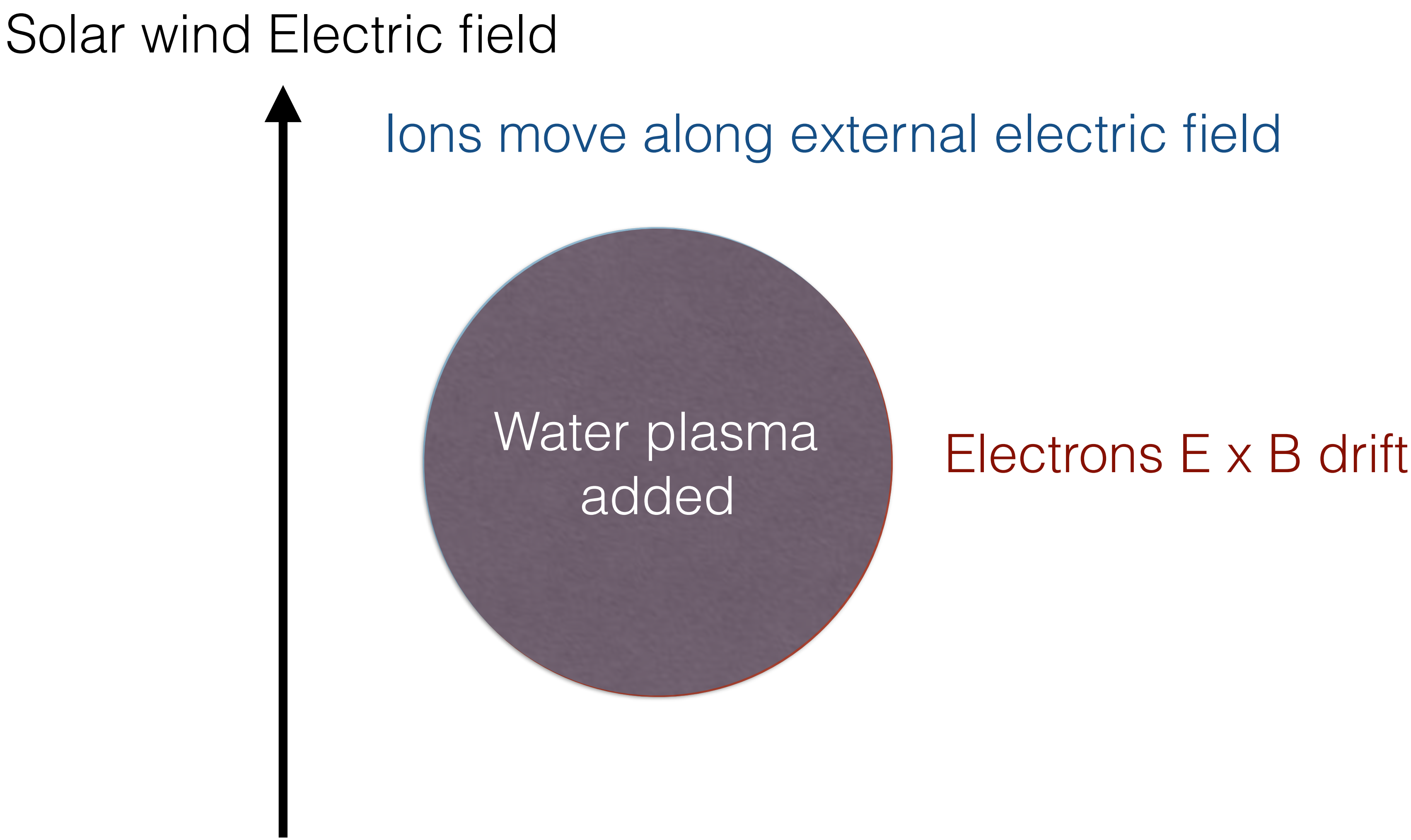
Cometary ions' bulk velocity vectors - CSE frame



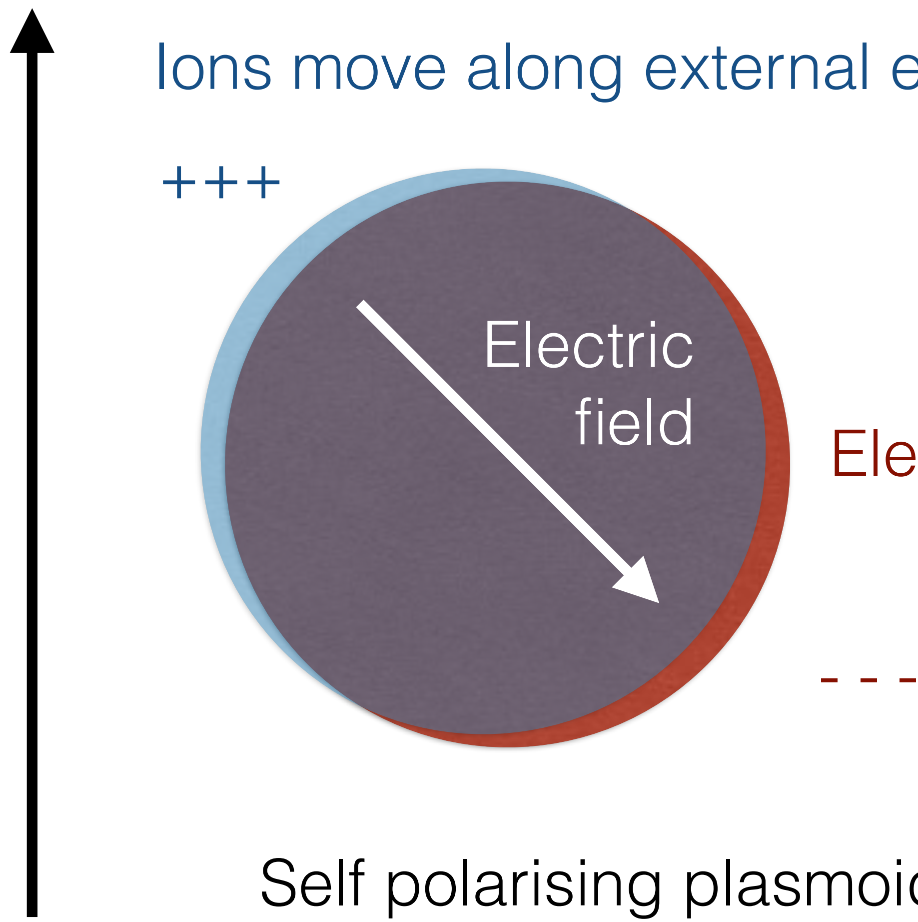
Berčič et al., A&A 2018

Solar wind Electric field




Solar wind Electric field
Ions move along external electric field
Water plasma added
Electrons E x B drift

Solar wind Electric field



Self polarising plasmoid

Barium release experiments: Haerendel and Brenning

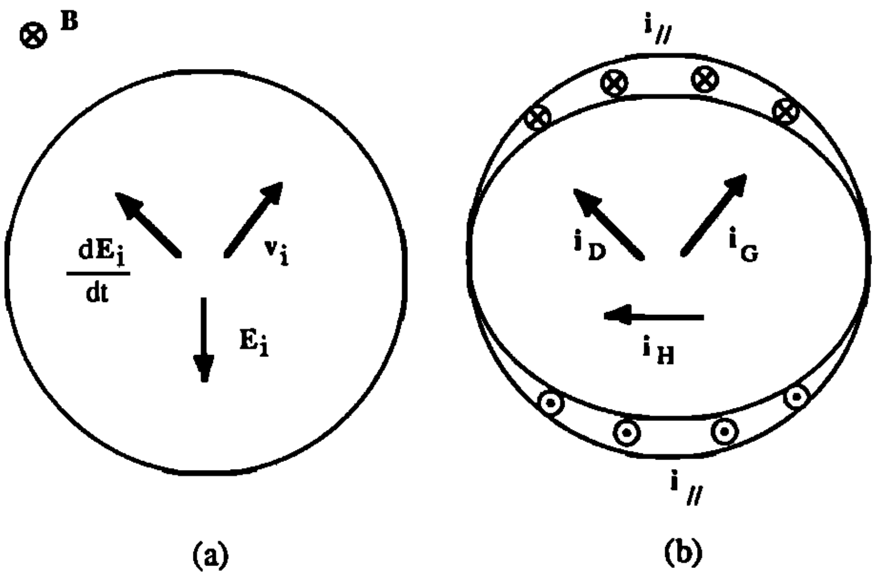


Fig. 4. The geometric relationship between the different types of currents and the internal electric field in the cylindrical cloud. (a) The ion motion and the electric and magnetic fields, which drive the different currents. (b) The currents.

of the initial conditions. One case of particular interest is the "quasi-steady-state" version of (12), where $d\mathbf{E}/dt \approx 0$ (this excludes a class of phenomena initiated by rapidly time-varying initial conditions):

$$0 = -\frac{1}{2}\frac{\mathbf{V}_i\,\Delta n\,e}{\varepsilon_0} + \frac{1}{2}\frac{\mathbf{E}_i \mathrm{x} \mathbf{B}}{B^2}\frac{\Delta n\,e}{\varepsilon_0} - \frac{2}{\varepsilon_0}\frac{\mathbf{E}_i}{\mu_0 V_A L_{//}} \qquad (14)$$

The solution is found after some vector algebra (where $\mathbf{E}\cdot\mathbf{B} = 0$ is assumed):

$$\mathbf{E}_i = -\mathbf{V}_i\frac{KB}{1+K^2} - \mathbf{V}_i \mathrm{x}\,\mathbf{B}\frac{K^2}{1+K^2} \qquad (15)$$

where

$$K = \frac{\Delta n\,e\,\mu_0 V_A L_{//}}{4\,B} \qquad (16)$$

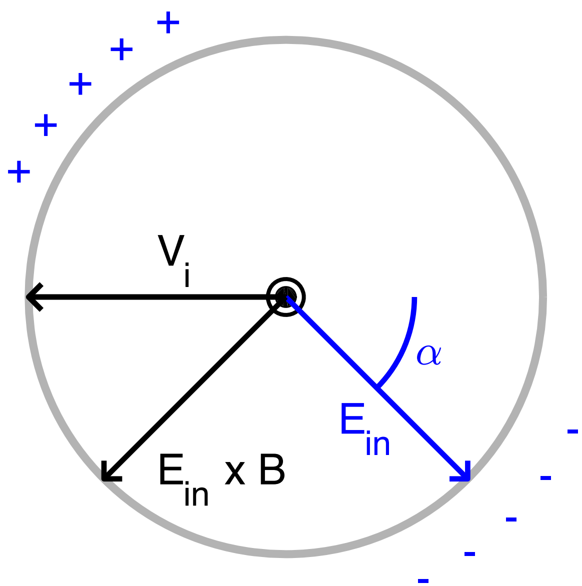
The electric field of (15) is dircted at an angle

$$\alpha = \mathrm{arctan}\,(K) \qquad (17)$$

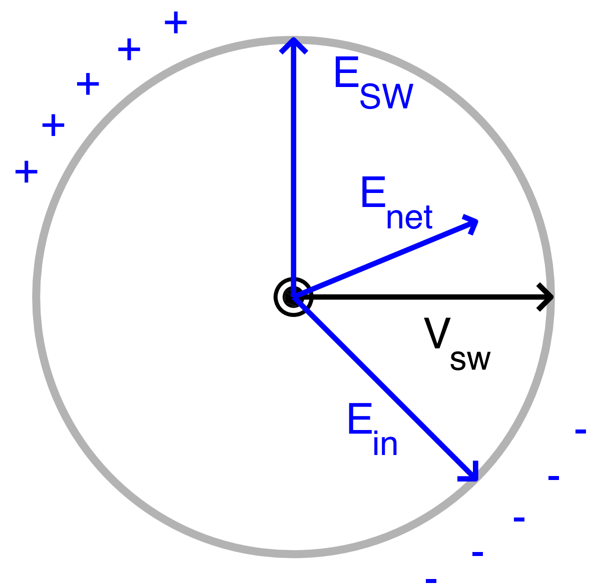
to the $-\mathbf{V}_i$ direction and has a strength

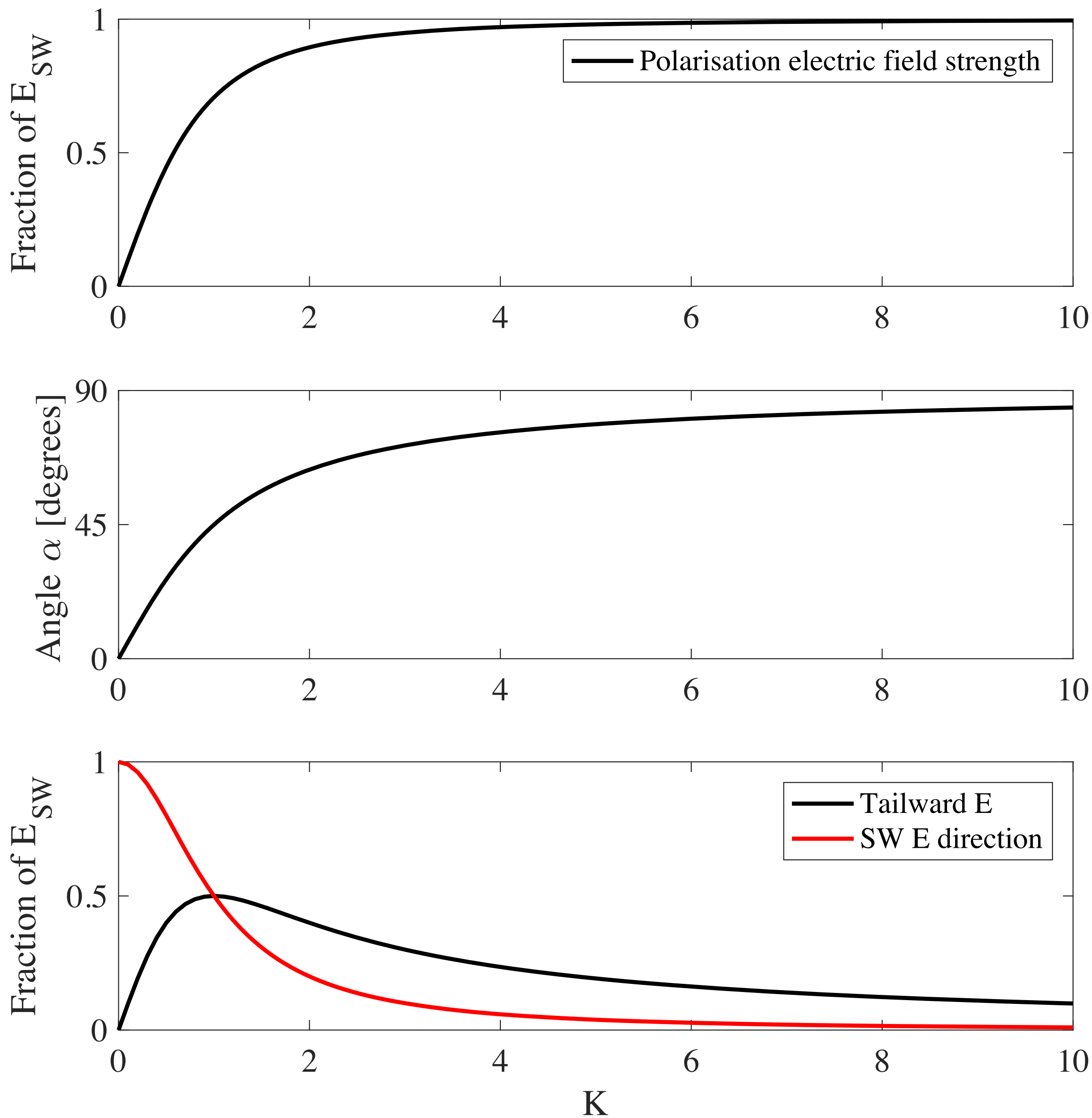
$$|E_i| = V_i\,B\frac{K}{(1+K^2)^{1/2}} \qquad (18)$$

Solar wind reference frame

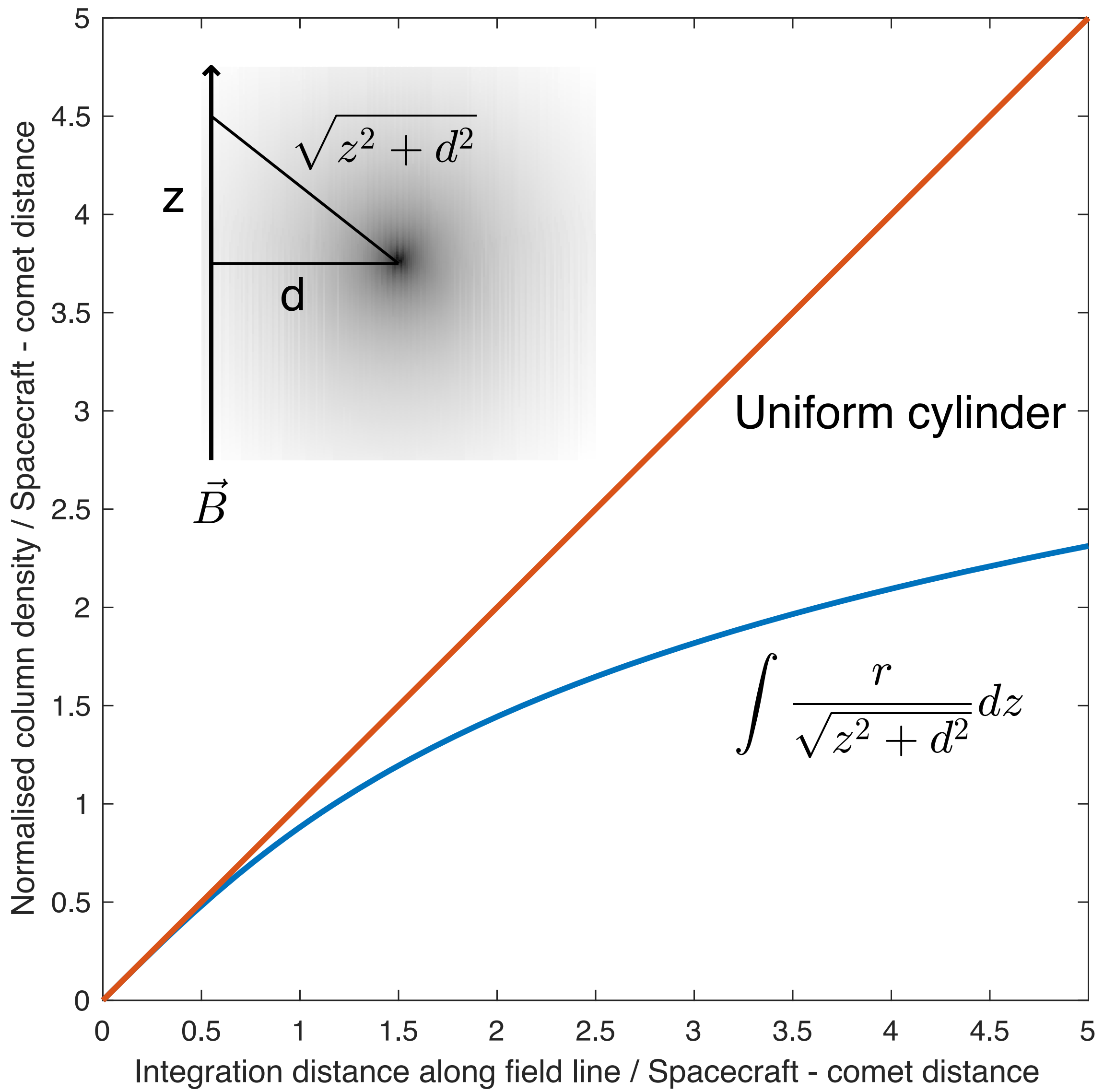


Comet reference frame





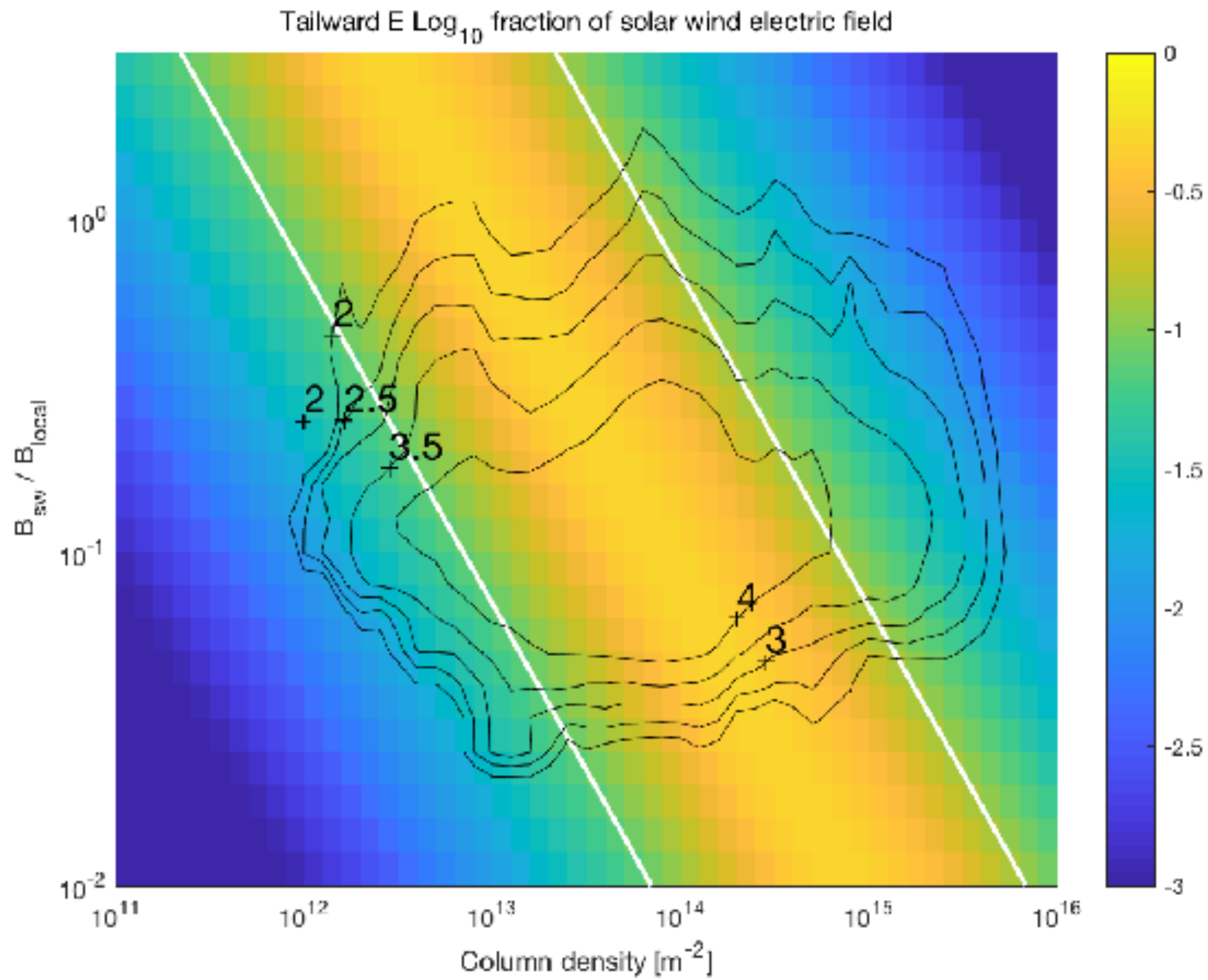
Fraction of E_{SW}
Polarisation electric field strength
Angle α [degrees]
Fraction of E_{SW}
Tailward E
SW E direction
K



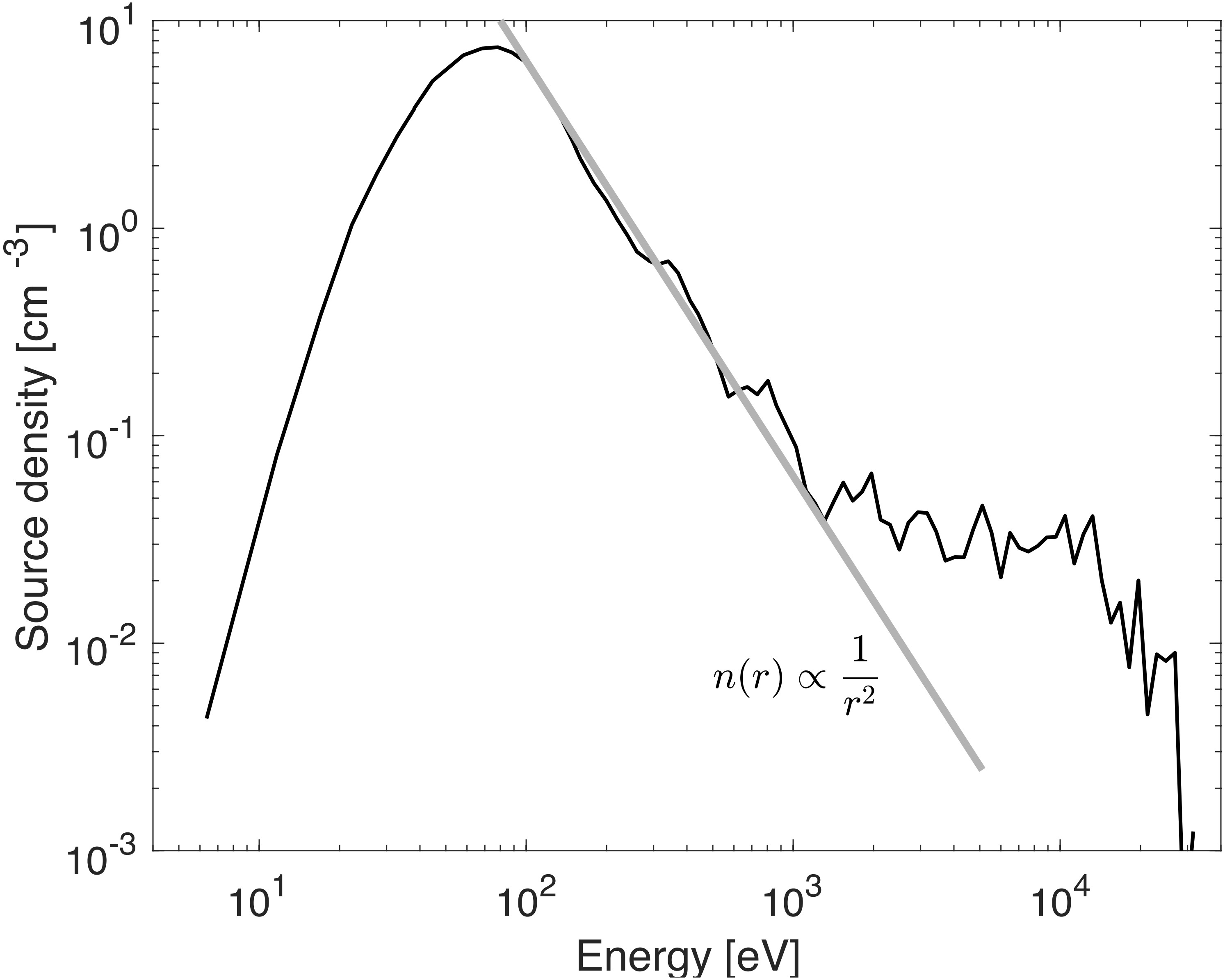
Normalised column density / Spacecraft - comet distance
Integration distance along field line / Spacecraft - comet distance
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
z
d
$\sqrt{z^2 + d^2}$
$\vec{B}$
Uniform cylinder
$\int \frac{r}{\sqrt{z^2 + d^2}} dz$

IRF

rosetta



Tailward E Log10 fraction of solar wind electric field
B_sw / B_local
Column density [m^-2]
10^0
10^-1
10^-2
10^11
10^12
10^13
10^14
10^15
10^16
0
-0.5
-1
-1.5
-2
-2.5
-3
2
2
2.5
3.5
4
3



Source density [cm -3]
Energy [eV]
$n(r) \propto \frac{1}{r^2}$
10^1
10^0
10^-1
10^-2
10^-3
10^1
10^2
10^3
10^4

Summary, solar wind

The comet environment is “kinetic” for low activity comets and evolves to a more “fluid” state at high activity

At intermediate activity the first boundary forms, a solar wind cavity

It is associated with a “caustic” that evolves into a bow wave

Mass loading slows down the total plasma, the solar wind ions are first deflected, then gyrates

The gyration can be seen as the heating of a fully developed shock

Summary, cometary ions

A diamagnetic cavity forms

A polarisation electric field develops, which largely shields the inner coma from the solar wind electric field

The polarisation electric field accelerates ions tailward, giving a more “fluid”-like behaviour for the dominant ion population

We have shown how we may remotely detect a comet ion shock

We can sometimes see bow waves or shock-lets - the first stage of going from “kinetic” to “fluid”?