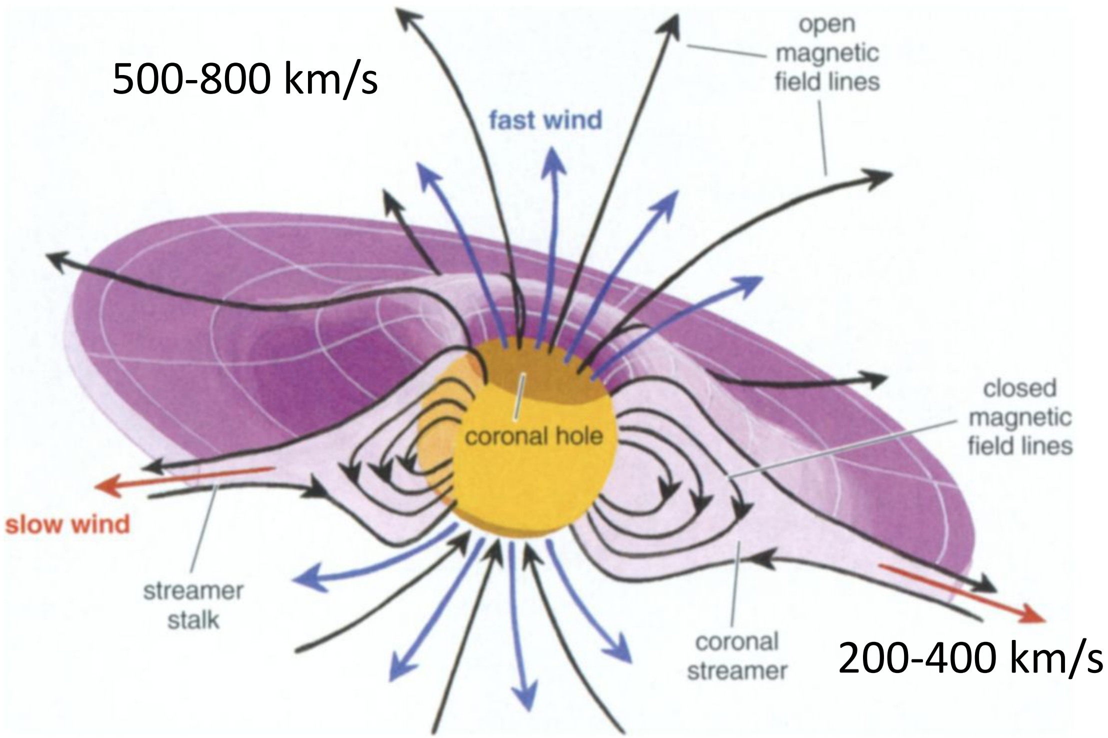
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Formation of a solar wind stream interaction region at two radial distances from the Sun

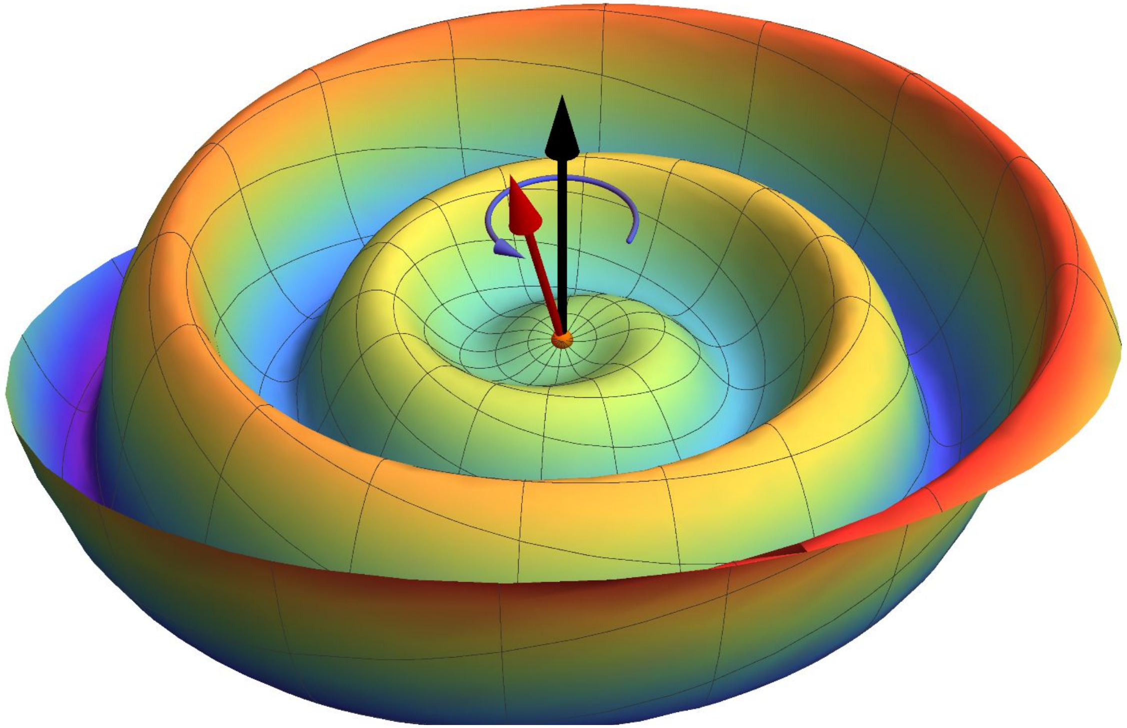
Société Française d'Astronomie & d'Astrophysique

Etienne Berriot, Olga Alexandrova, Pascal Démoulin,
Arnaud Zaslavsky, Milan Maksimovic, Georgios Nicolaou

Solar wind sources and Heliospheric Current Sheet (HCS)

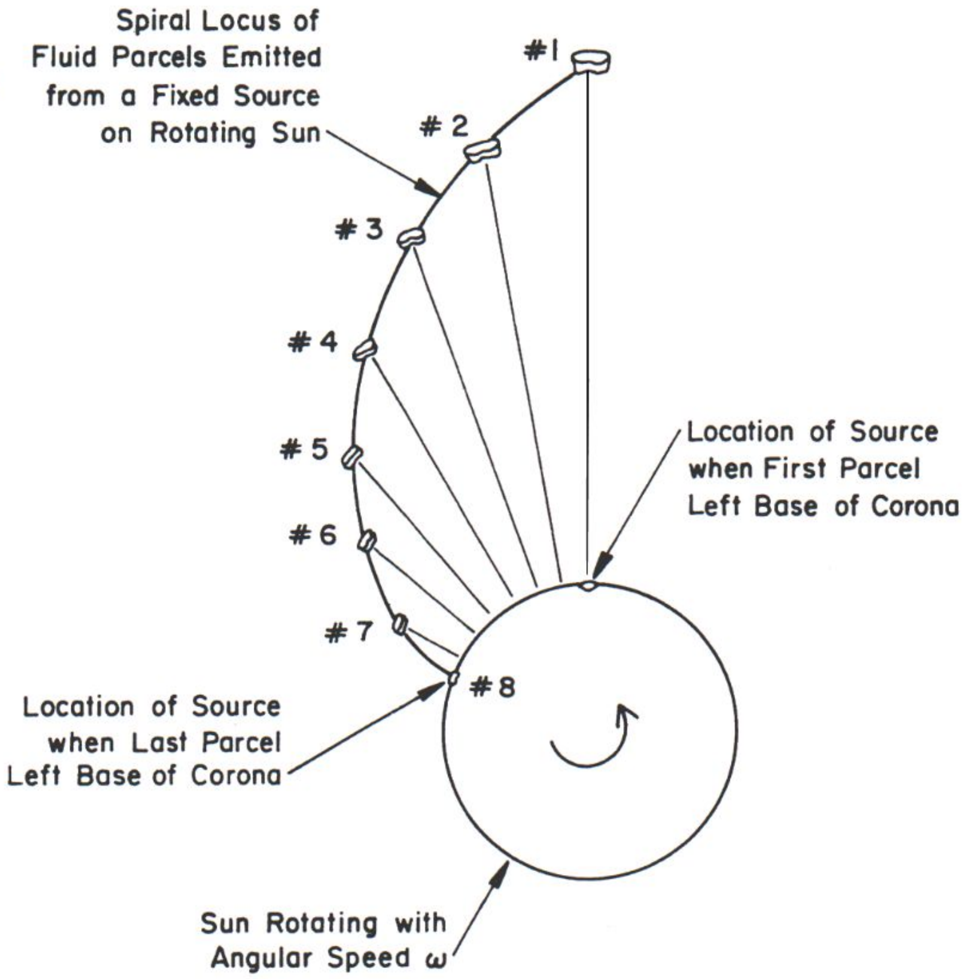


Schematic of the heliospheric magnetic field and solar wind sources close to the Sun.
(Woo and Habbal 2002)

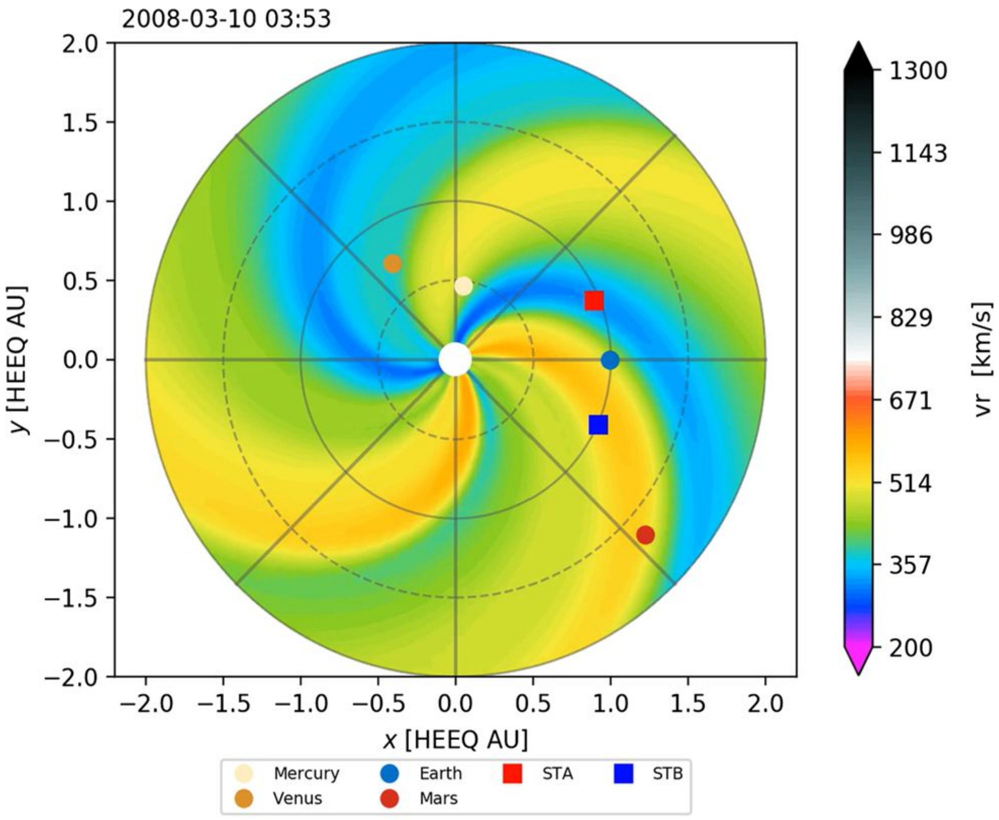


Graphical representation of the heliospheric current sheet (HCS) large scale shape.
(Orcinha et al. 2019)

Parker spiral and solar wind streams

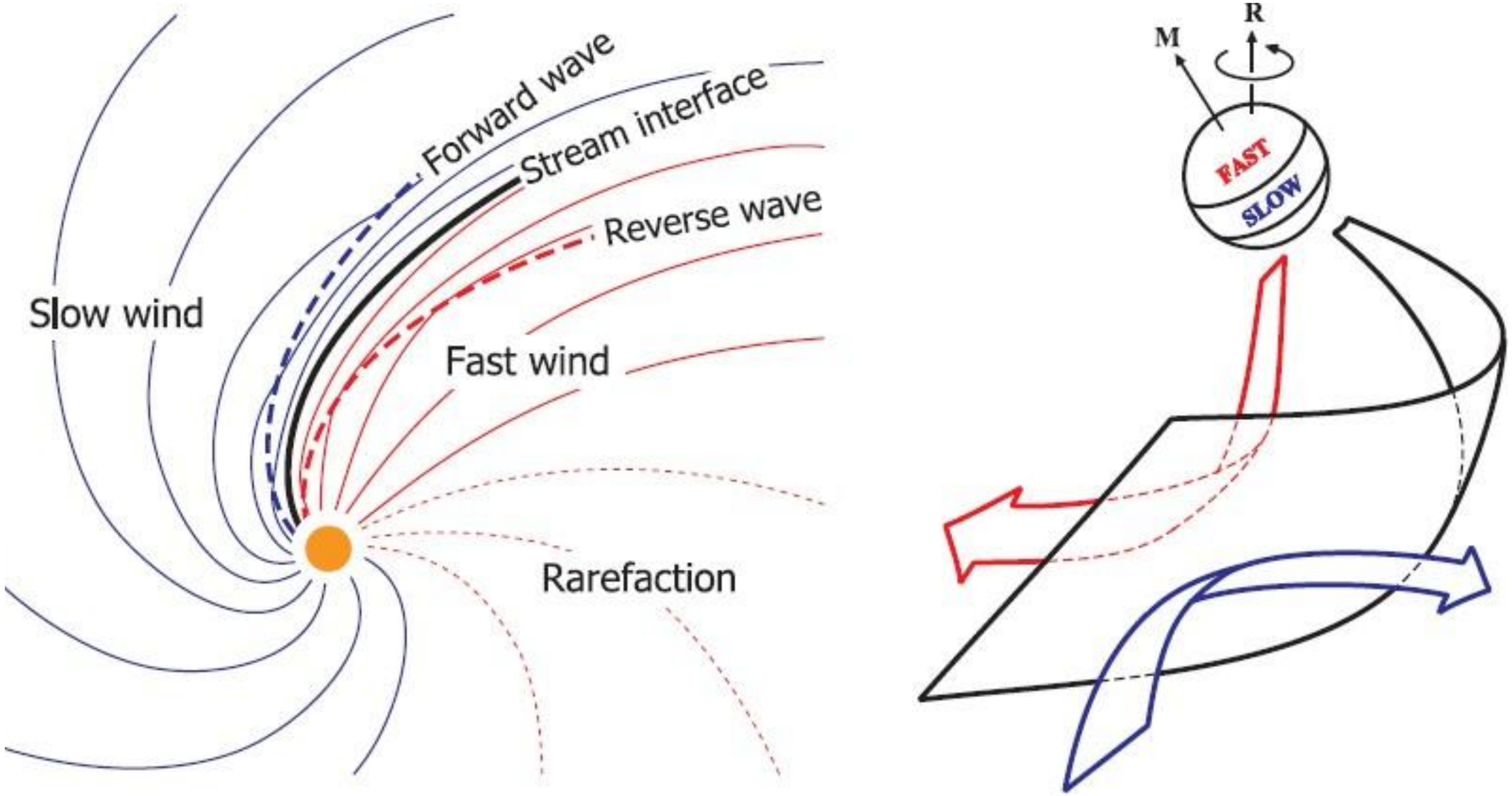


Locations of plasma parcels successively emitted from the same solar source.
(Kivelson et al. 1995)



Ecliptic snapshot of the solar-wind radial speed modeled by EUHFORIA (MHD code).
(Hinterreiter et al. 2019)

Stream interaction regions (SIRs)



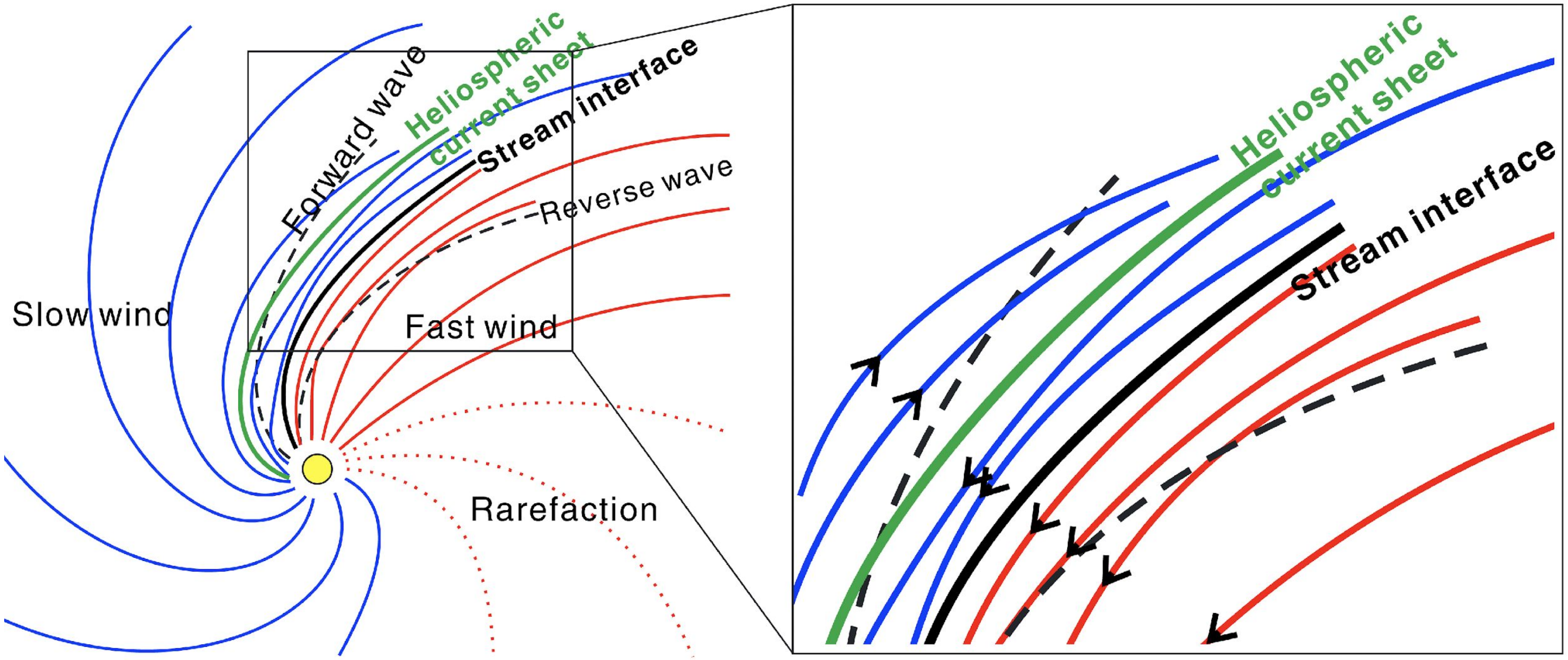
Stream Interaction region schematic
(Owens & Forsyth 2013)

- Due to the Sun's rotation the slow wind can be caught up by a faster wind => formation of SIR.
- A pair of propagating shocks can also develop at the edges of the interaction region.
- This type of pattern is 3D
- Property of the SIR depends on the sources parameters.
- The shocks tend to develop with distance from the Sun.

Streams Interaction Regions (SIR) and HCS

- Due to the Sun's rotation the slow wind can be caught up by a faster wind ⇒ formation of SIR.
  ⇒A pair of propagating shocks can also develop at the edges of the interaction region.

- Depending on the magnetic field topologie SIR can also engulf the HCS and HPS.

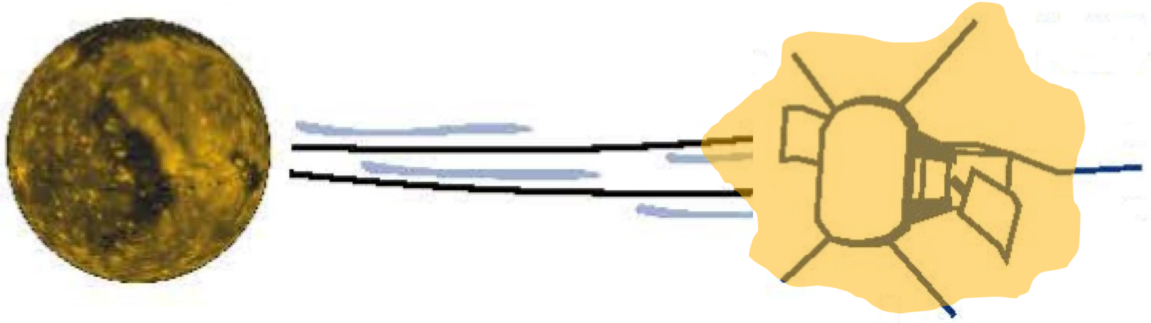


Schematic a SIR engulfing the HCS.
(Huang et al. 2016)

Goal : detect and study the same parcel of solar wind at different distances from the Sun (plasma line-up)

Sun

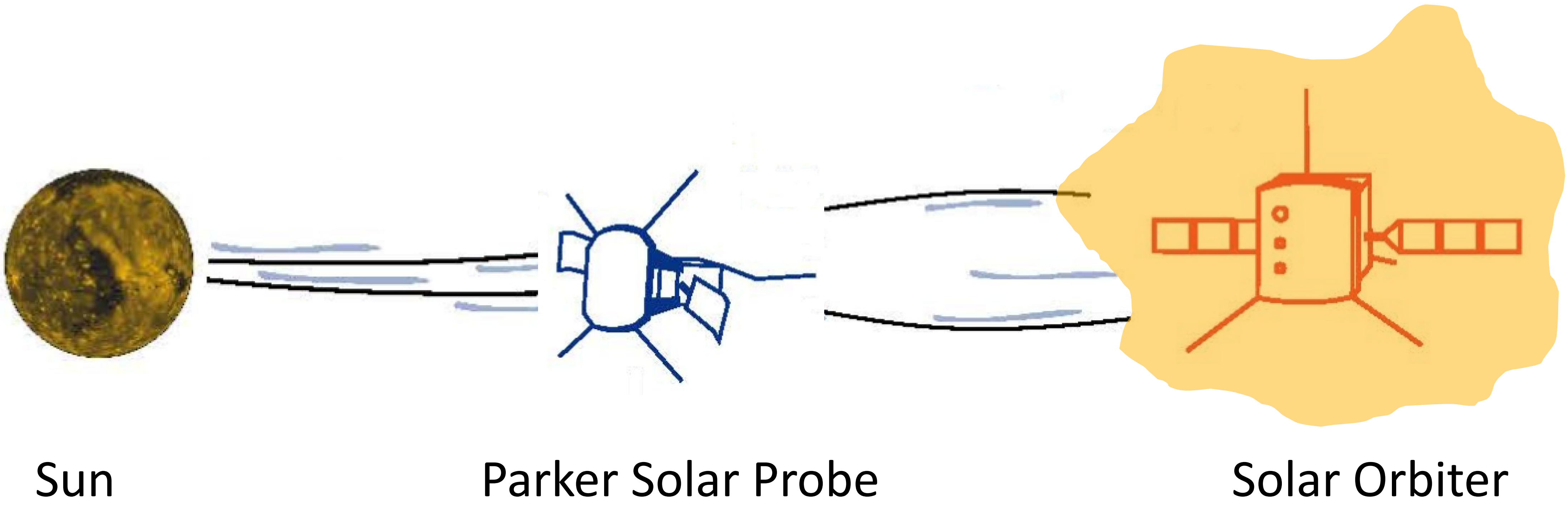
Goal : detect and study the same parcel of solar wind at different distances from the Sun (plasma line-up)



Sun

Parker Solar Probe

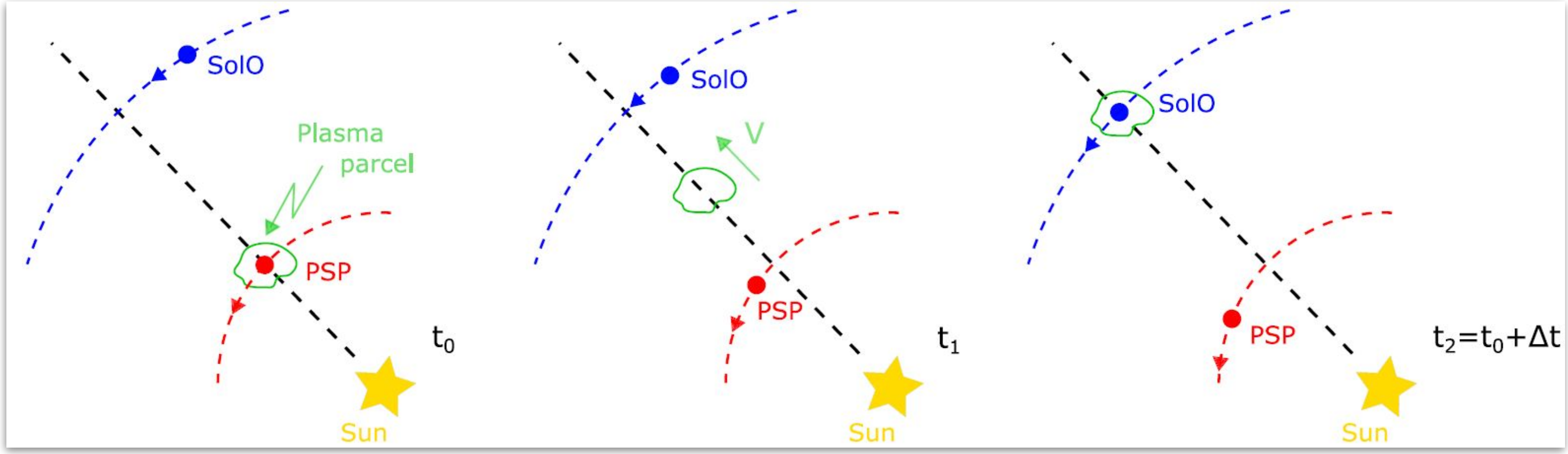
Goal : detect and study the same parcel of solar wind at different distances from the Sun (plasma line-up)

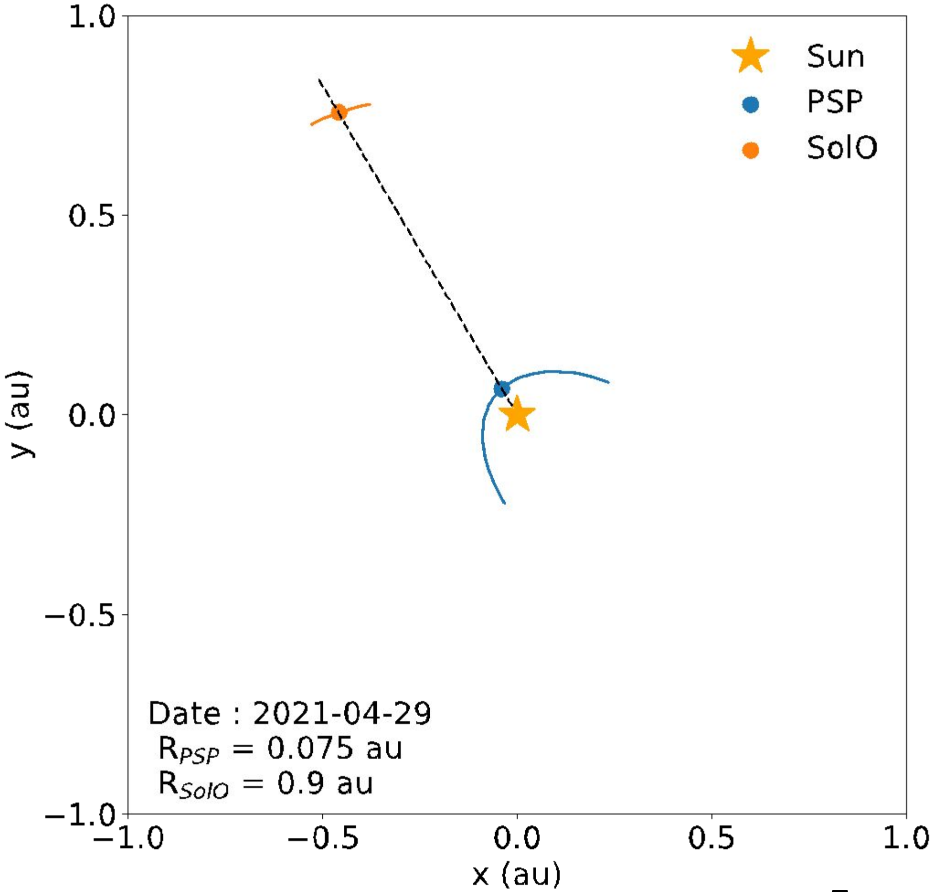


Caracterisation of the solar wind radial evolution !

PSP, SolO : new opportunity to study solar wind radial alignments

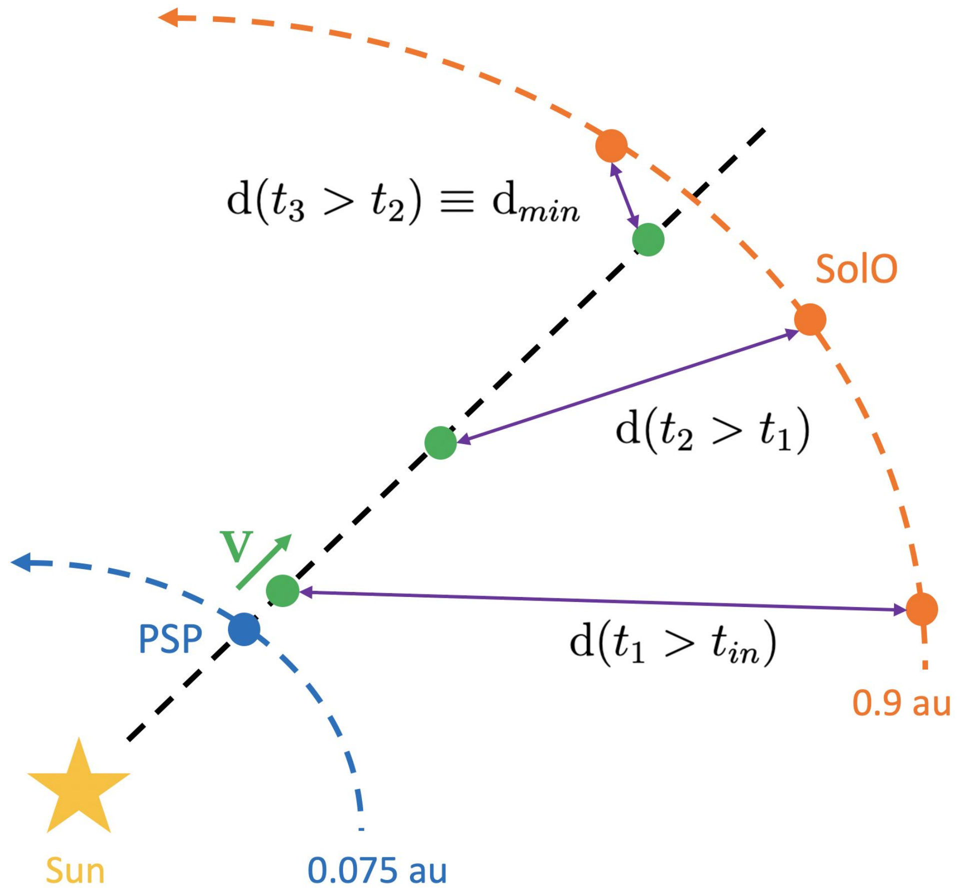
Schematic: Telloni et al. [2021]



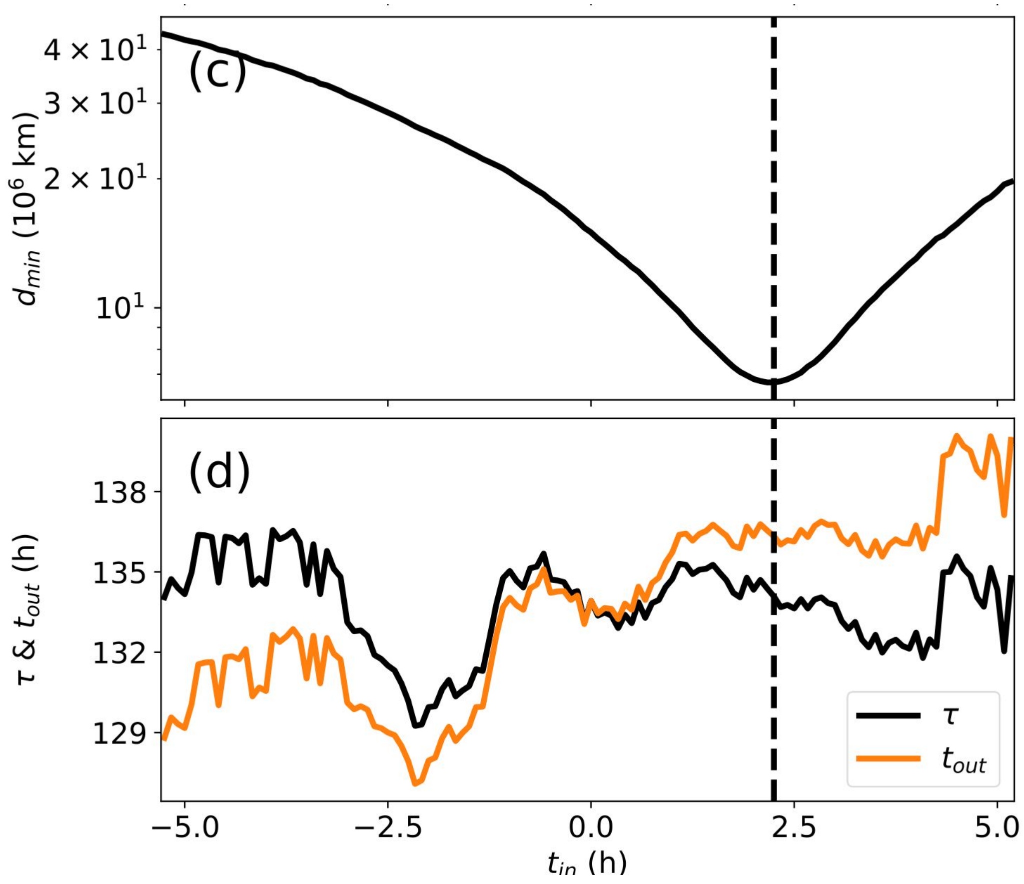


1. Find an approximate alignment between the two spacecraft.
2. Establish a propagation model using the inner spacecraft measurements.
3. Identify the same plasma on both spacecraft.

Plasma propagation method



$$d(t, t_{in}) = |\mathbf{R}_{out}(t) - \mathbf{R}_{parcel}(t, t_{in})|$$



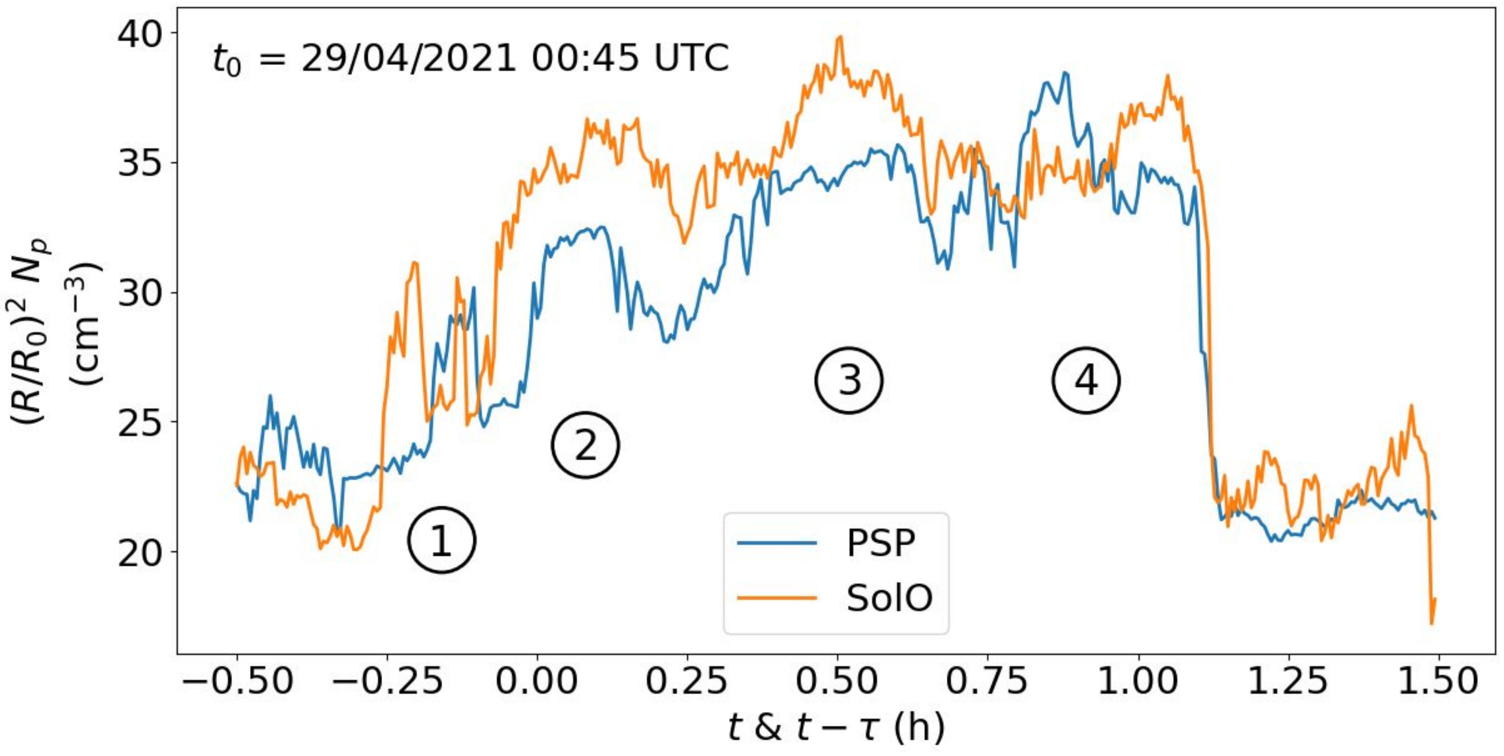
propagation time (~134 h).

Refinements :

- Constant acceleration constrained by measurements
- Non-radial propagation

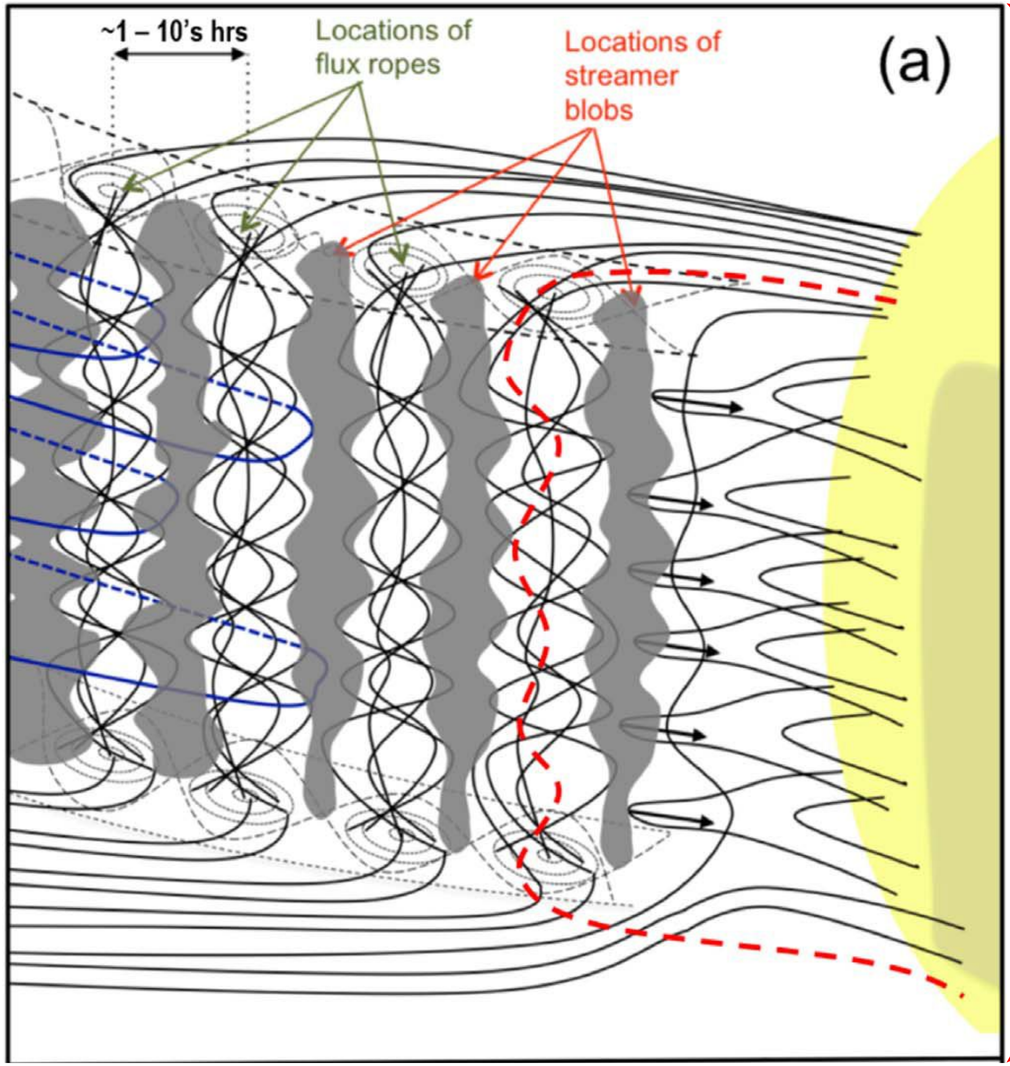
Same structure identification

Matching density structures

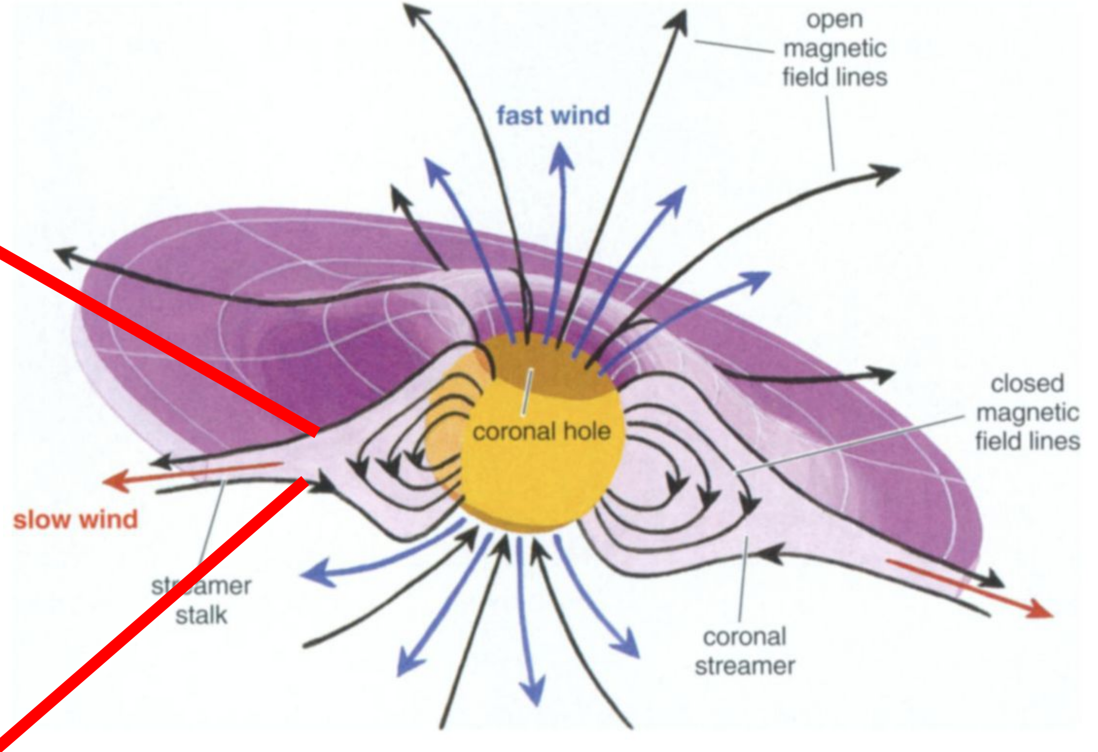


- Same density structure observed on both SC.
- Propagation time of ~137 h over 0.8 au.
- Structure composed of several (~4) substructures.
- Density structure is remarkably well conserved during the propagation.

Heliospheric Current and Plasma Sheets (HCS/HPS) substructures



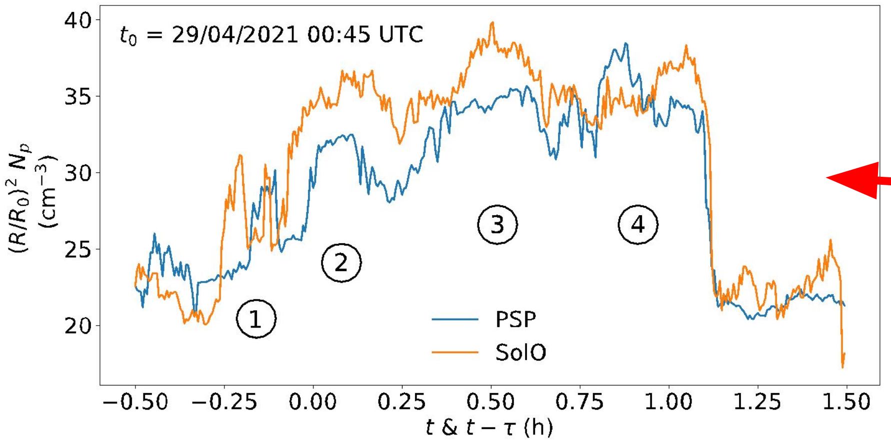
Schematic of the HCS/HPS close to the Sun.
(Lavraud et al. 2020)

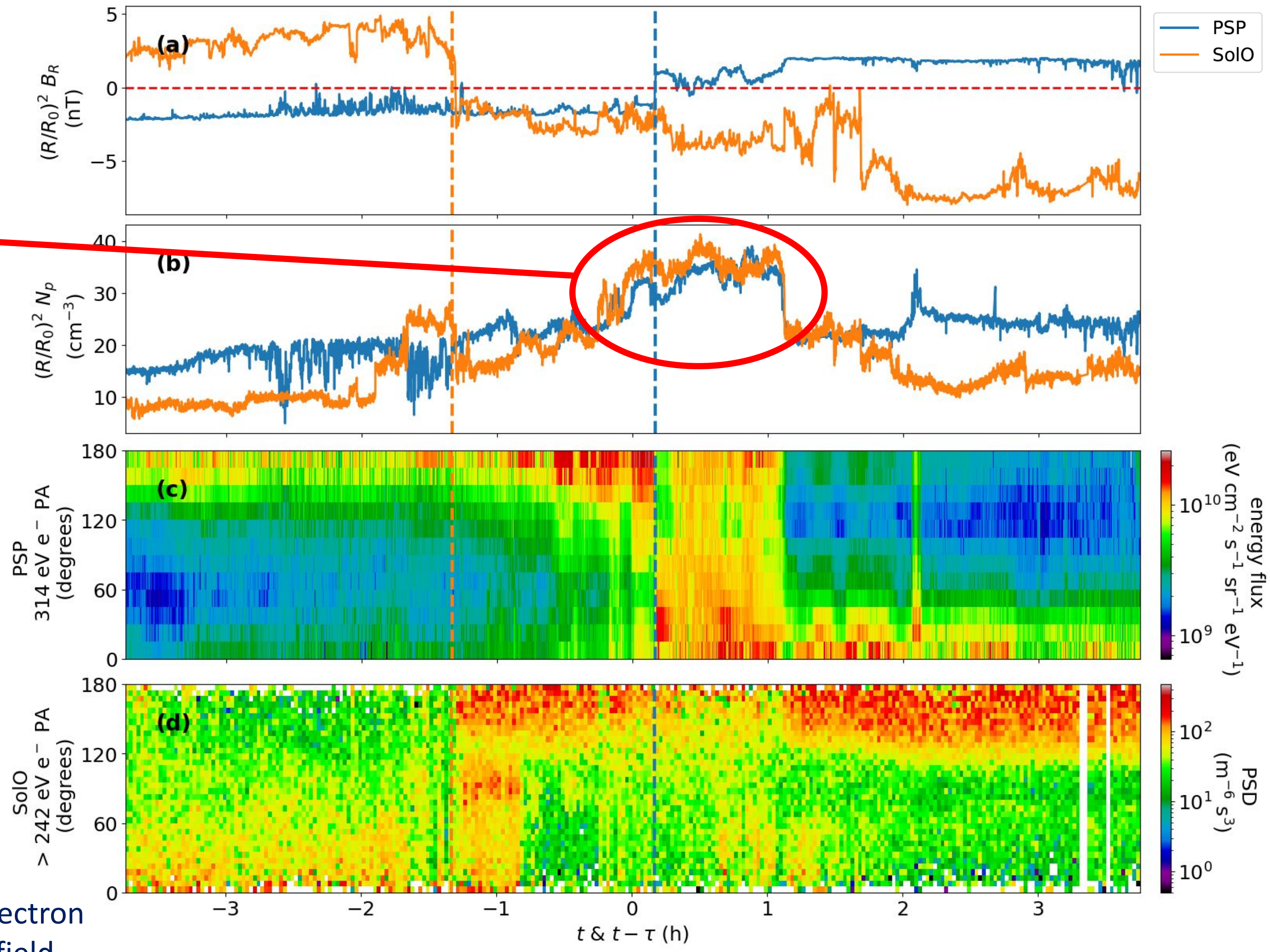


Schematic of the heliospheric magnetic field and solar wind sources.
(Woo and Habbal 2002)

- The Heliospheric Plasma Sheet has a complex topology and is formed of several substructures.

Comparison PSP-SolO (zoom out)



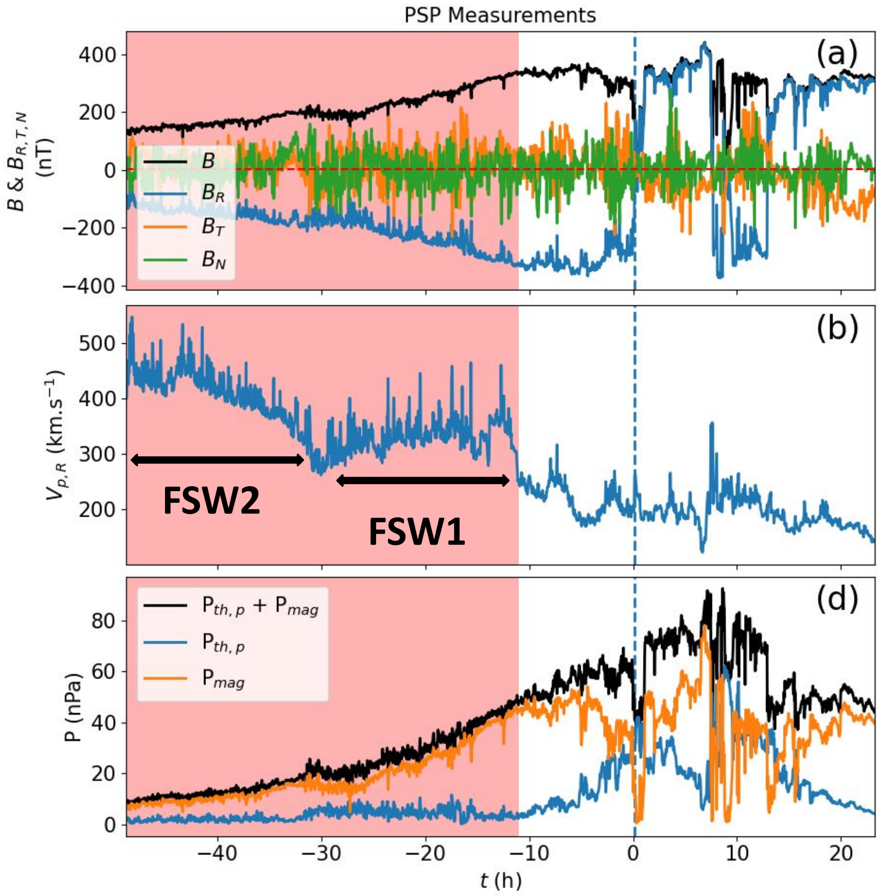


- Physical parameters indicate crossings of the HCS/HPS on both PSP and SolO.
- B-data ⇒ PSP & SolO go through the HCS in opposite directions.

Pitch Angle (PA) = angle between electron energy flux and local magnetic field

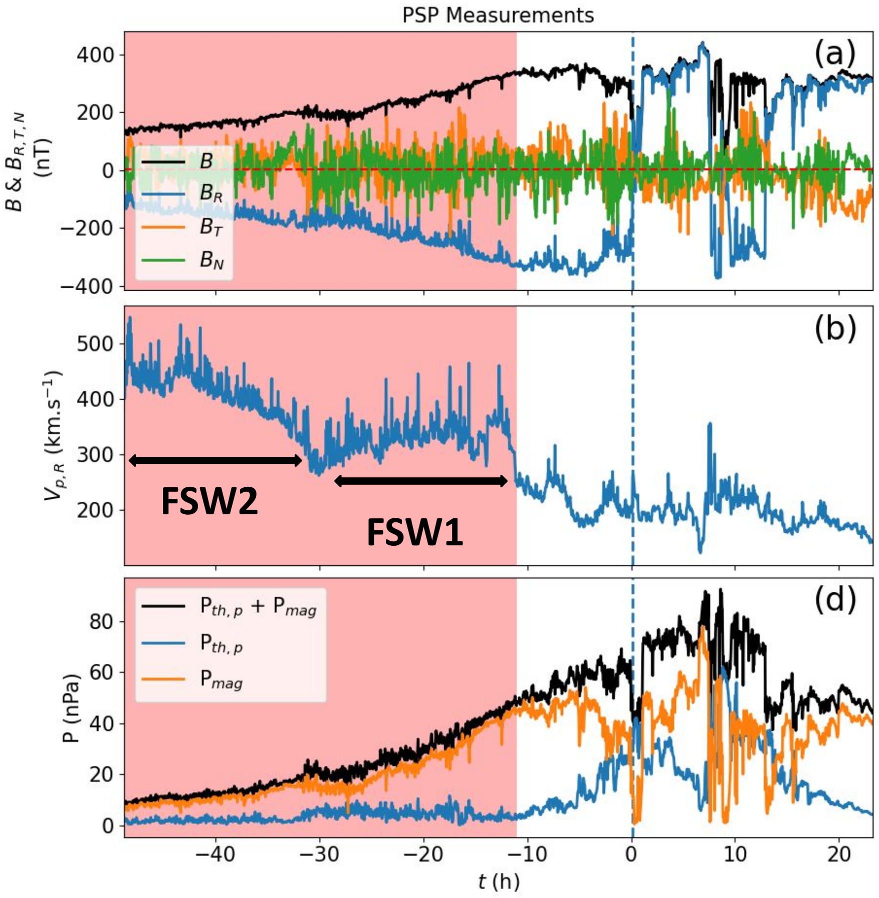
Zoom-out:
Stream Interaction Region (SIR)

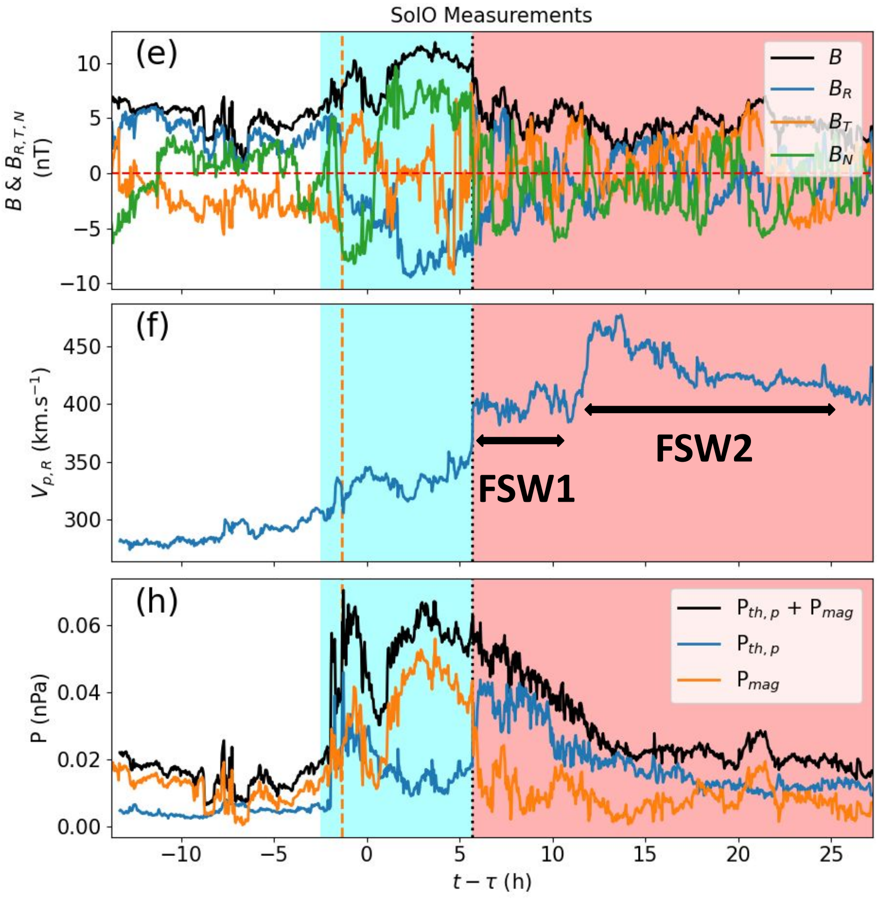
- Unperturbed slow and fast wind streams observed at PSP (~0.1 au).

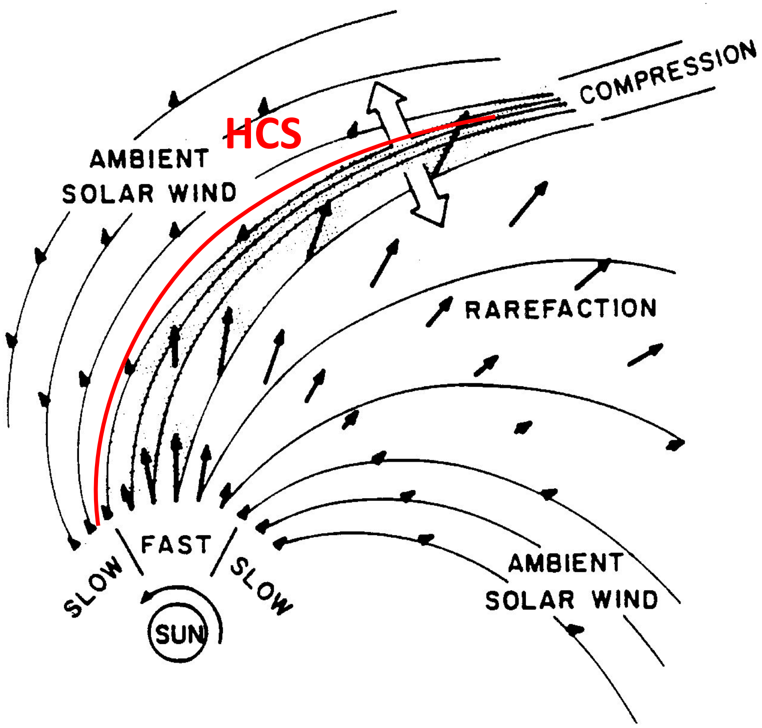


Zoom-out:
Stream Interaction Region (SIR)

- Unperturbed slow and fast wind streams observed at PSP (~0.1 au).
- The slow wind and HCS have been caught up and compressed by the faster wind + sharp pressure discontinuity between the unperturbed and compressed winds.

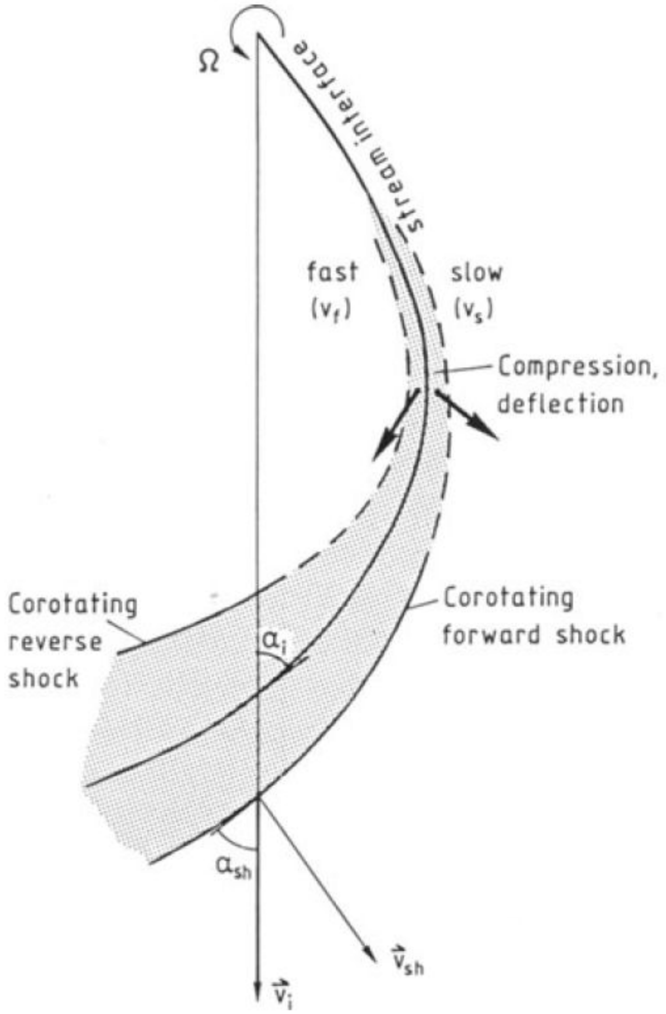






Stream Interaction region schematic **(Gosling et al. 1999)**

Shock normal and Mach number estimation



Sketch of a SIR involving a pair of quasistationary corotating shocks. **(Schwenn & Marsch 1990)**

$$\Delta B_n = 0$$

$$v_n = \mathbf{v} \cdot \mathbf{n}$$

$$c_{ms} = \sqrt{v_a^2 + c_s^2}$$

Minimum Variance Analysis (MVA):

(Sonnerup & Scheibel 1998)

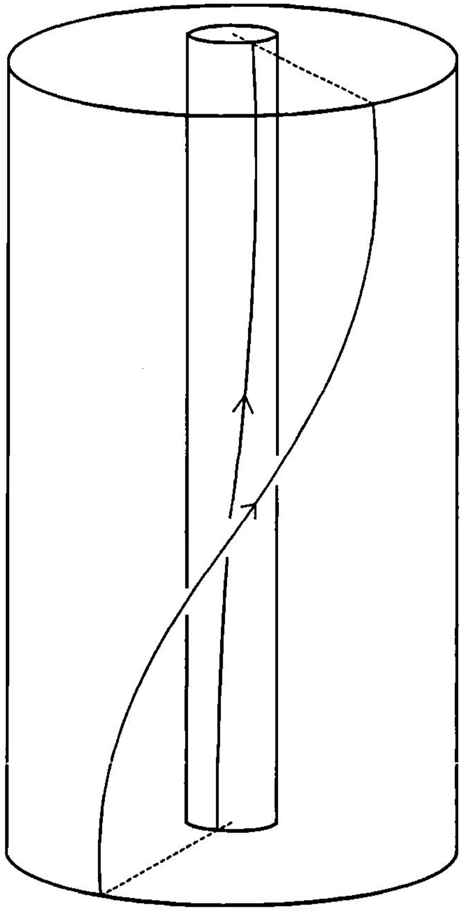
Magnetic field's covariance matrix:

$$M_{\mu\nu}^B \equiv \langle B_\mu B_\nu \rangle - \langle B_\mu \rangle \langle B_\nu \rangle$$

The eigenvector associated with the smallest eigenvalue gives the direction normal to the discontinuity

$$M_{ms} = \frac{v_n}{c_{ms}} \sim 1.1 - 1.2$$

Complex interface and in-situ identification of twisted magnetic field.



Flux rope schematic.
(Priest 1990)

Force-free equilibrium:

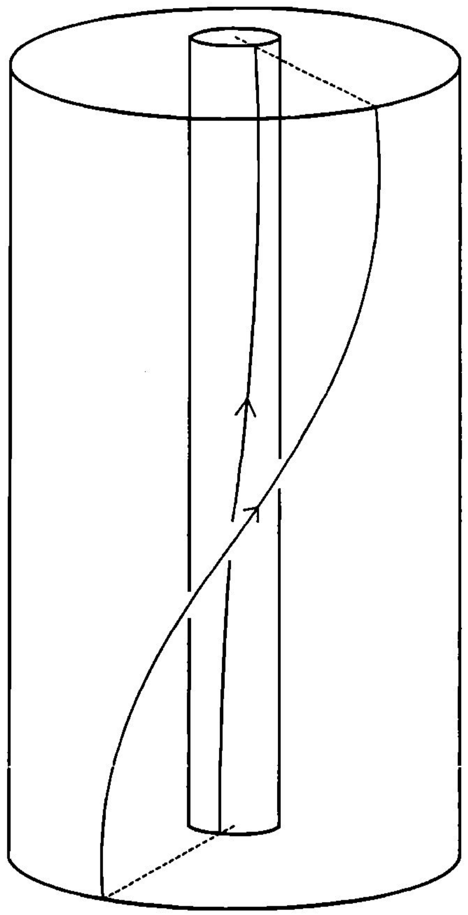
$$\mathbf{j} \times \mathbf{B} = 0 \quad \Rightarrow \quad \nabla \times \mathbf{B} = \alpha \mathbf{B}$$

In cylindrical symmetry, solutions are:

$$\mathbf{B} = B_z \mathbf{e}_z + B_\theta \mathbf{e}_\theta$$

$$B_z = B_0 \mathbf{J}_0(\alpha R) \quad B_\theta = B_0 \mathbf{J}_1(\alpha R)$$

Complex interface and in-situ identification of twisted magnetic field.



Flux rope schematic.
(Priest 1990)

Force-free equilibrium:

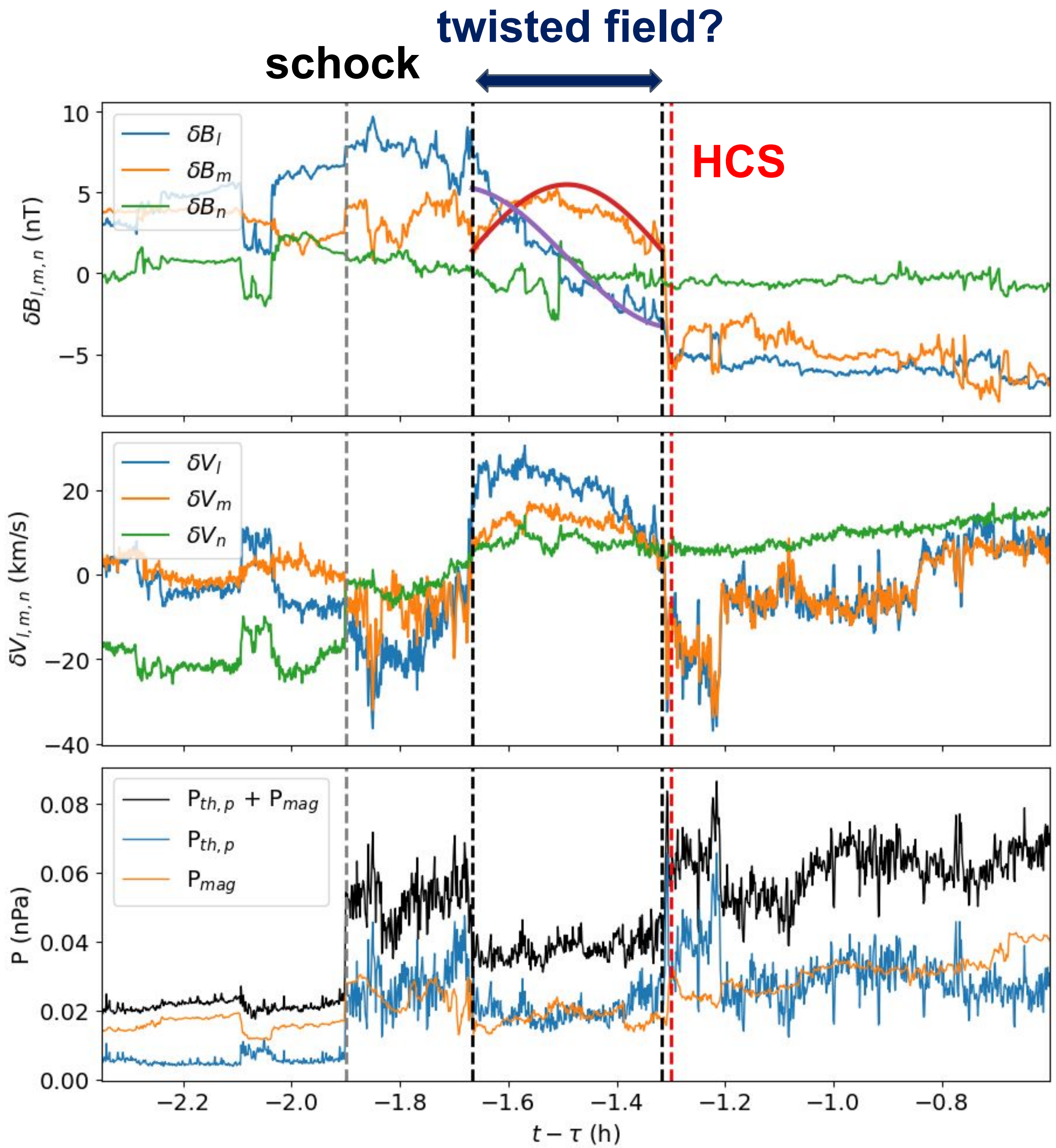
$$\mathbf{j} \times \mathbf{B} = 0 \quad \Rightarrow \quad \nabla \times \mathbf{B} = \alpha \mathbf{B}$$

In cylindrical symmetry, solutions are:

$$\mathbf{B} = B_z \mathbf{e}_z + B_\theta \mathbf{e}_\theta$$

$$B_z = B_0 \mathbf{J}_0(\alpha R) \quad B_\theta = B_0 \mathbf{J}_1(\alpha R)$$

<u>Interpretation</u>:
Forcing of magnetic reconnection due to the SIR-HCS interaction => creation of twisted magnetic structure at the boundaries.



Summary

- Propagation Method:
  Constant Velocity ⇒ Constant acceleration ⇒ Non-radial propag.
- Identification of a same density structure.
- Density structure corresponds to a sector boundary substructure.
- Observation of Stream Interaction Region forming then engulfing the Heliospheric Current Sheet at SolO.
- Shock Mach number ~ 1.1 - 1.2.
- Driving of magnetic reconnection and formation of twisted fields by interaction of shock and HCS.

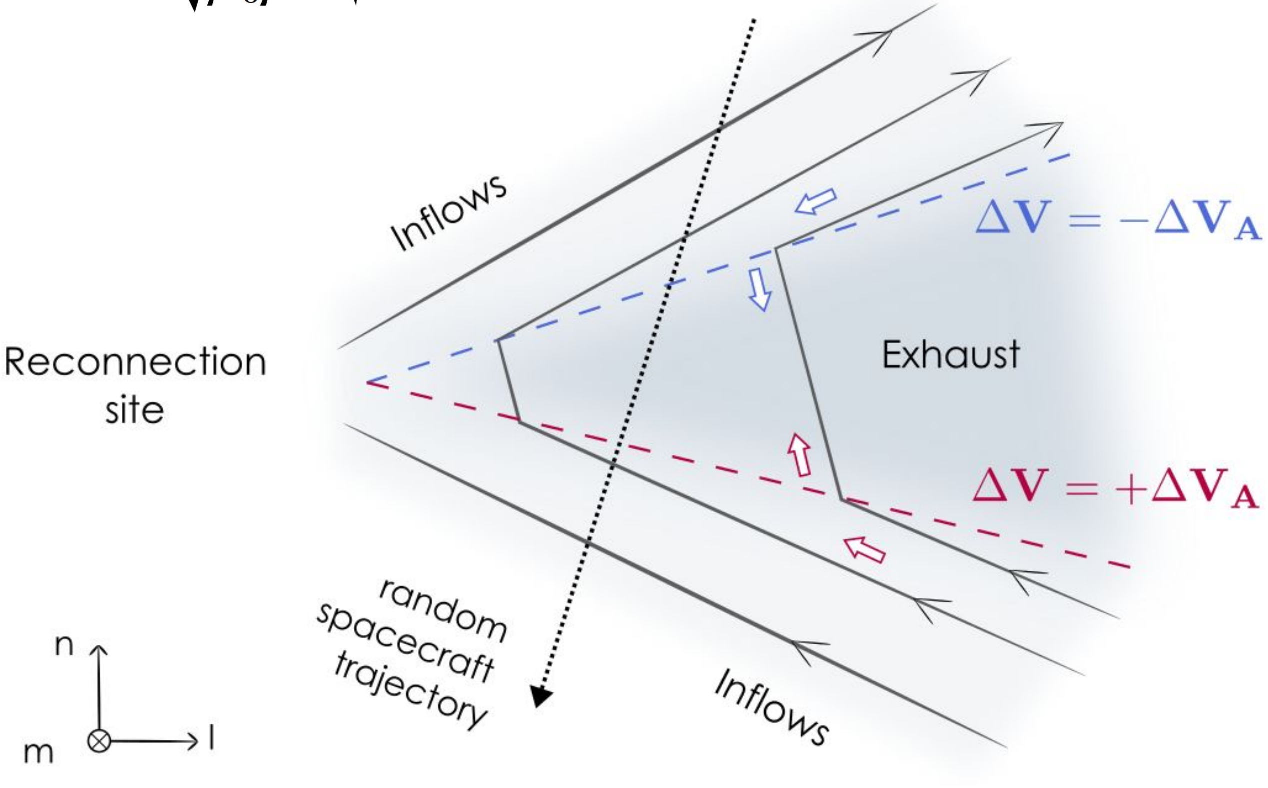
Futur work

- Better characterization of the boundary structuring.
- Studying other event of HCS embedded in SIRs.
- Accounting for temperature anisotropy.

Finir ici?

In-situ identification of magnetic reconnection exhaust?

$$\mathbf{V_A} = \frac{\mathbf{B}}{\sqrt{\mu_0 \rho}} \sqrt{1 - \frac{\mu_0}{B^2}(P_\parallel - P_\perp)}$$



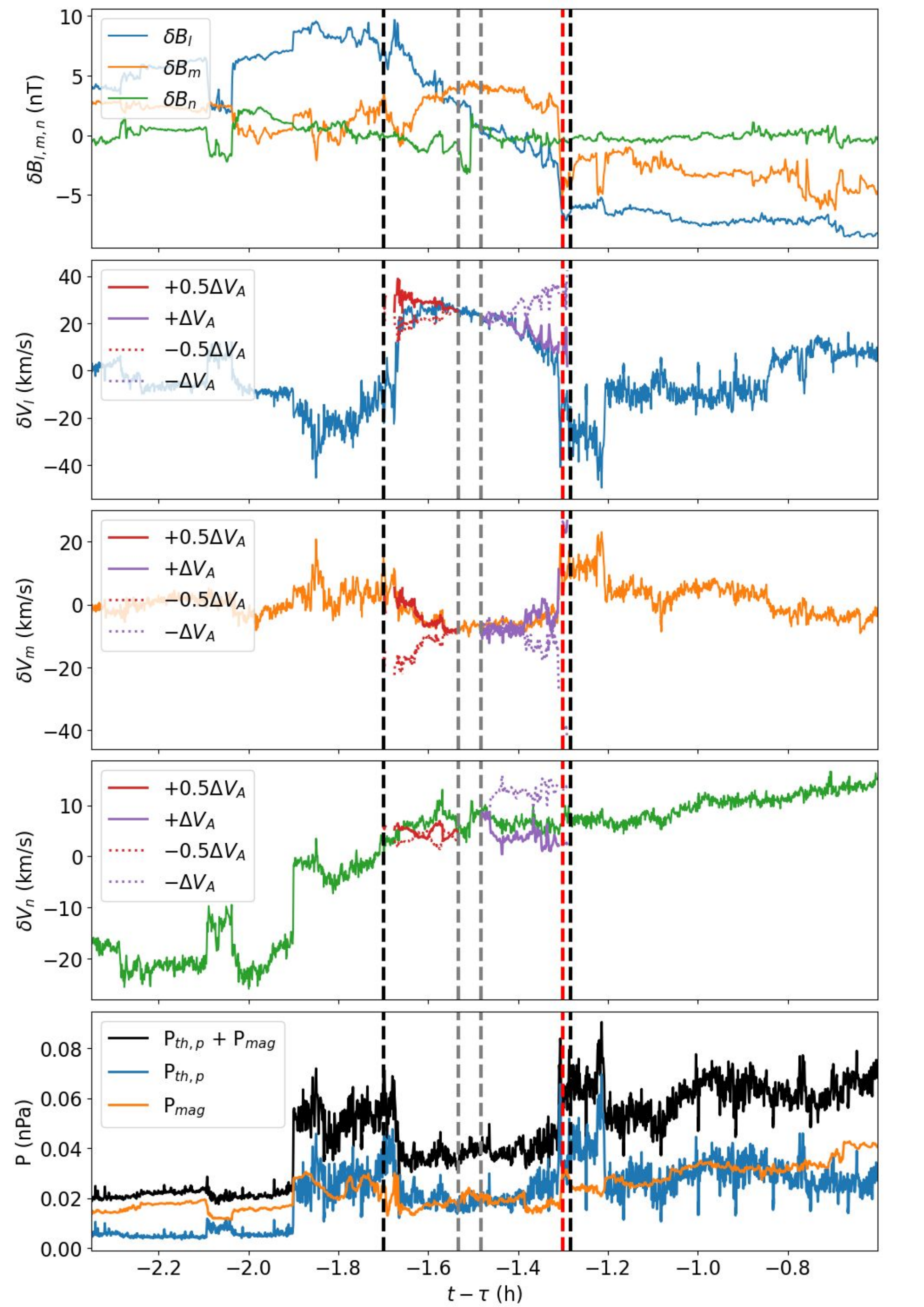
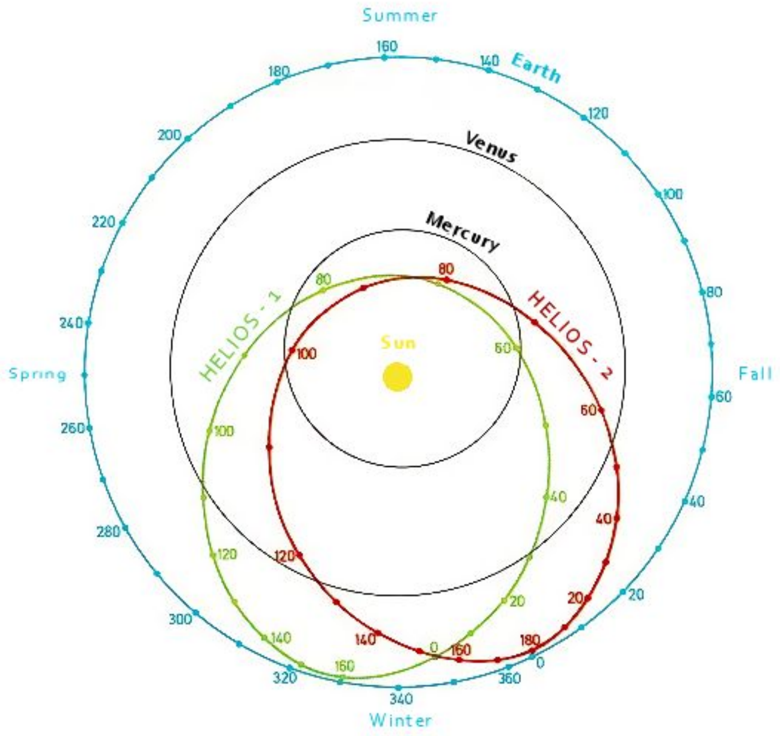
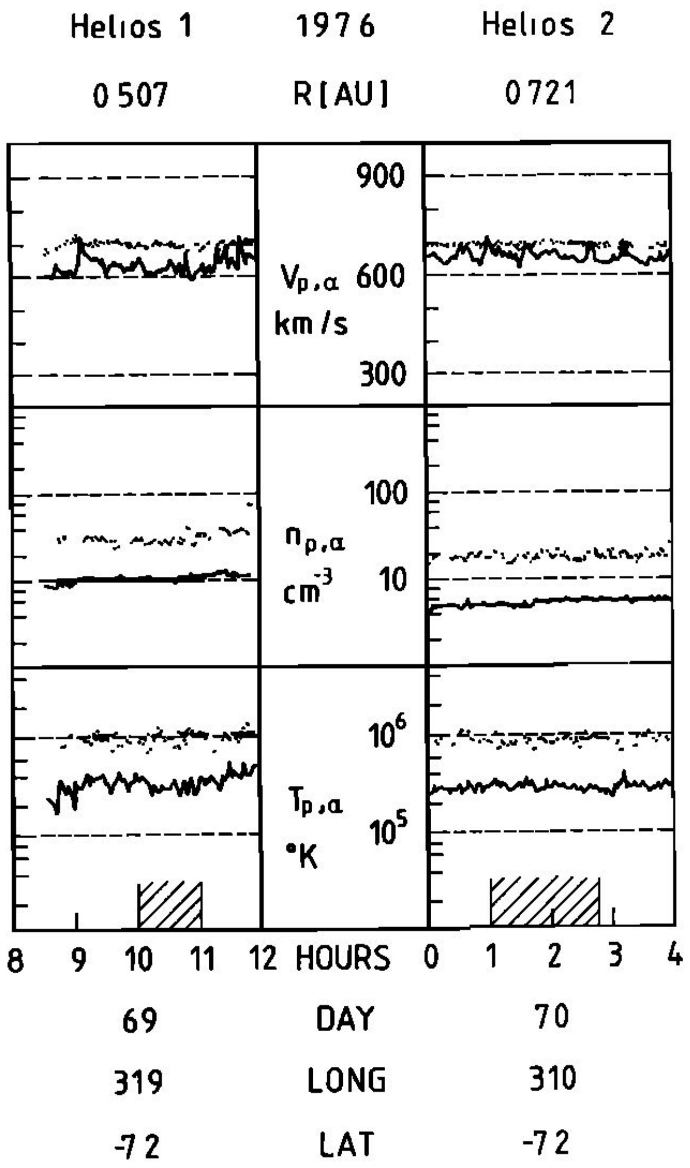


Illustration of the Walén relation across a reconnection site.

(Fargette et al. 2023)

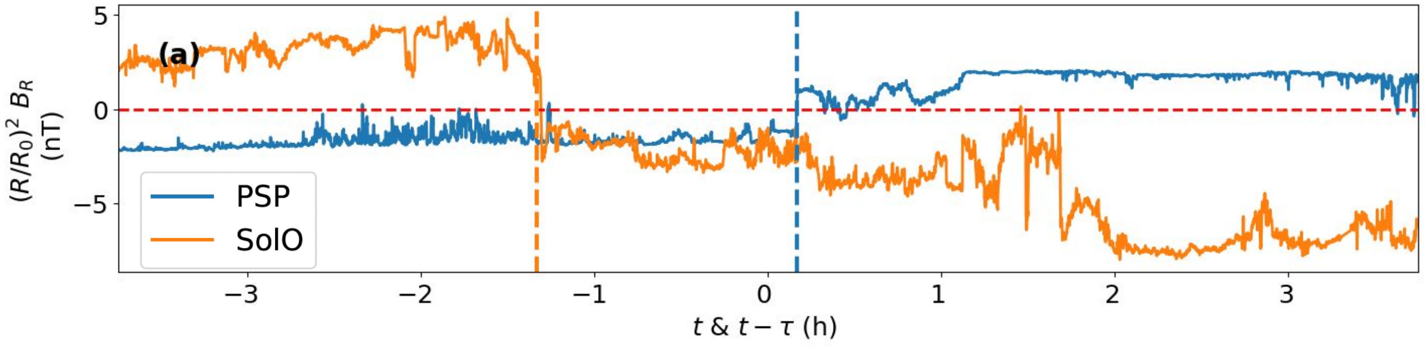
1st case study of plasma line-up with Helios 1 & 2 : Schwartz & Marsch, 1983

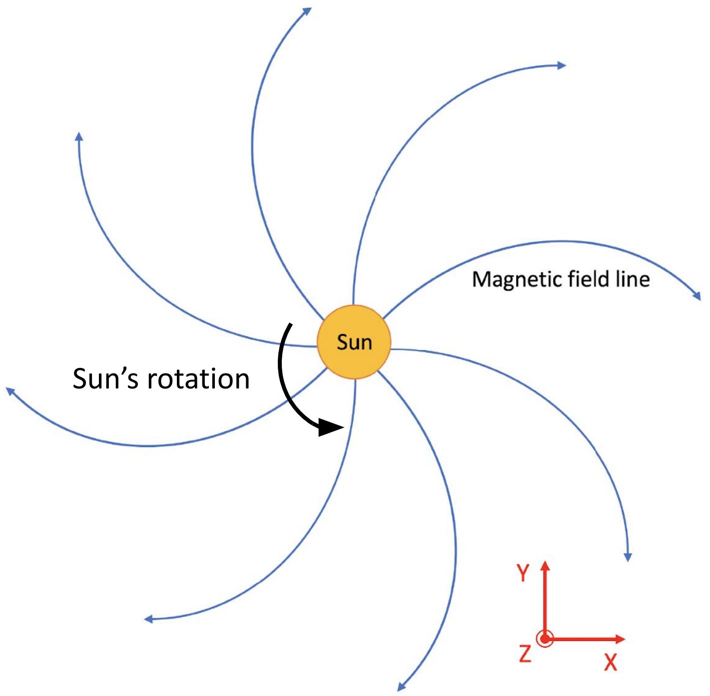


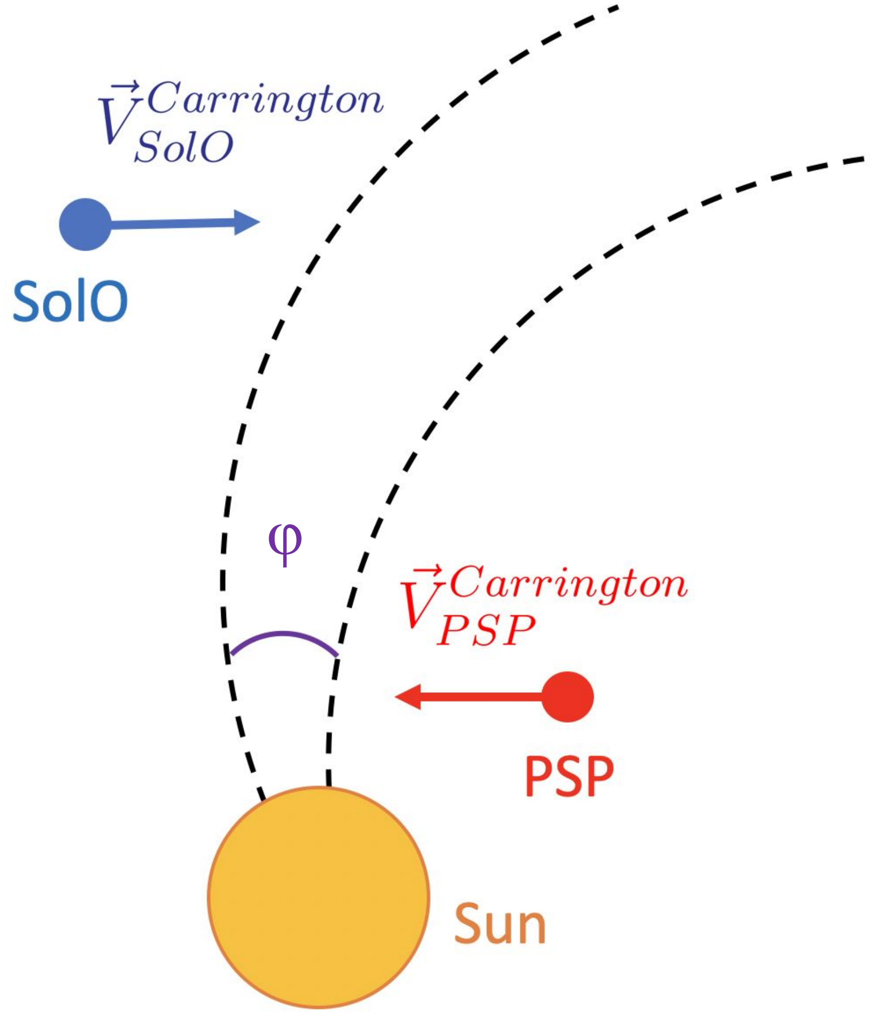


- Fast solar wind
- Prediction assuming a constant and radial propagation velocity.
- Solar wind's expansion taken into account.
- Helios era : few studies, not very concluding (large error bars, data gaps)

Taking into account the Sun's rotation



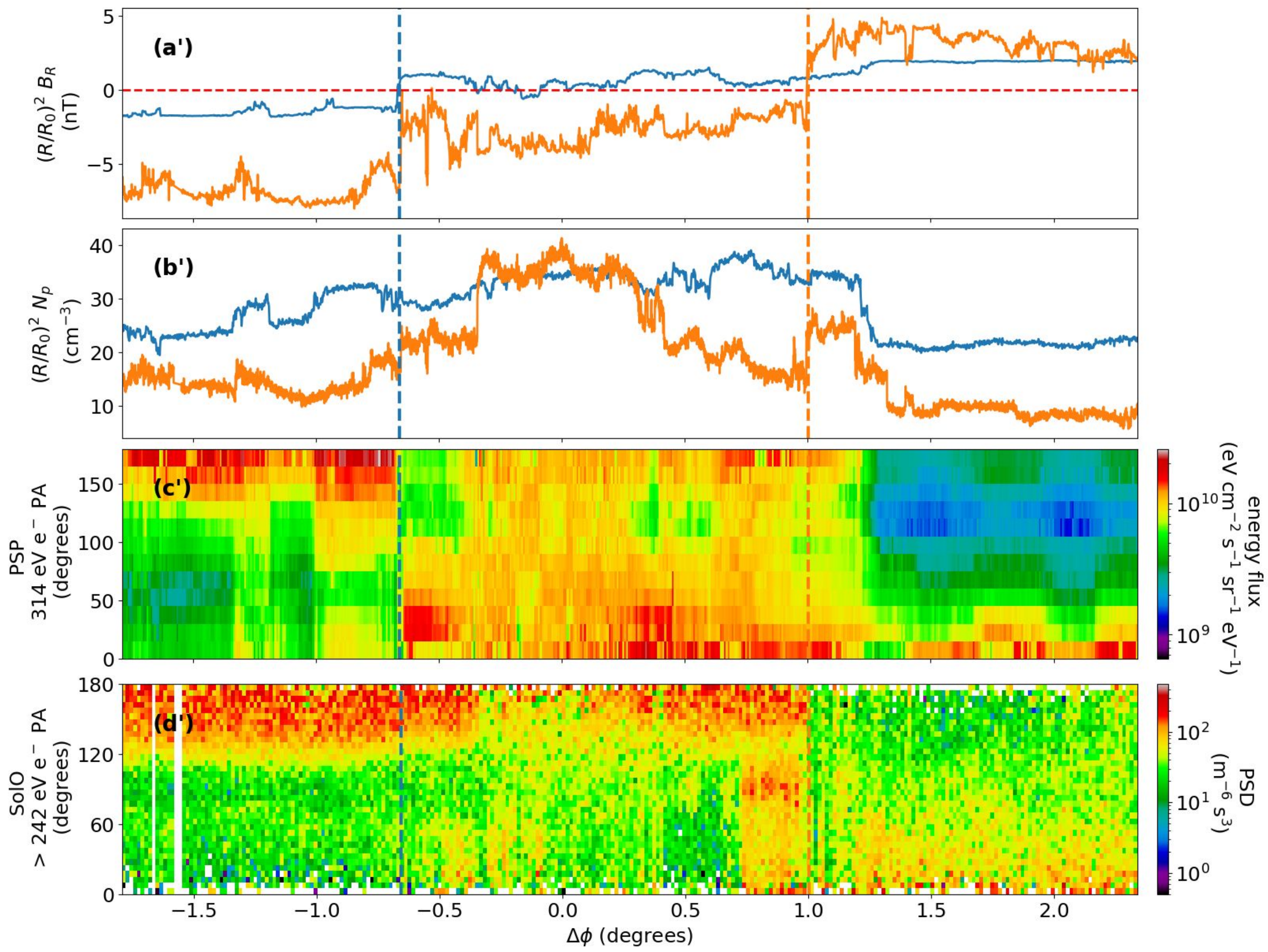


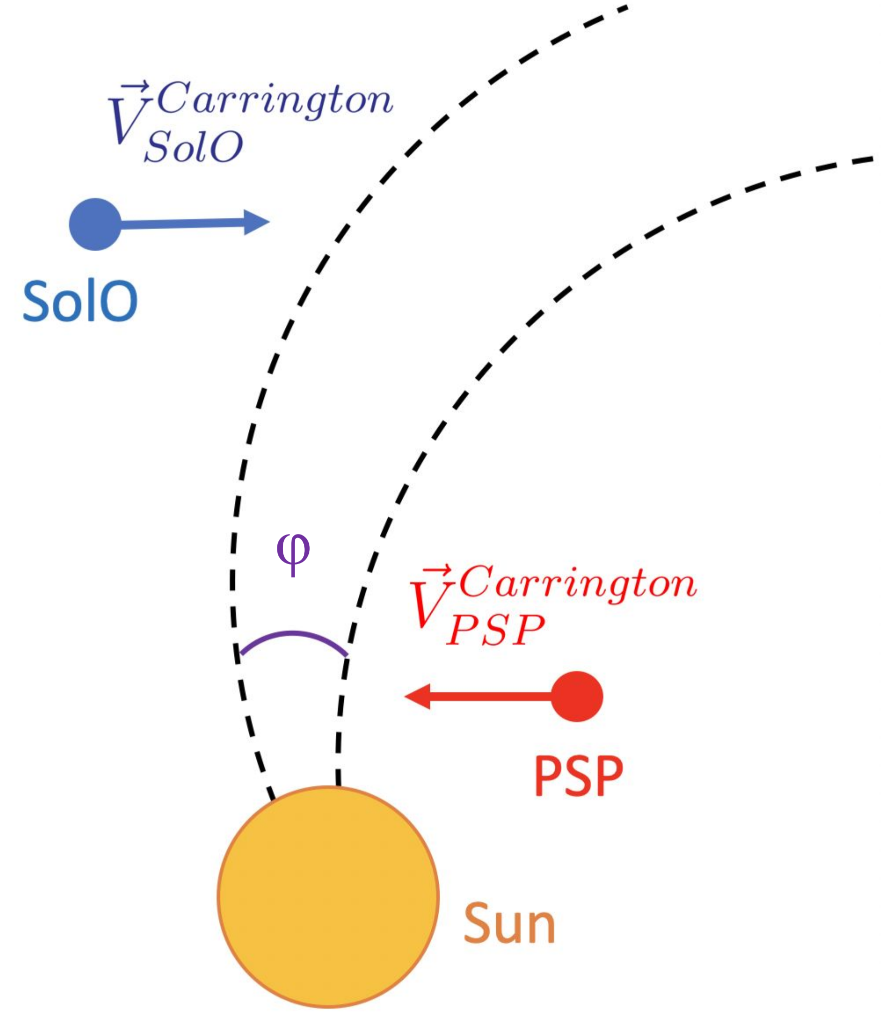


- We take into account the solar and spacecraft rotations:

$$\Delta\phi = (\omega_{inner} - \omega_{Sun})\Delta t_{inner}$$
$$\Delta\phi = (\omega_{outer} - \omega_{Sun})\Delta t_{outer}$$

Taking into account the Sun's rotation

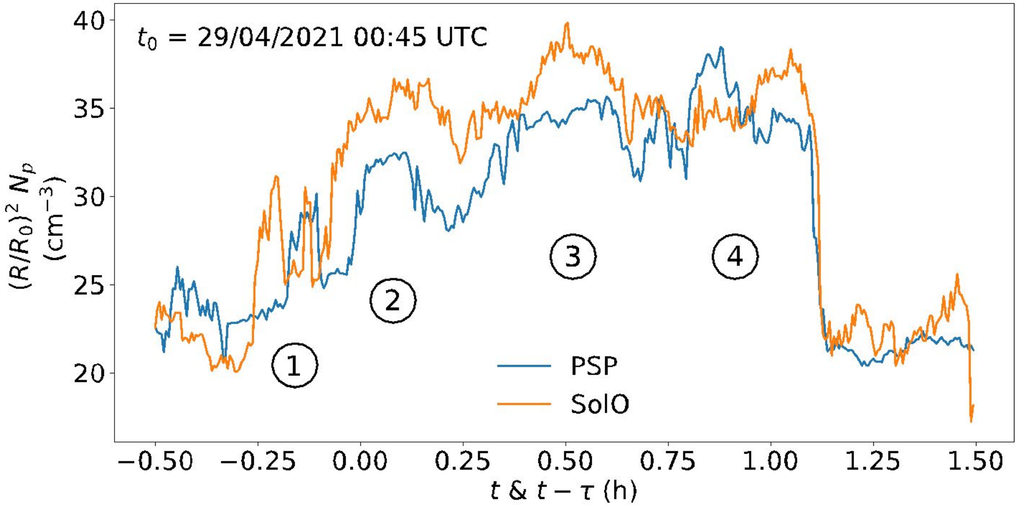




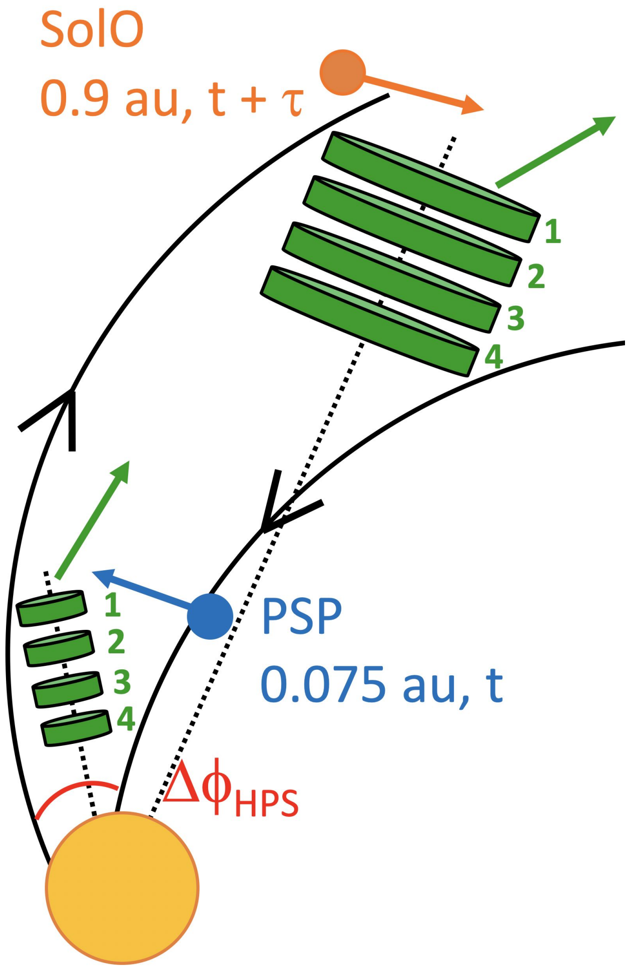
- We take into account the solar and spacecraft rotations:

$$\Delta\phi = (\omega_{inner} - \omega_{Sun})\Delta t_{inner}$$
$$\Delta\phi = (\omega_{outer} - \omega_{Sun})\Delta t_{outer}$$

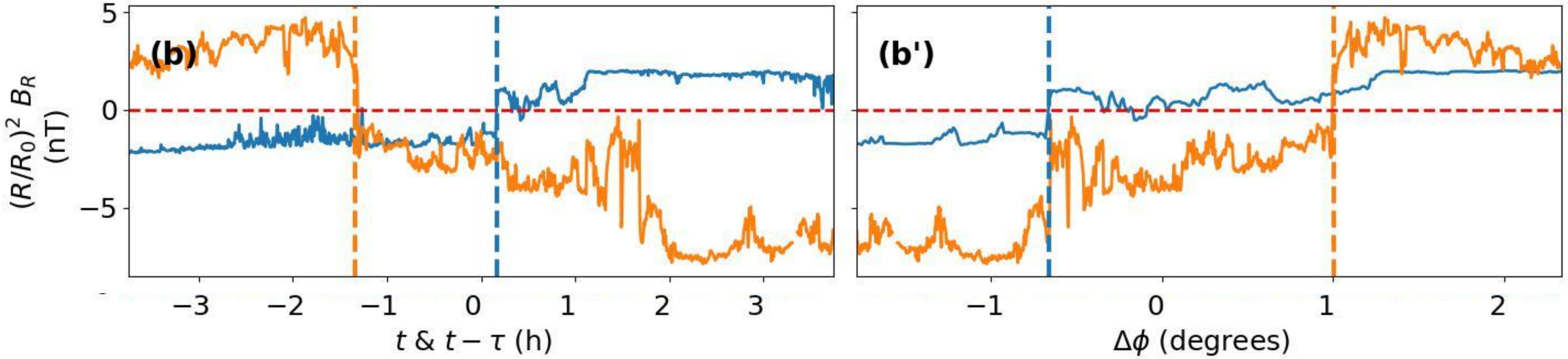
Interpretation



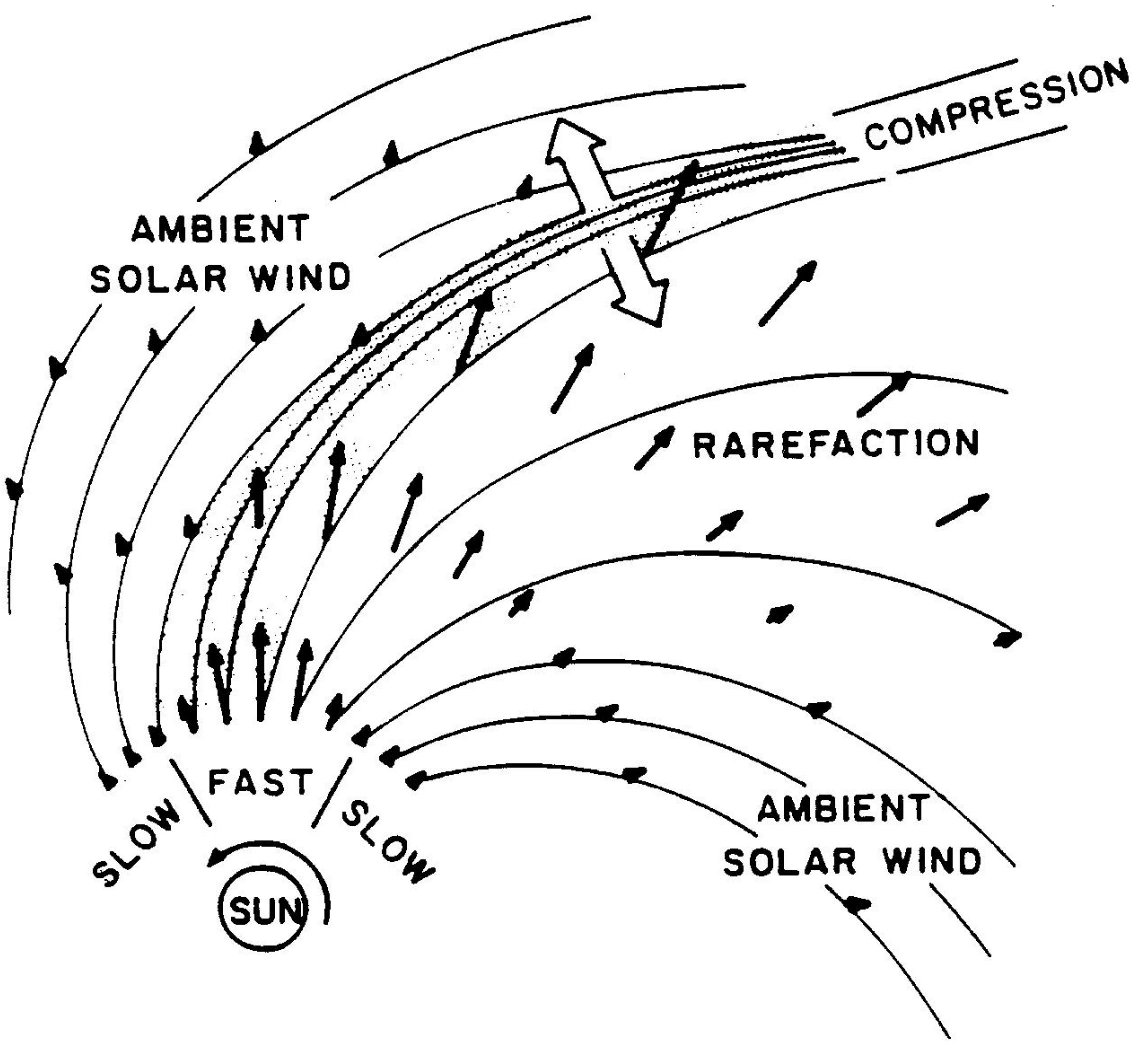
Density structure advected by the solar wind ⇒ radial gradients



Magnetic inversion linked with the solar wind sources ⇒ longitudinal gradients



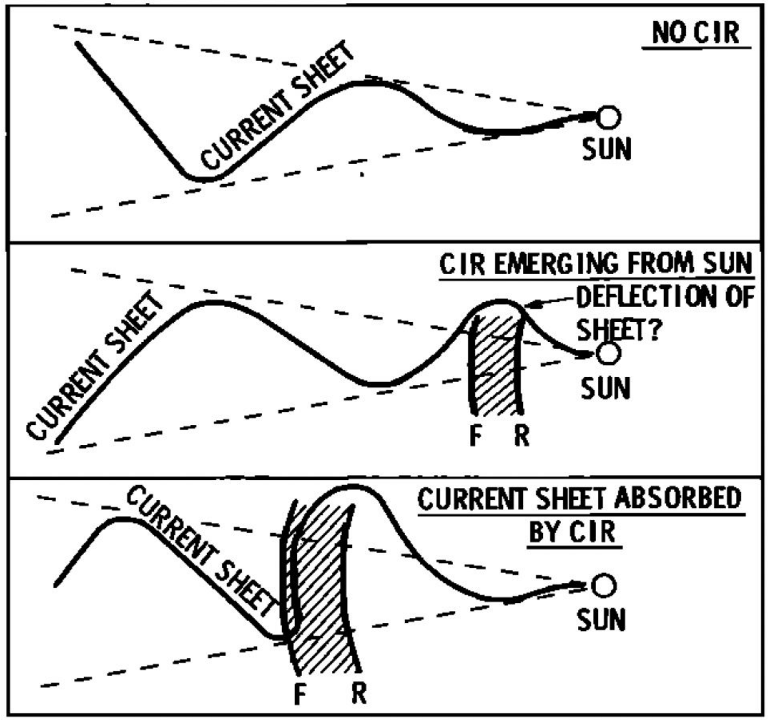
HCS and Streams Interaction Regions (SIR)



Stream Interaction region schematic
Gosling et al. 1999

- Due to the Sun's rotation the slow wind can be caught up by a faster wind => formation of SIR.
  A pair of propagating shocks can also develop at the edges of the interaction region.

- Depending on the magnetic field topologie SIR can also engulf the HCS and HPS.



Schematic a SIR interacting with the HCS
Thomas et al. 1981

Constrained constant acceleration

Constant acceleration:

$$\mathbf{R}(t) = \mathbf{R}_{\text{in}} + (t - t_{\text{in}})\mathbf{V}_{\text{in}} + \frac{(t-t_{\text{in}})^2}{2}\,\mathbf{a}$$
$$\mathbf{V}(t) = \mathbf{V}_{\text{in}} + (t - t_{\text{in}})\,\mathbf{a}$$

After propagation:

$$\mathbf{R}_{\text{out}} \approx \mathbf{R}_{\text{in}} + \tau\mathbf{V}_{\text{in}} + \frac{\tau^2}{2}\mathbf{a}$$
$$\mathbf{V}_{\text{out}} \approx \mathbf{V}_{\text{in}} + \tau\,\mathbf{a}$$

Modeled acceleration:

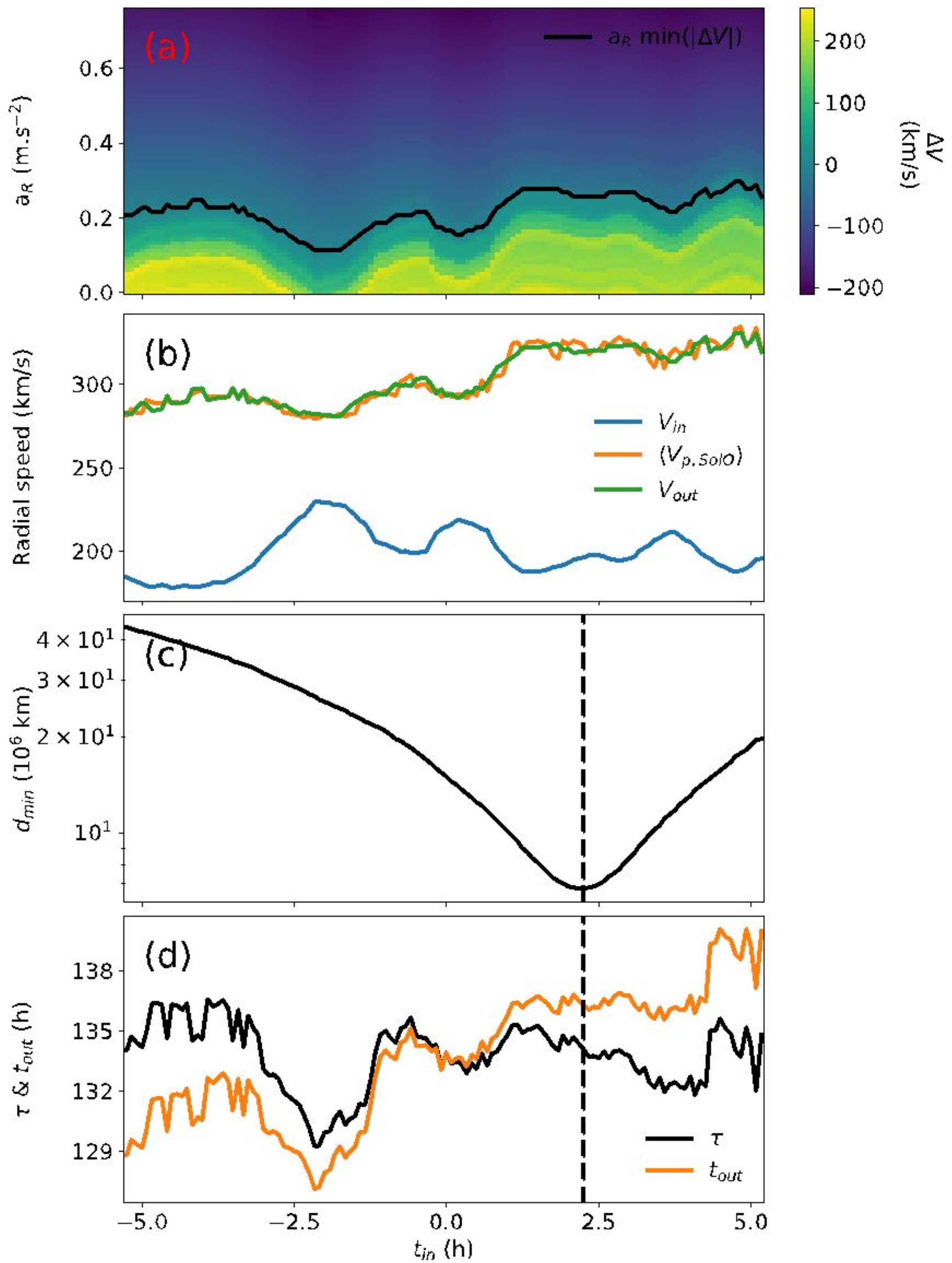
$$\mathbf{a} \approx \frac{||\mathbf{V}_{\text{out}} + \mathbf{V}_{\text{in}}||}{2\,||\mathbf{R}_{\text{out}} - \mathbf{R}_{\text{in}}||}\,(\mathbf{V}_{\text{out}} - \mathbf{V}_{\text{in}})$$

Max acceleration:

$$a_{\max} = \frac{V_{\text{out,max}}^2 - V_{\text{in,min}}^2}{2\,||\mathbf{R}_{\text{out}} - \mathbf{R}_{\text{in}}||}$$

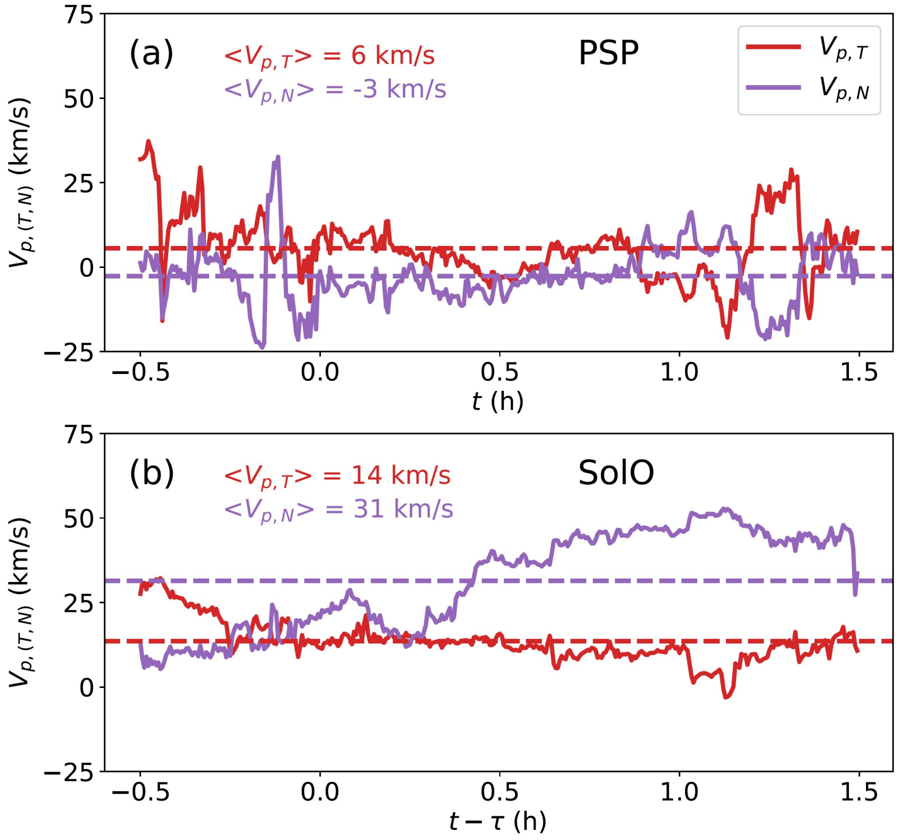
Data - model:

$$\Delta V = \langle V_{p,SolO} \rangle - V_{\text{out}}$$

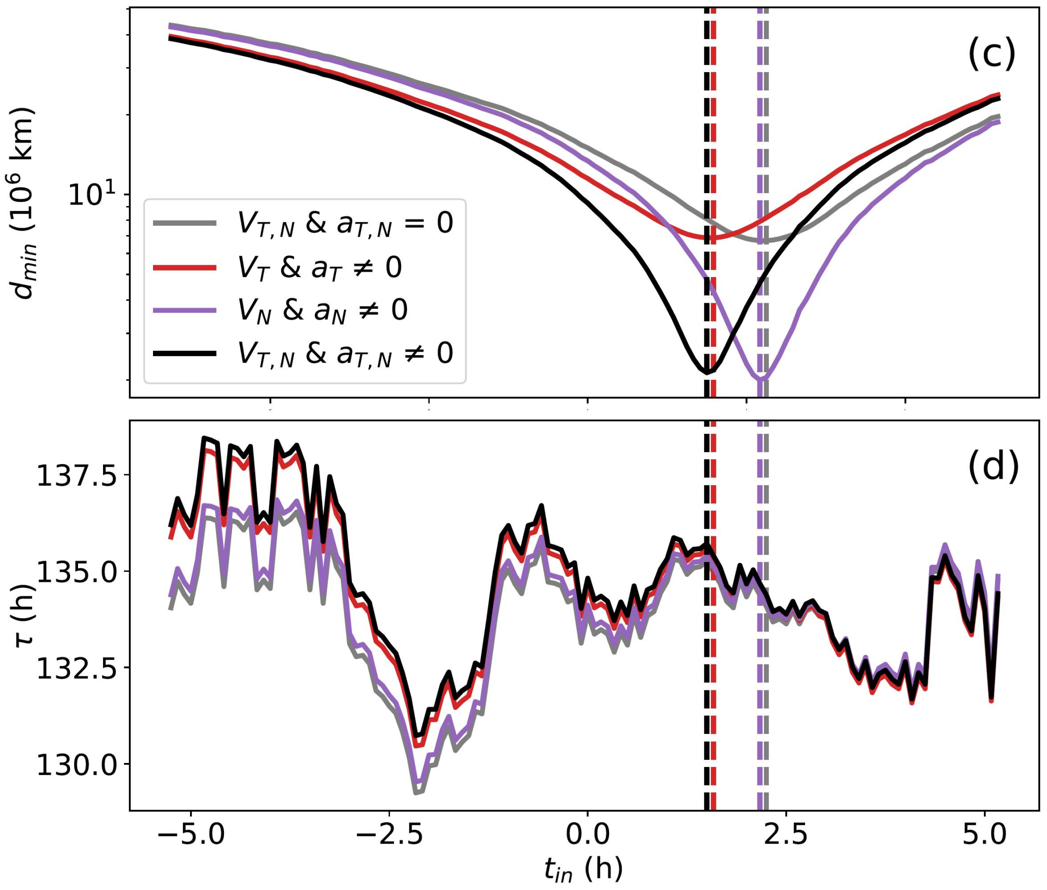


Non-radial propagation

Due to the SIR deflection:
non-zero V_T and V_N around the identified structure



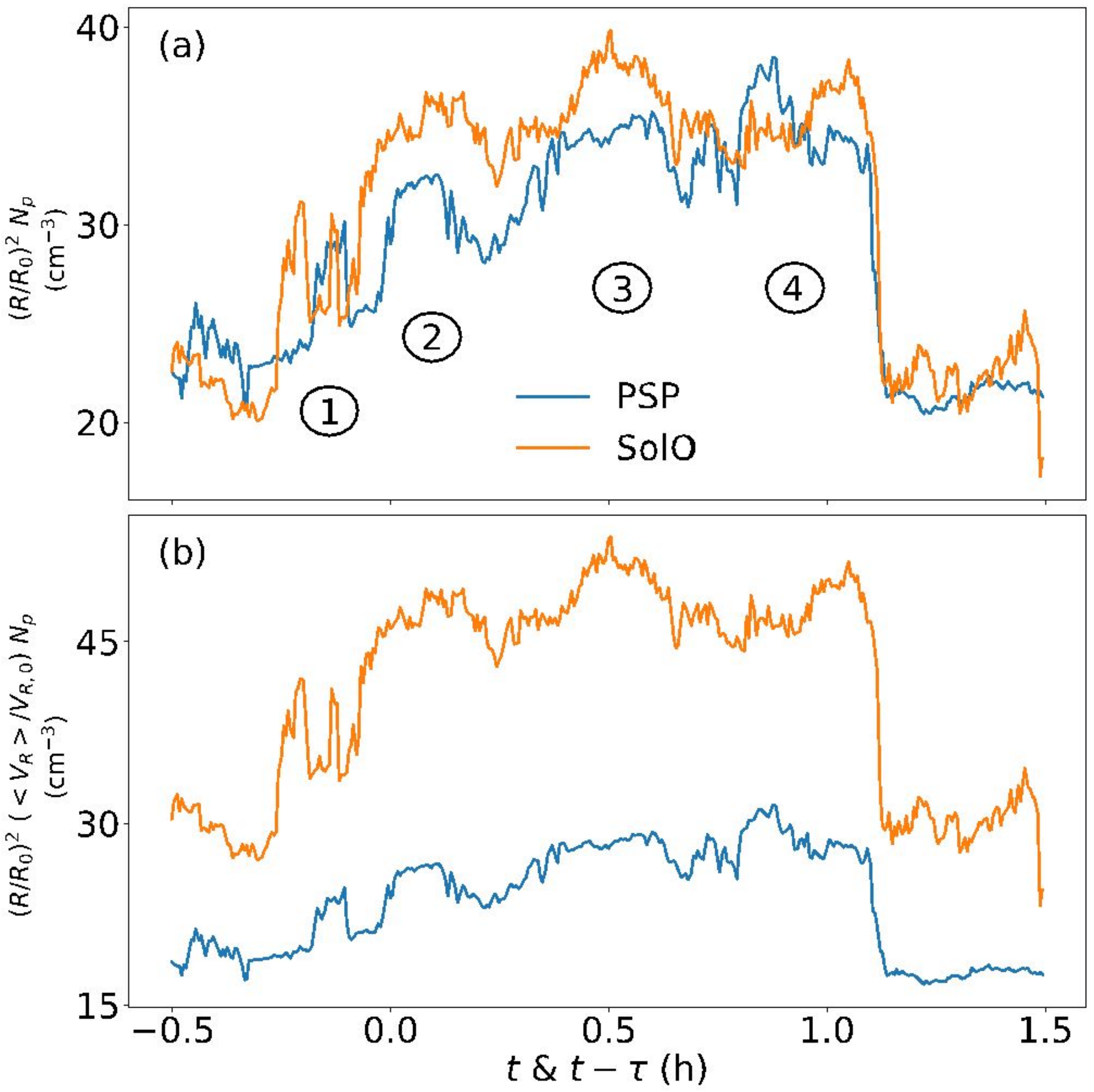
$$V_{(in,out),j} = \langle V_{p,(PSP,SolO),j} \rangle$$



$$\mathbf{V}(t) = (V_R(t), V_T(t), V_N(t))$$

$$V_j(t) = V_{in,j} + (t - t_{in})\, a_j$$

$$a_j = \frac{V_{out,R} + V_{in,R}}{2\|\Delta \mathbf{R}\|} \left(V_{out,j} - V_{in,j}\right)$$



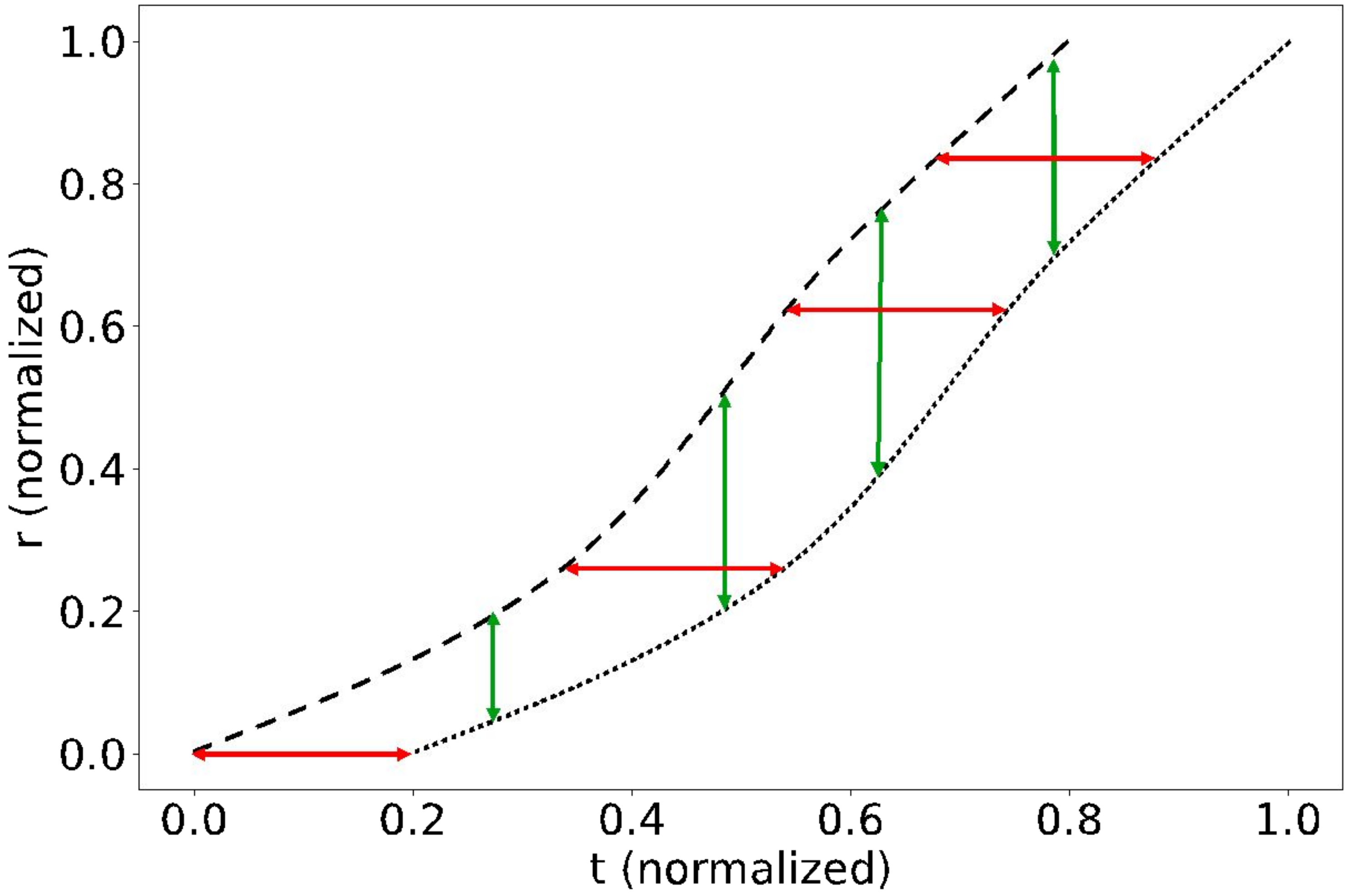
Correction of plasma acceleration

Assumptions : spherical expansion + stationnarity

$$\partial_r(R^2 n V_R) = 0 \Rightarrow n V_R \propto R^{-2}$$

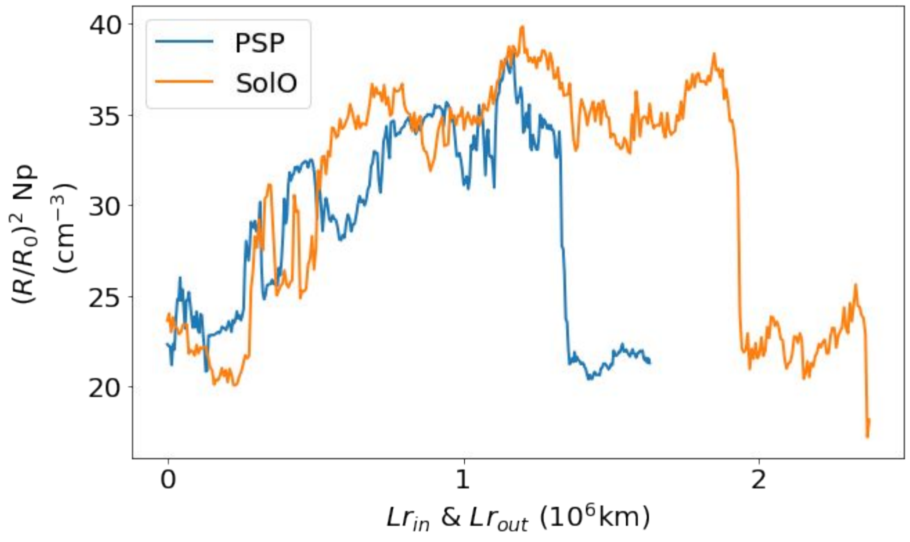
Density at SolO is higher than at PSP after correction
 compression effect during the plasma's expansion

Stretching due to acceleration

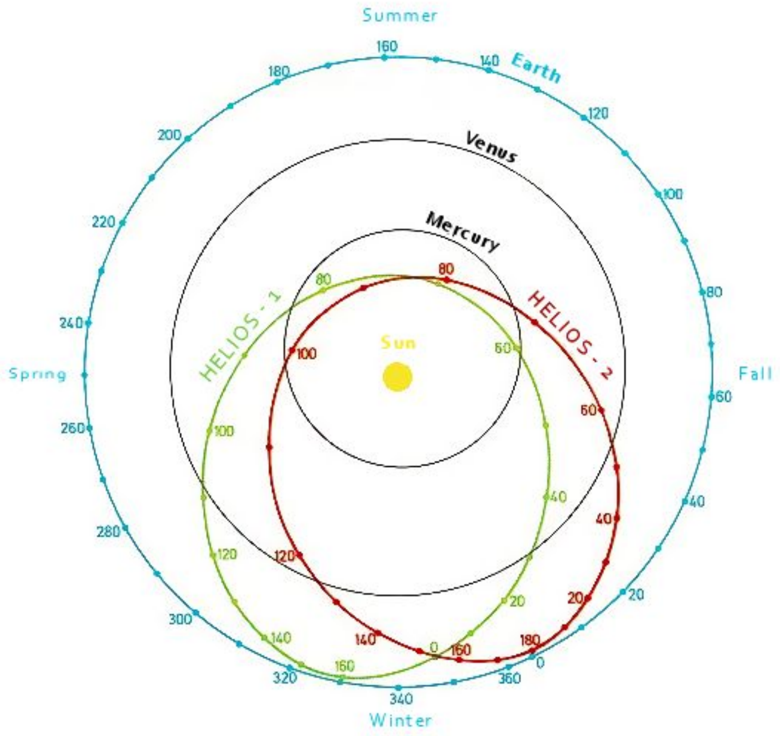


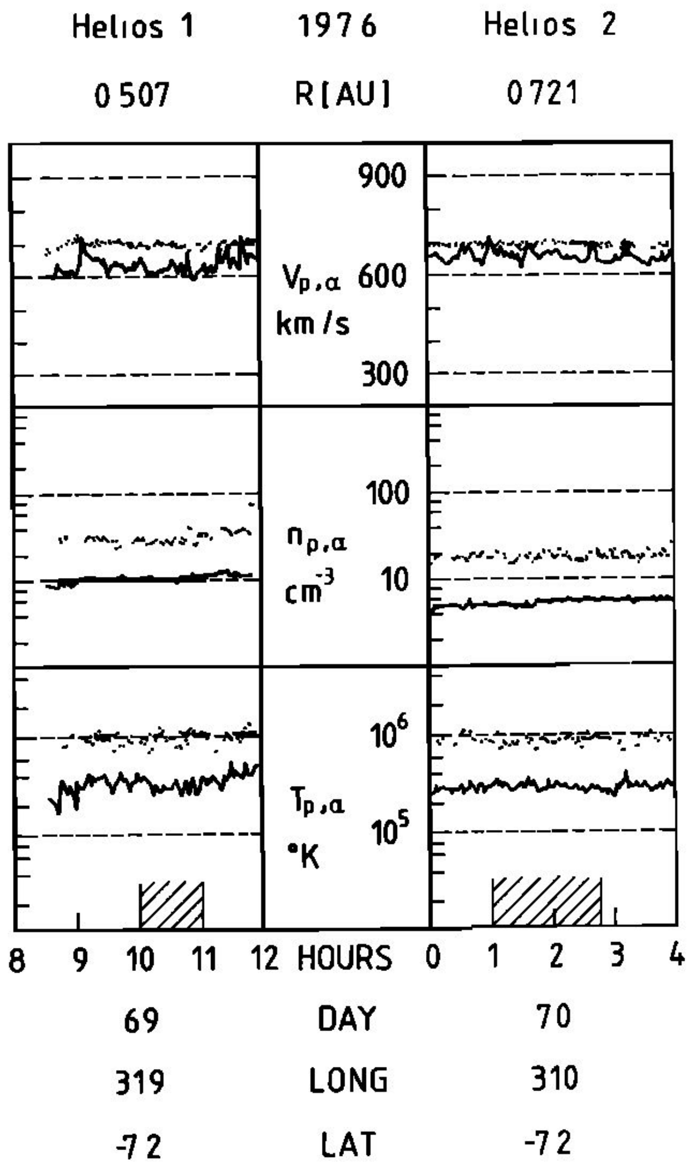
Schematic of two points separated with a time offset and propagating with the same speed profile.

We can't compare lengths because of stretching we should adapt time variable



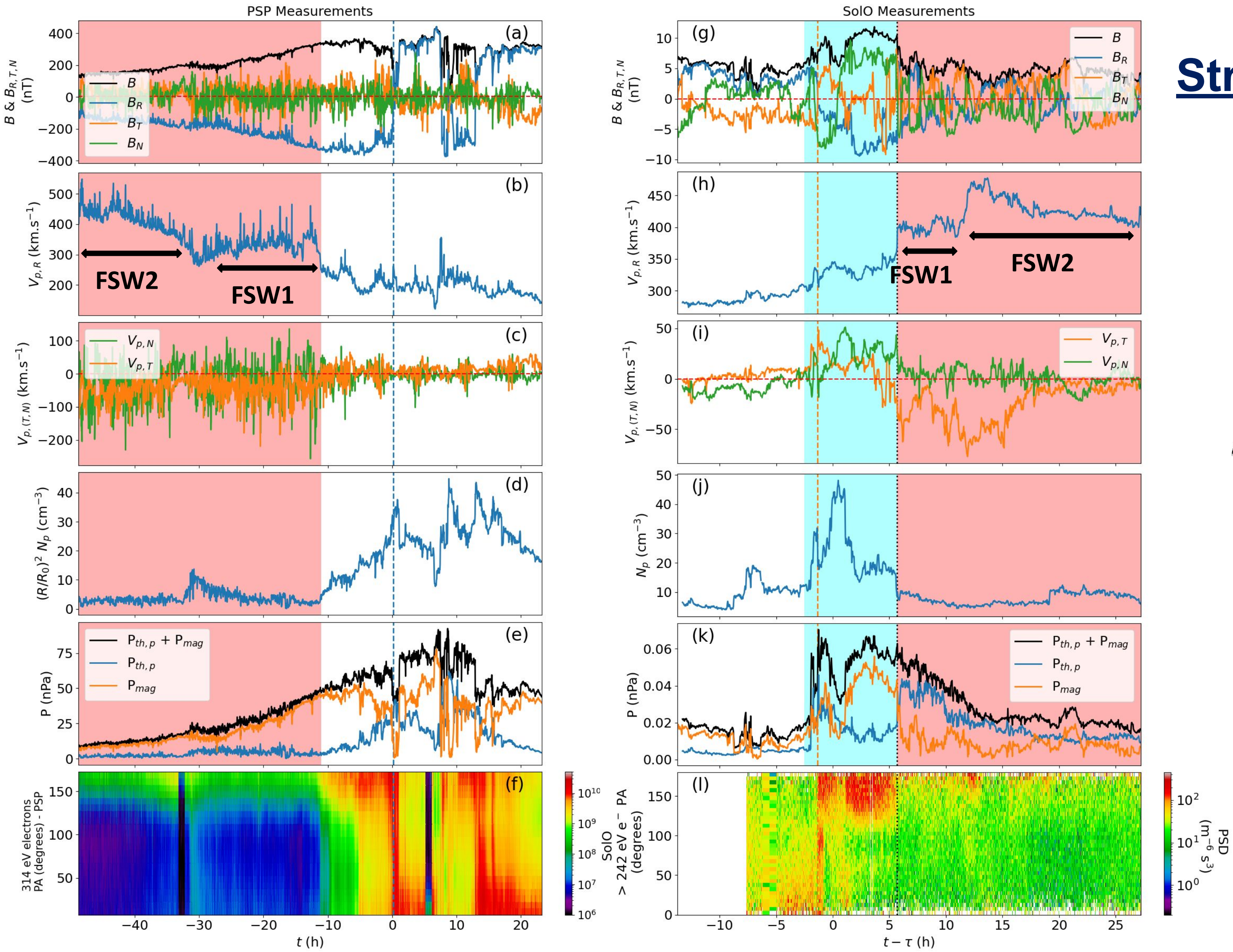
1st study of plasma line-up with Helios 1 & 2 : Schwartz & Marsch, 1983

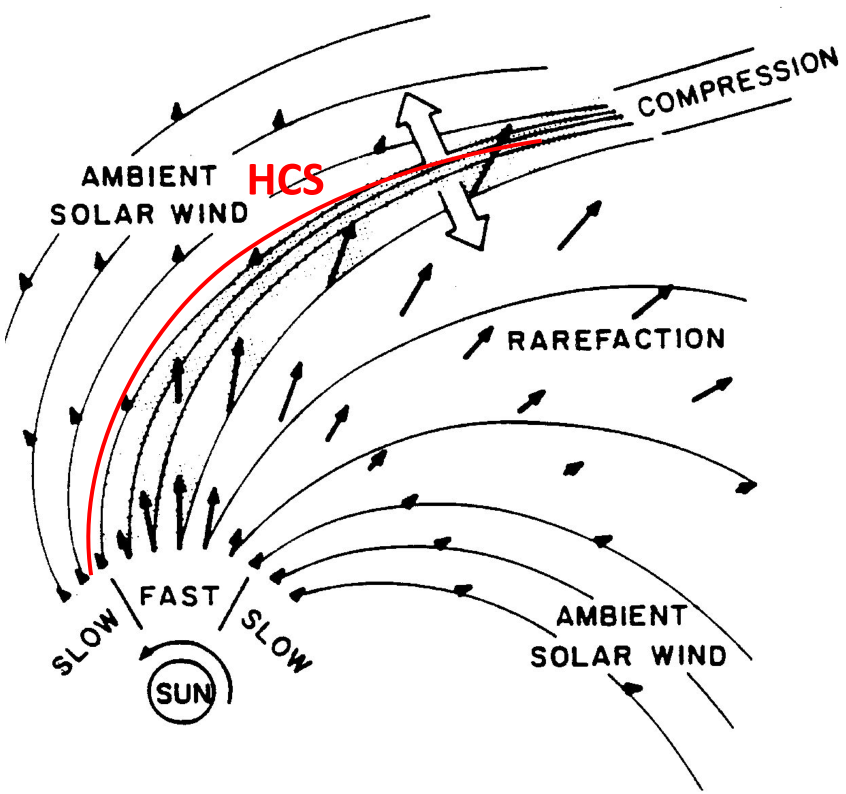




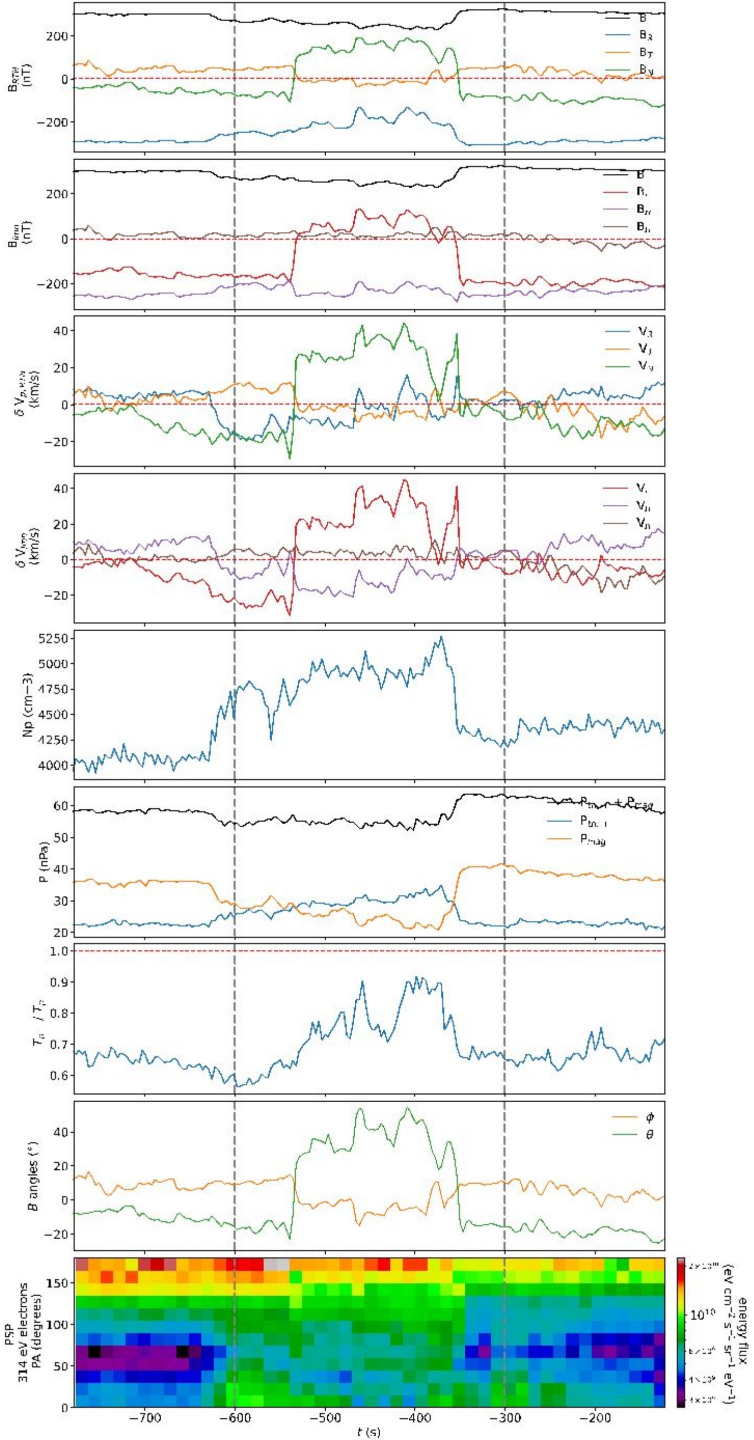
- Fast solar wind
- Prediction assuming a constant and radial propagation velocity.
- Solar wind's expansion taken into account.
- Helios era : few studies, not very concluding (large error bars, data gaps)

Zoom-out
Stream Interaction Region (SIR)

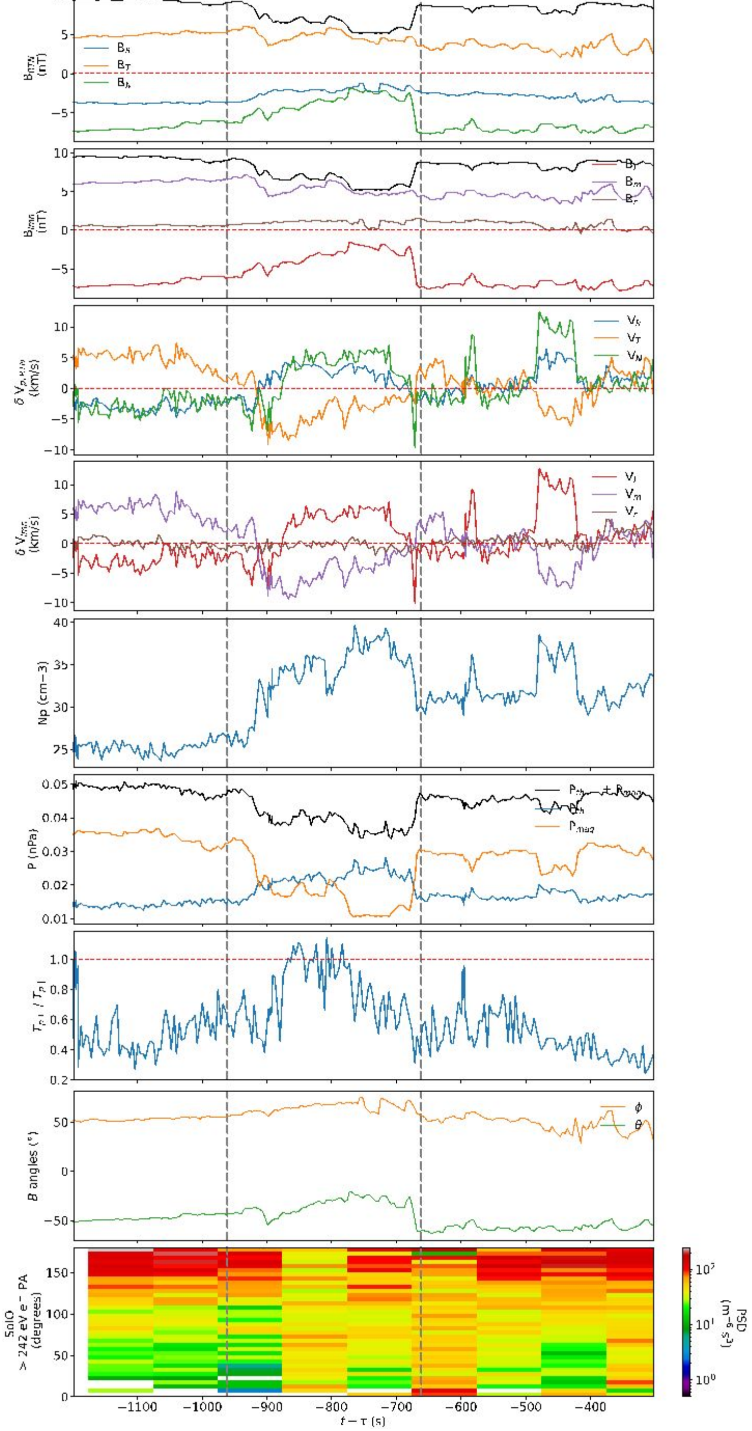




Stream Interaction region schematic
Gosling et al. 1999

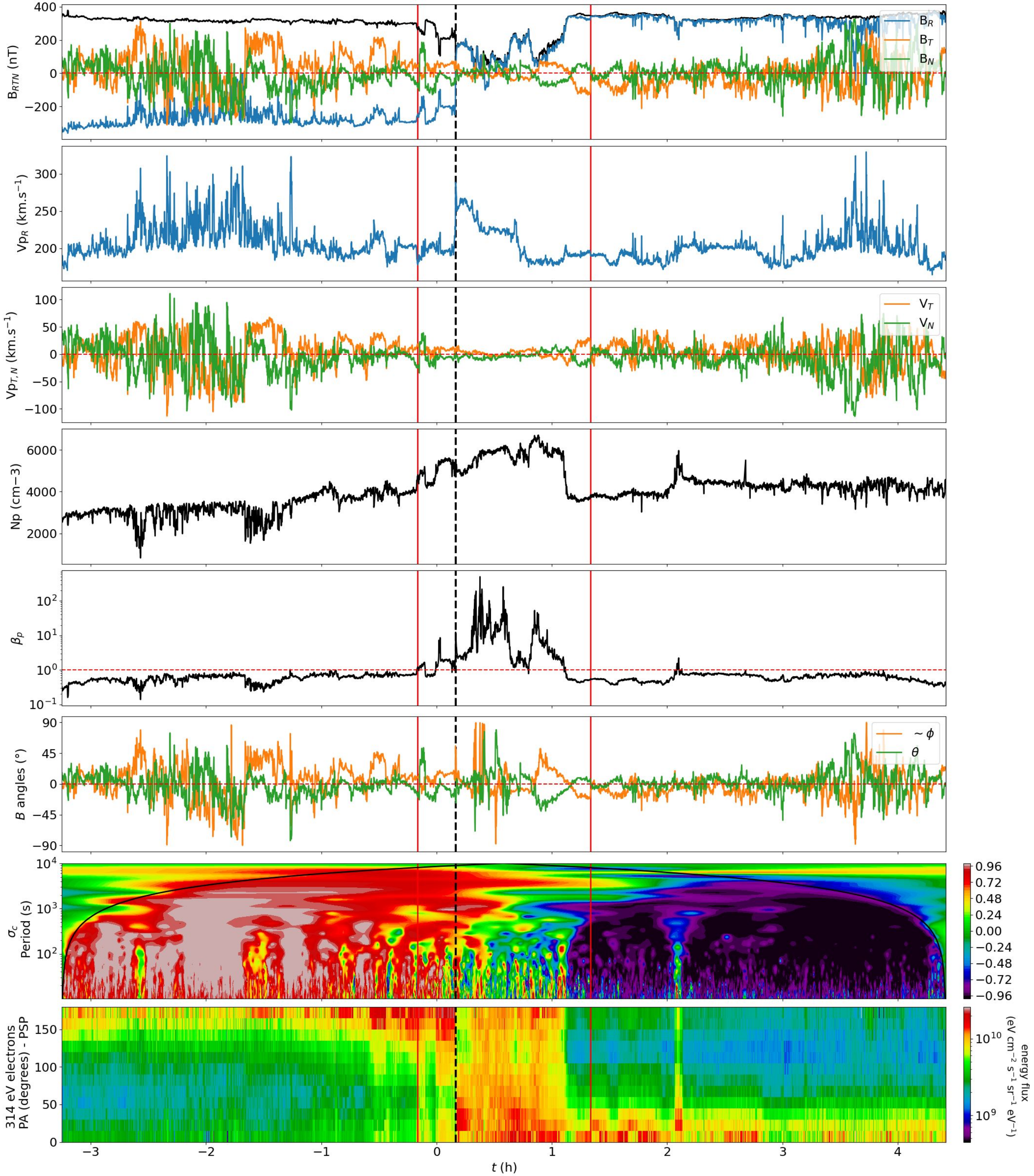


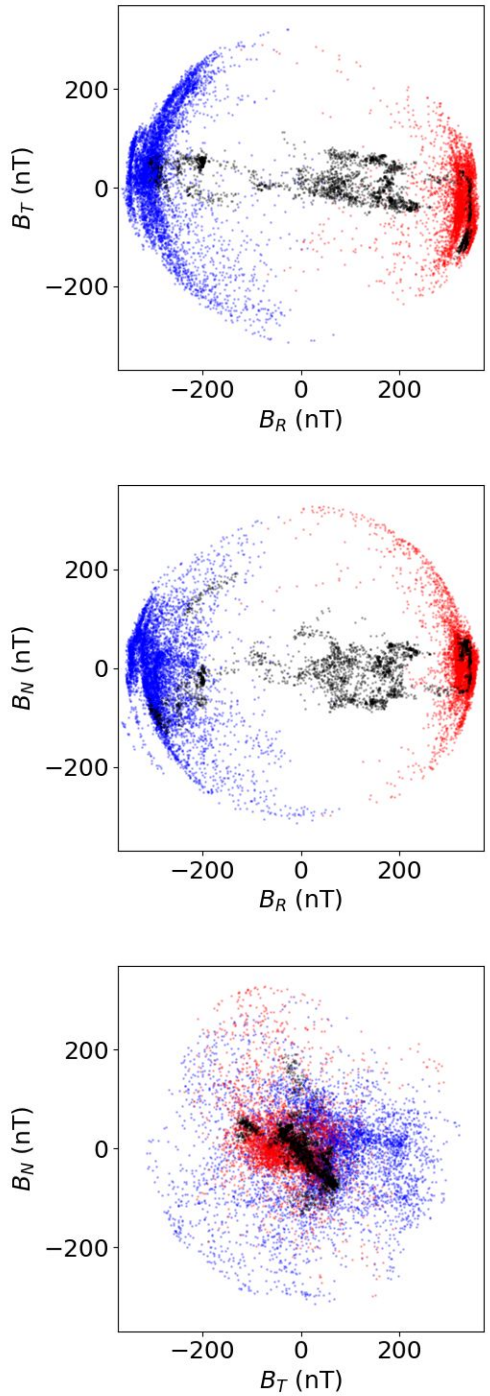
Np (cm−3)
P (nPa)
B angles (°)
PSP
314 eV electrons
PA (degrees)
t (s)



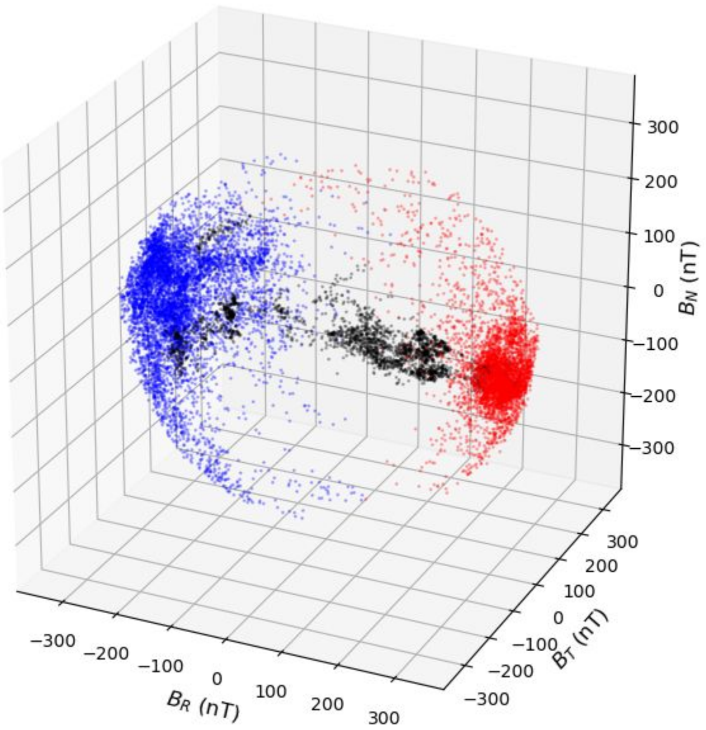
Np (cm−3)
P (nPa)
B angles (°)
SolO
> 242 eV e⁻ PA
(degrees)
t − τ (s)

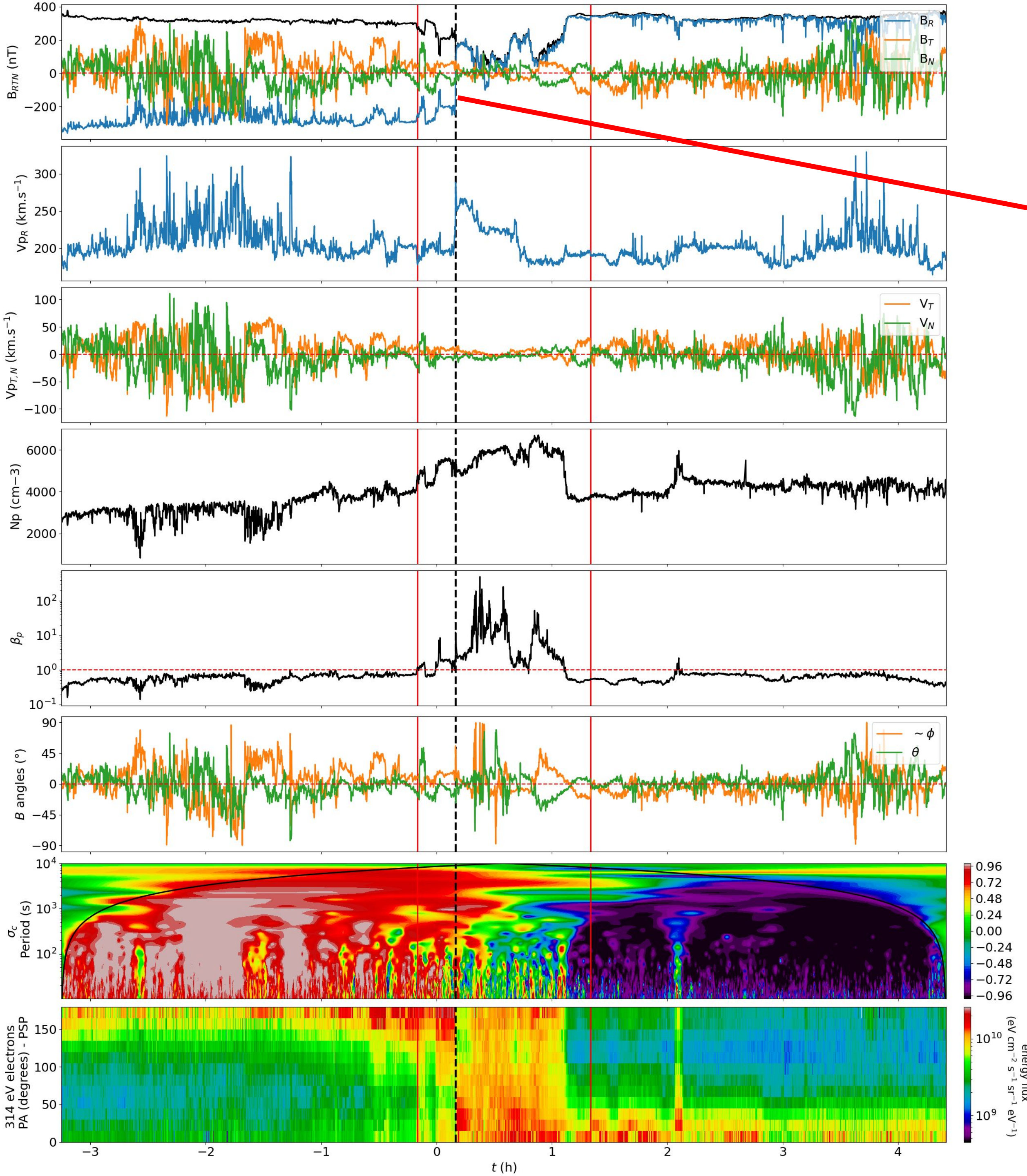
PSP HPS

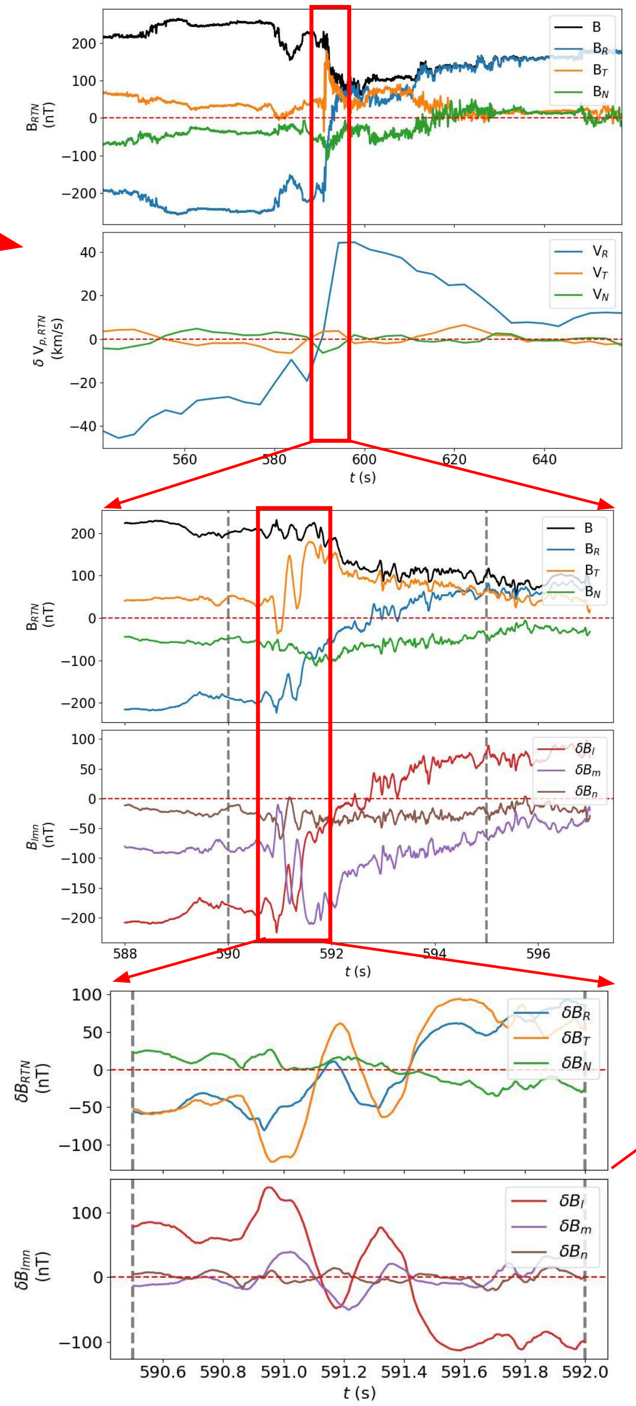

B$_{RTN}$ (nT)
B$_R$
B$_T$
B$_N$
Vp$_R$ (km.s^{-1})
Vp$_{T,N}$ (km.s^{-1})
V$_T$
V$_N$
Np (cm−3)
β_p
B angles (°)
$\sim\phi$
θ
σ_c
Period (s)
314 eV electrons
PA (degrees) - PSP
energy flux
(eV cm^{-2} s^{-1} sr^{-1} eV^{-1})
t (h)


B_T (nT)
B_R (nT)
B_N (nT)
B_R (nT)
B_N (nT)
B_T (nT)

Hodograms

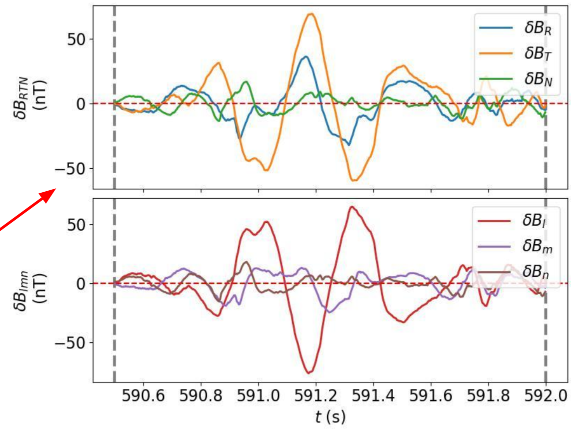

B_R (nT)
B_T (nT)
B_N (nT)

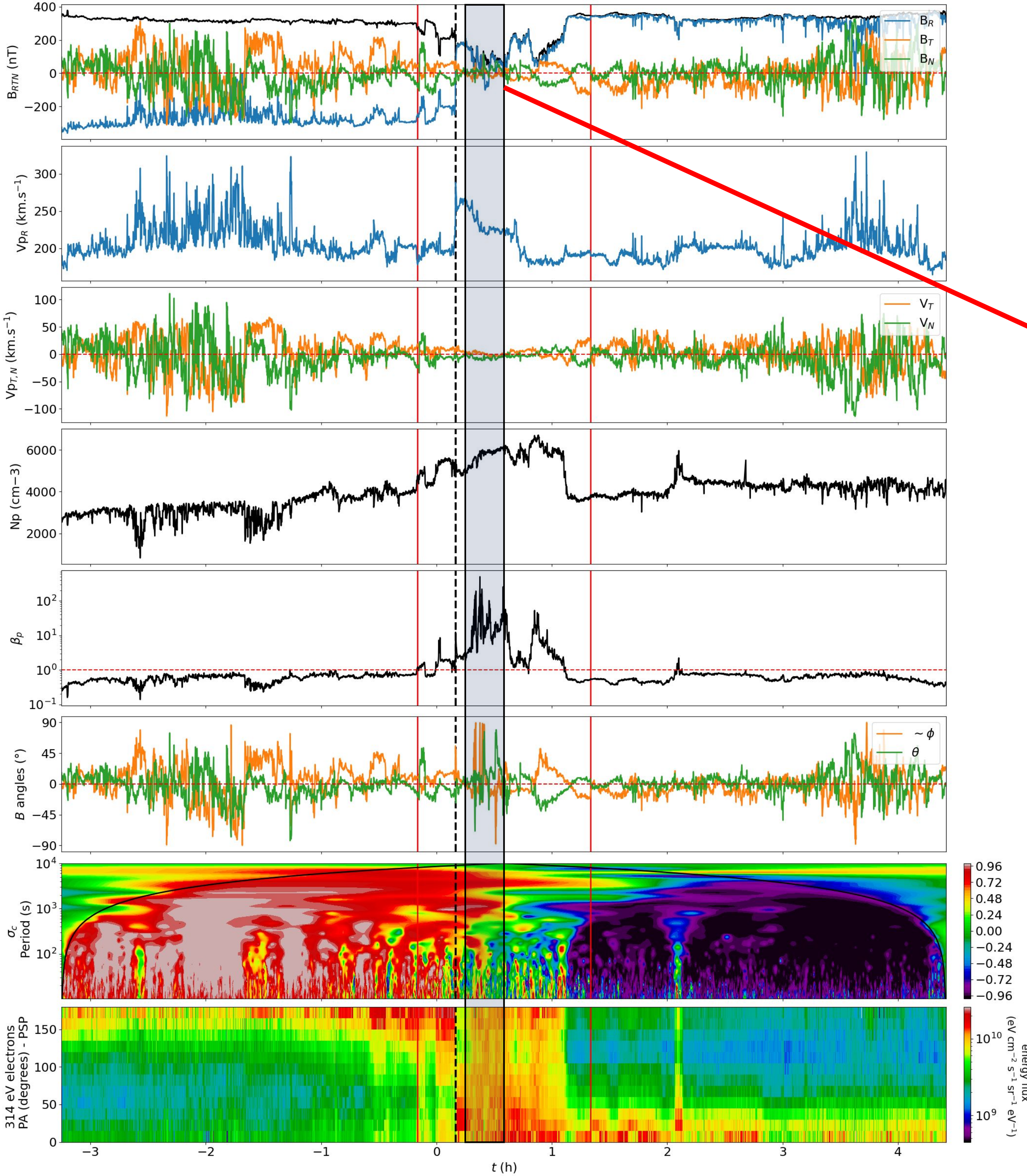




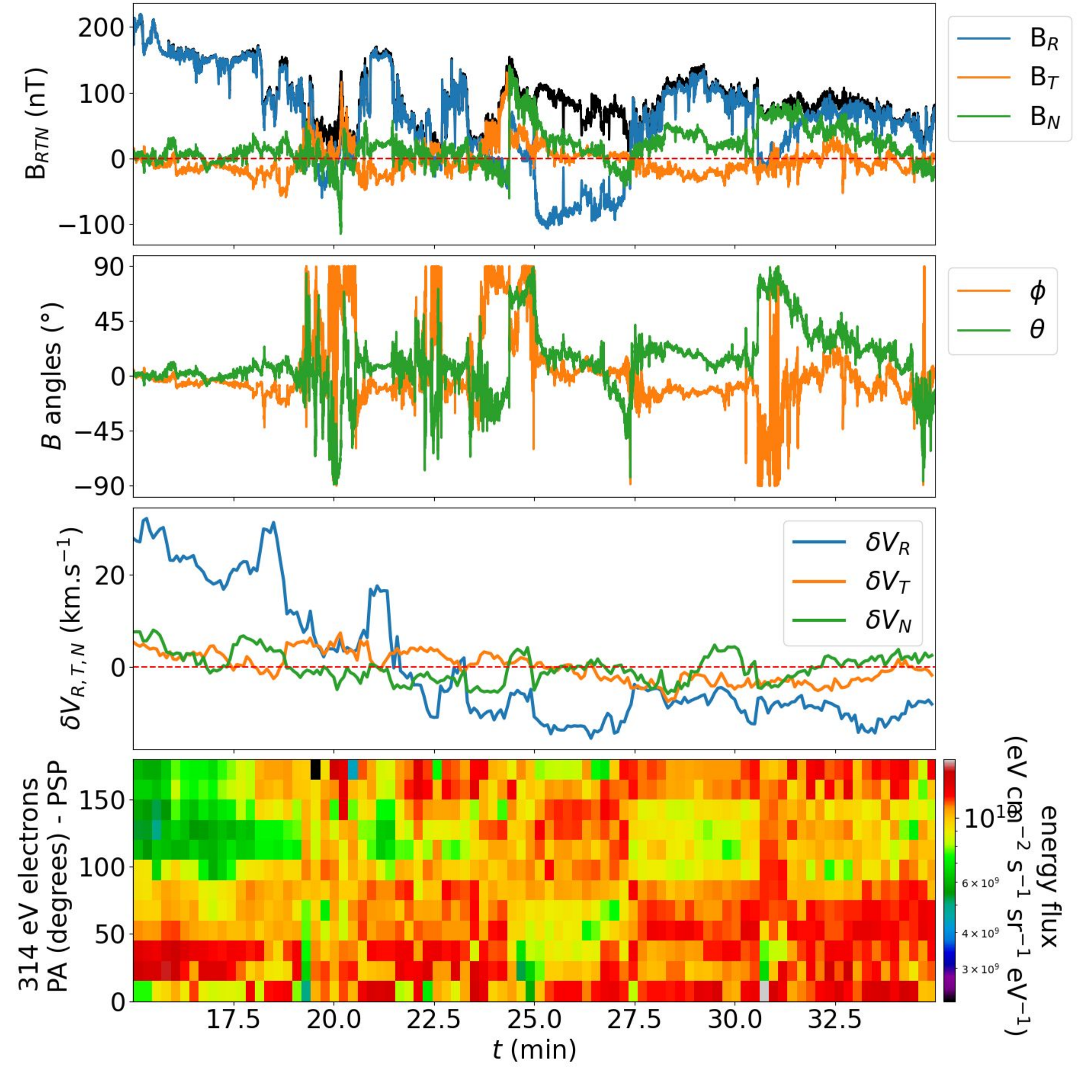
HCS-"surfing" vortex?

Filtered 0.3s

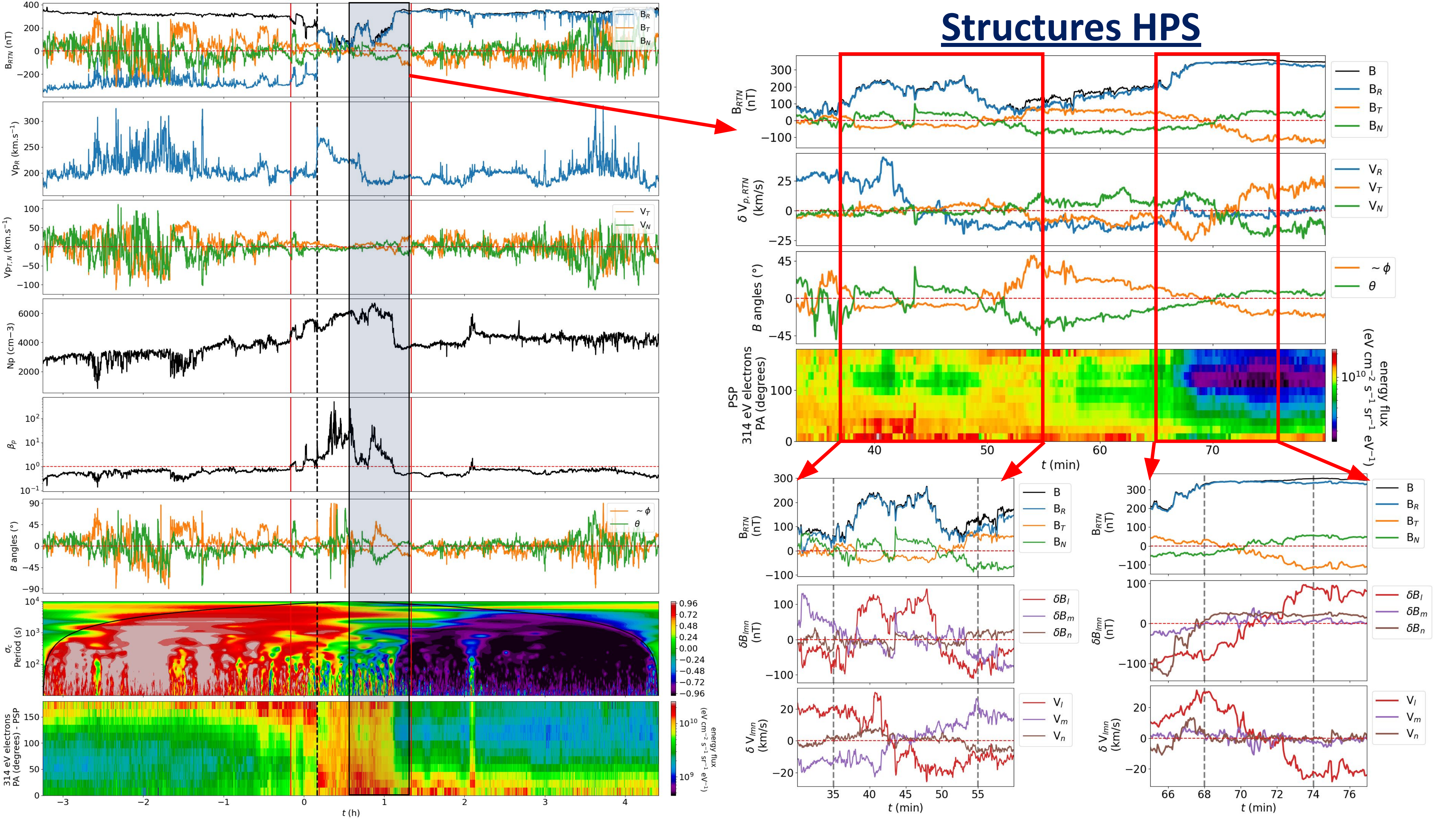


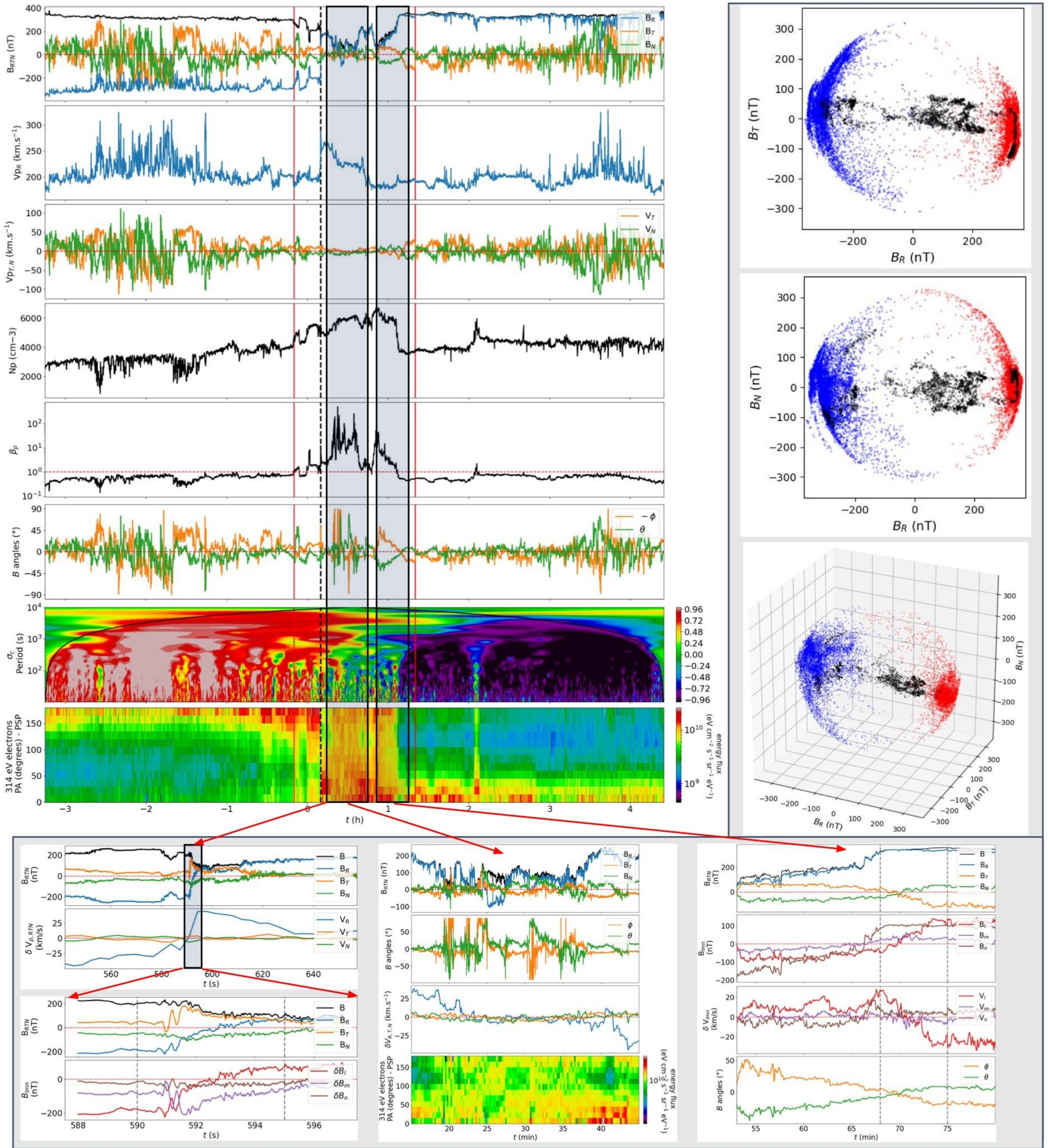


Small scale magnetic structures/fluctuations

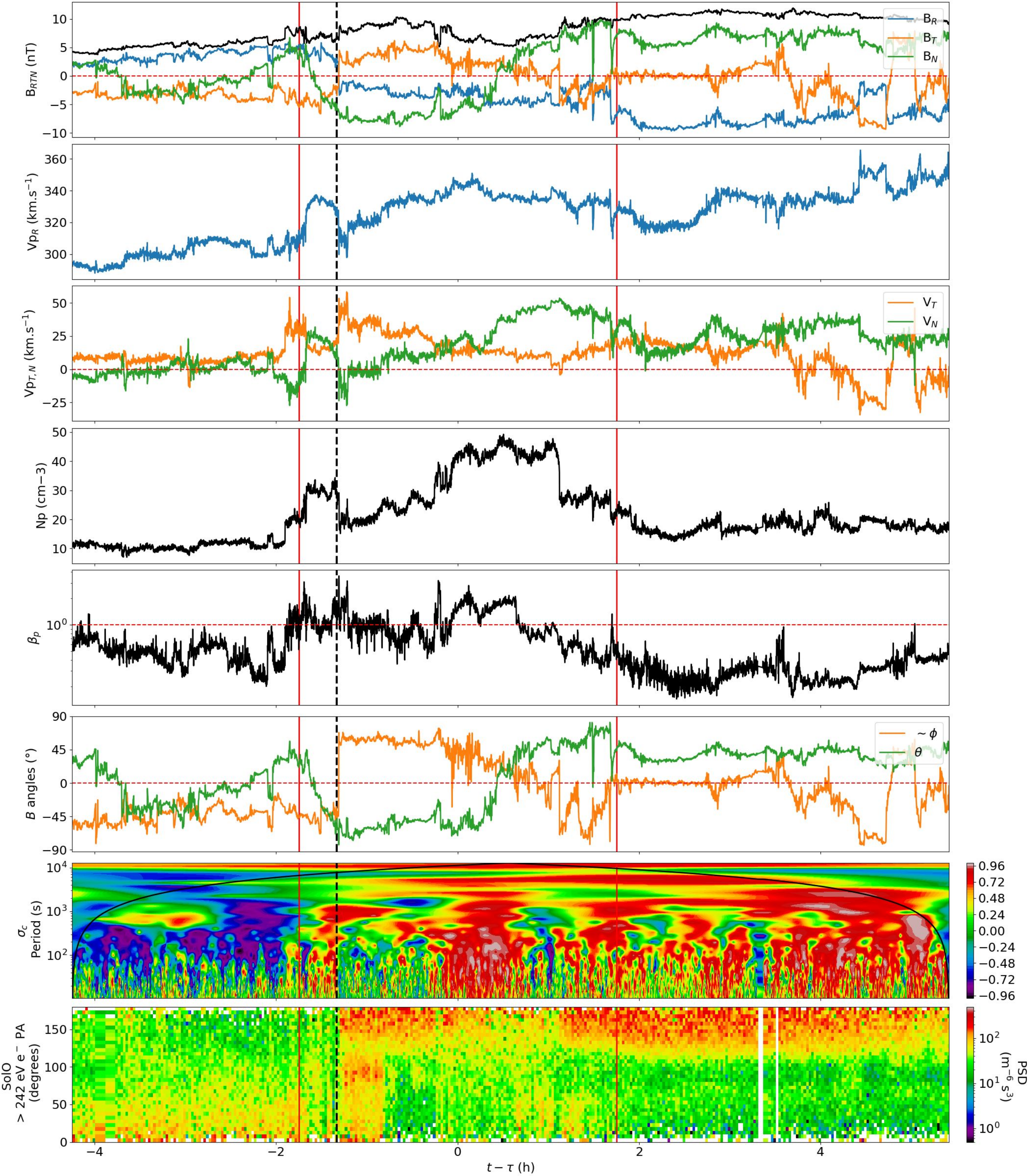


Structures HPS

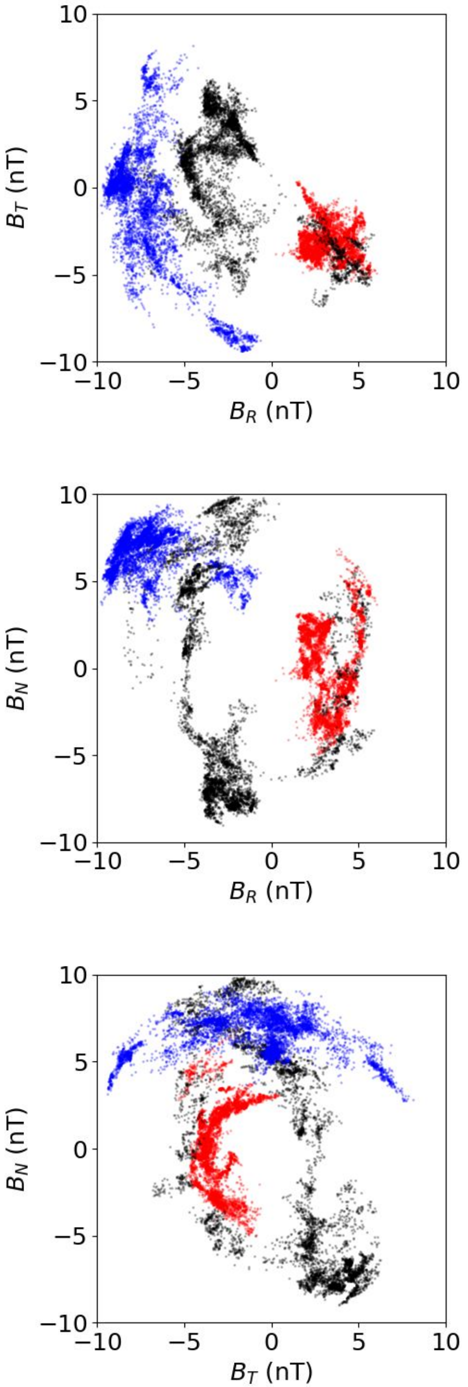


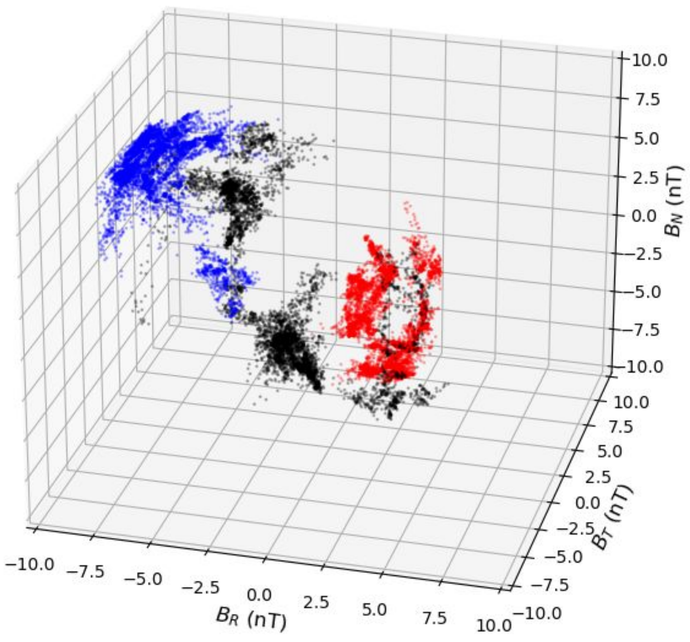

B_RTN (nT)
B_R
B_T
B_N
Vp_R (km.s^-1)
Vp_T,N (km.s^-1)
V_T
V_N
Np (cm−3)
β_p
B angles (°)
~ϕ
θ
σ_c Period (s)
314 eV electrons PA (degrees) - PSP
energy flux (eV cm^-2 s^-1 sr^-1 eV^-1)
t (h)
B_T (nT)
B_R (nT)
B_N (nT)
B
δ V_p,RTN (km/s)
V_R
t (s)
B_lmn (nT)
δB_l
δB_m
δB_n
δV_R,T,N (km.s^-1)
t (min)
B_l
B_m
B_n
δ V_lmn (km/s)
V_l
V_m
V_n

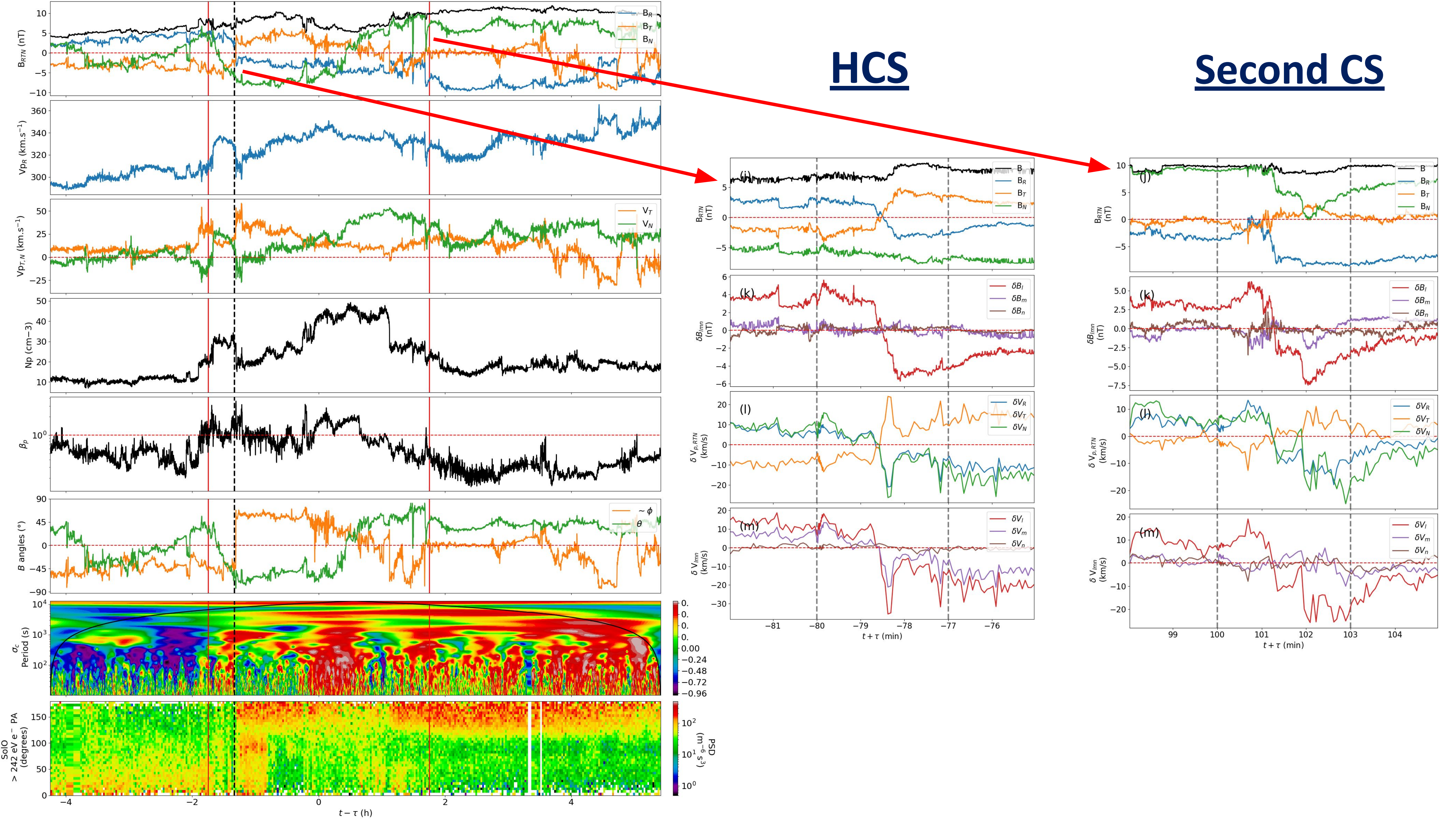
SolO HPS


B_R
B_T
B_N
B_RTN (nT)
Vp_R (km.s^-1)
V_T
V_N
Vp_T,N (km.s^-1)
Np (cm−3)
β_p
~ϕ
θ
B angles (°)
σ_c
Period (s)
SolO
> 242 eV e^− PA
(degrees)
PSD
(m^−6 s^3)
t − τ (h)

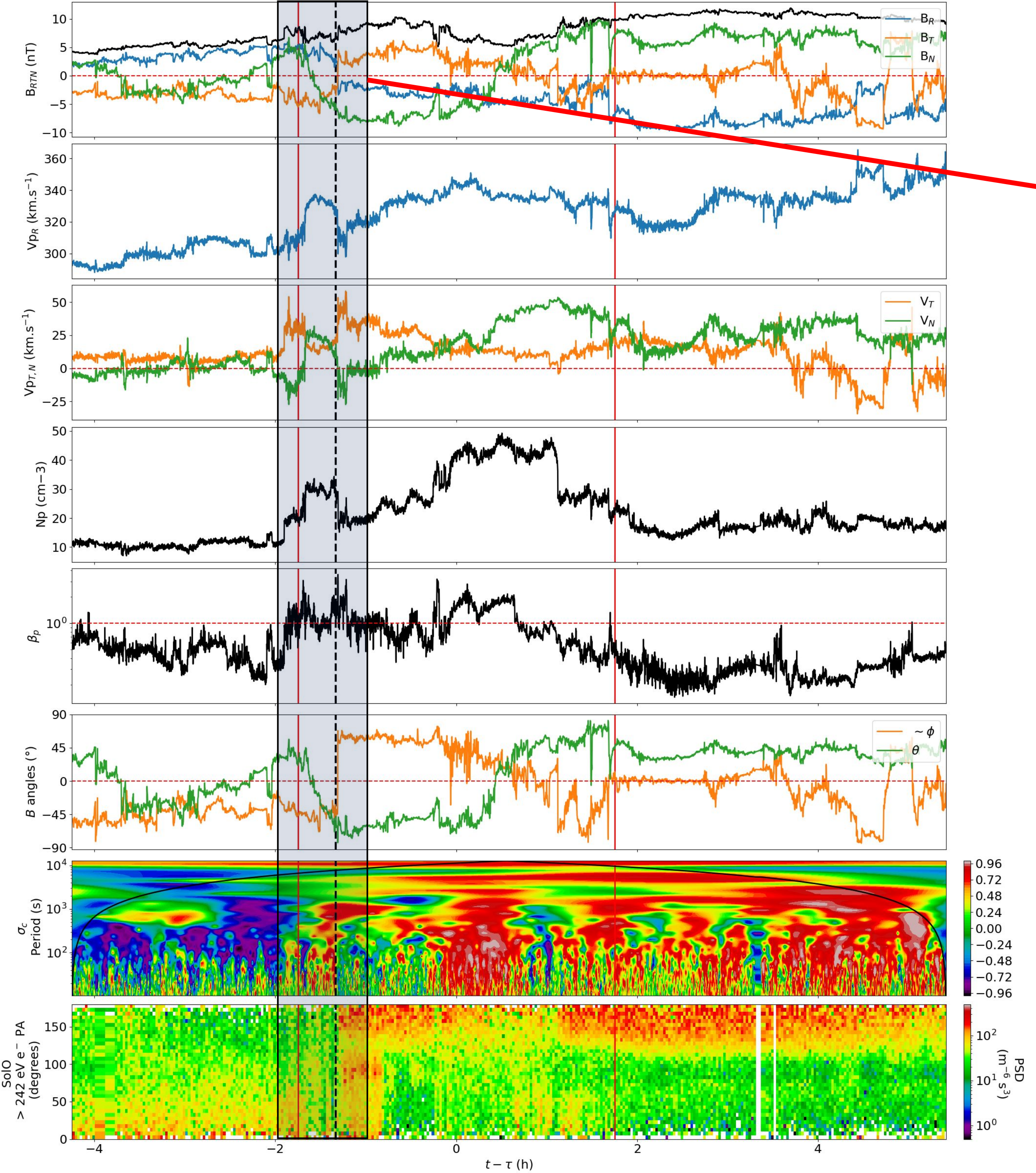
Hodograms

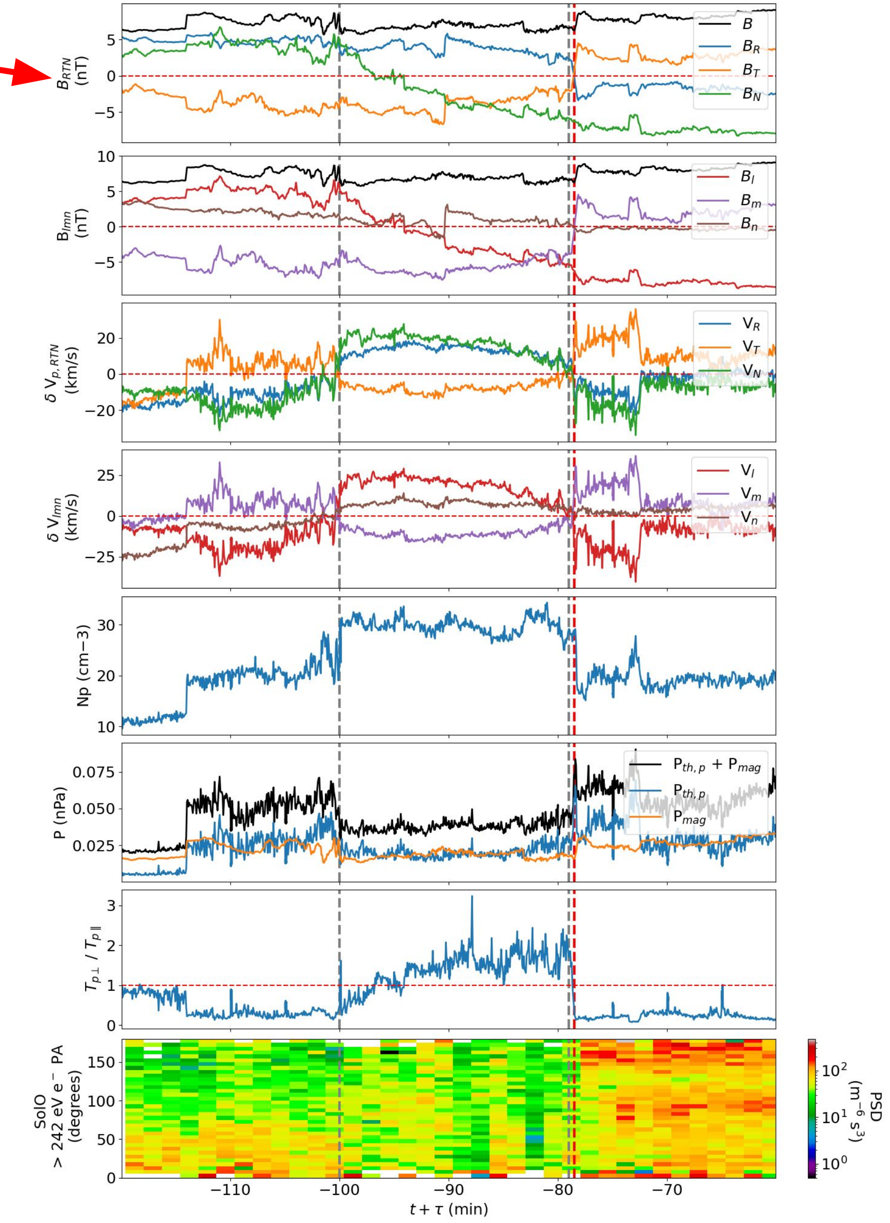

B_T (nT)
B_R (nT)
B_N (nT)
B_R (nT)
B_N (nT)
B_T (nT)

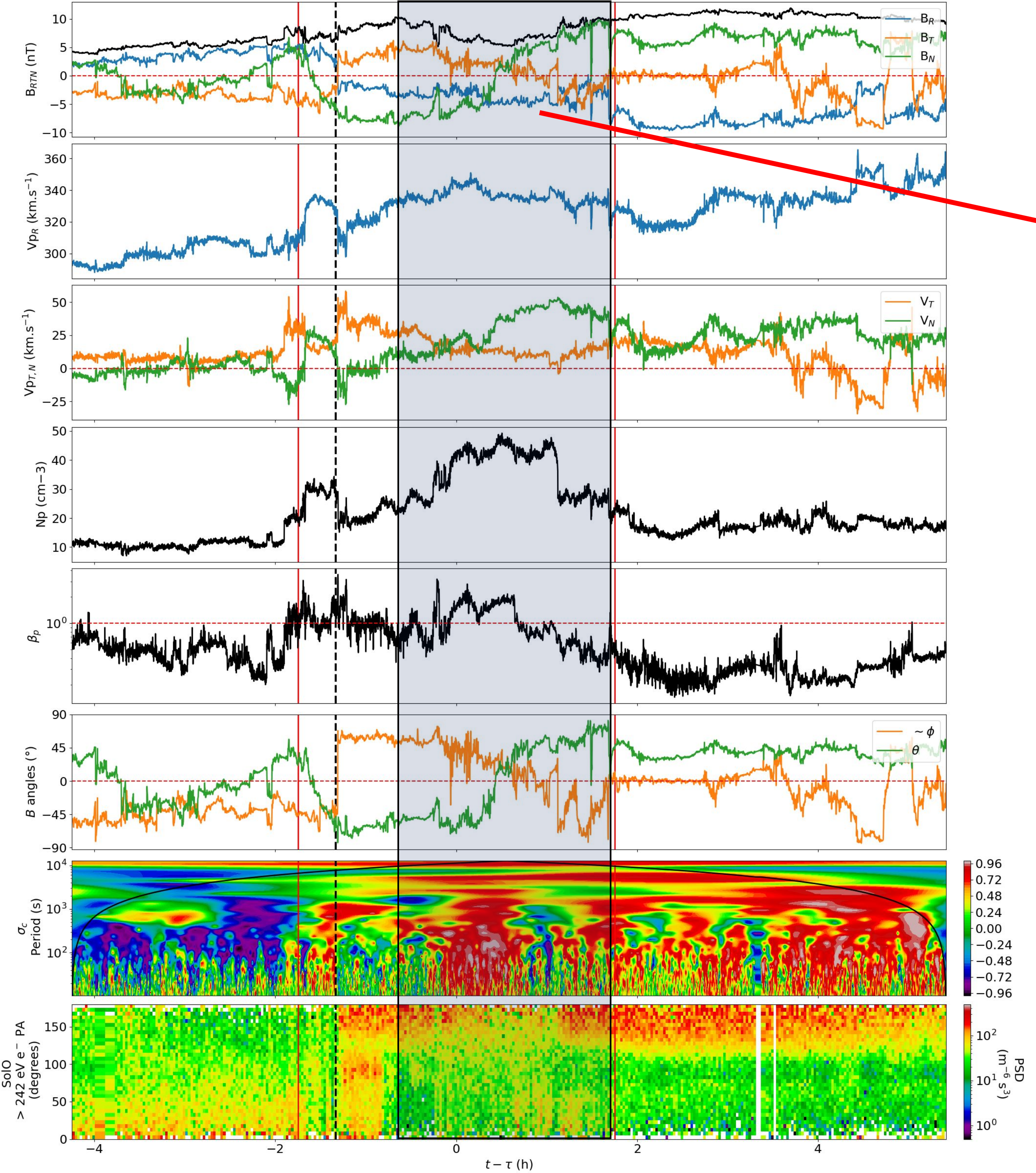

B_N (nT)
B_T (nT)
B_R (nT)


HCS
Second CS
B$_{RTN}$ (nT)
B$_R$
B$_T$
B$_N$
Vp$_R$ (km.s^{-1})
Vp$_{T,N}$ (km.s^{-1})
V$_T$
V$_N$
Np (cm−3)
β_p
B angles (°)
$\sim\phi$
θ
σ_c
Period (s)
SolO
> 242 eV e$^-$ PA
(degrees)
PSD
(m^{-6} s^3)
$t - \tau$ (h)
(j)
(k)
(l)
(m)
B
δB_l
δB_m
δB_n
δB_{lmn} (nT)
δV_R
δV_T
δV_N
δ V$_{p,RTN}$ (km/s)
δV_l
δV_m
δV_n
δ V$_{lmn}$ (km/s)
$t + \tau$ (min)

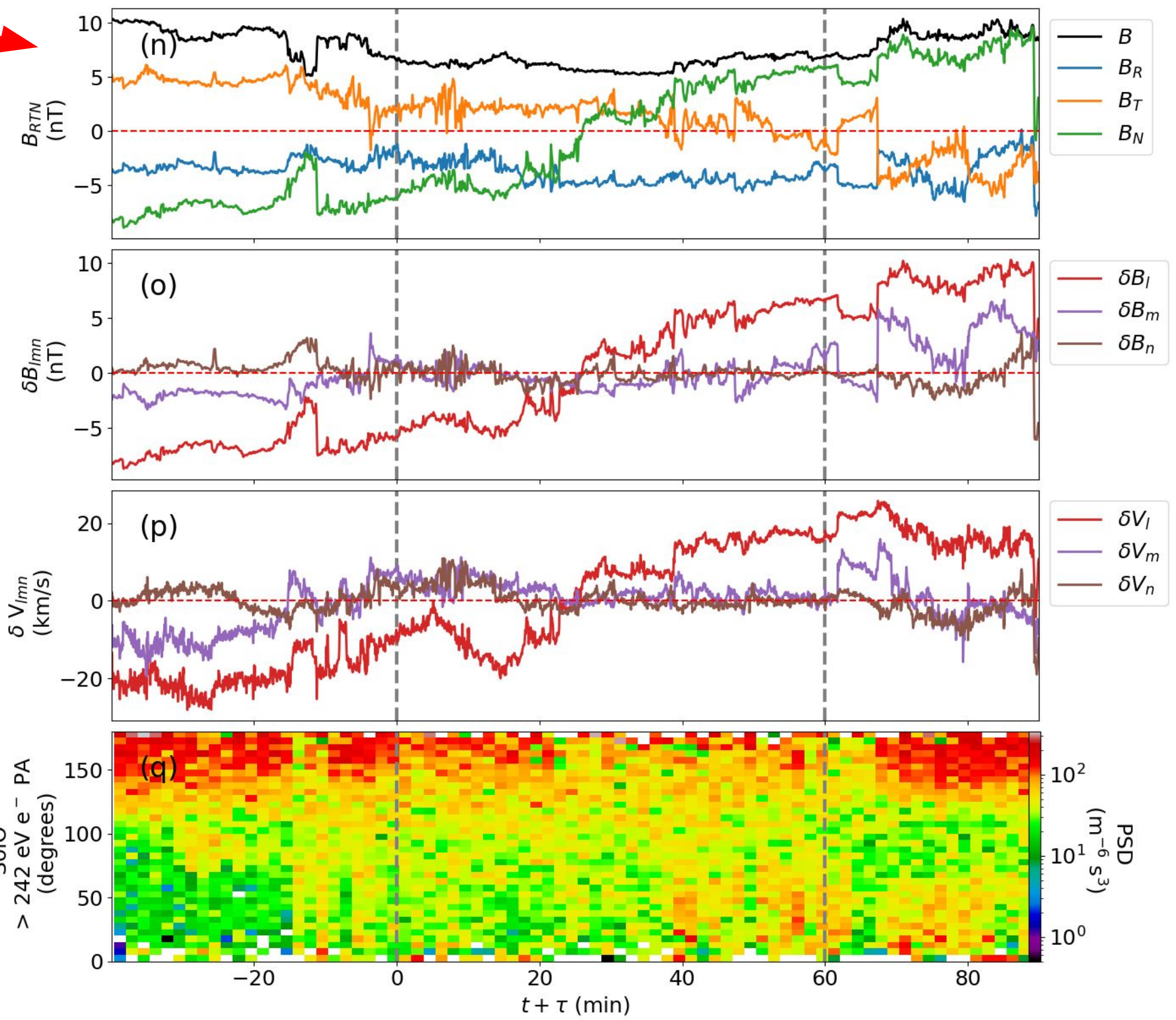
Jet? Flank HCS

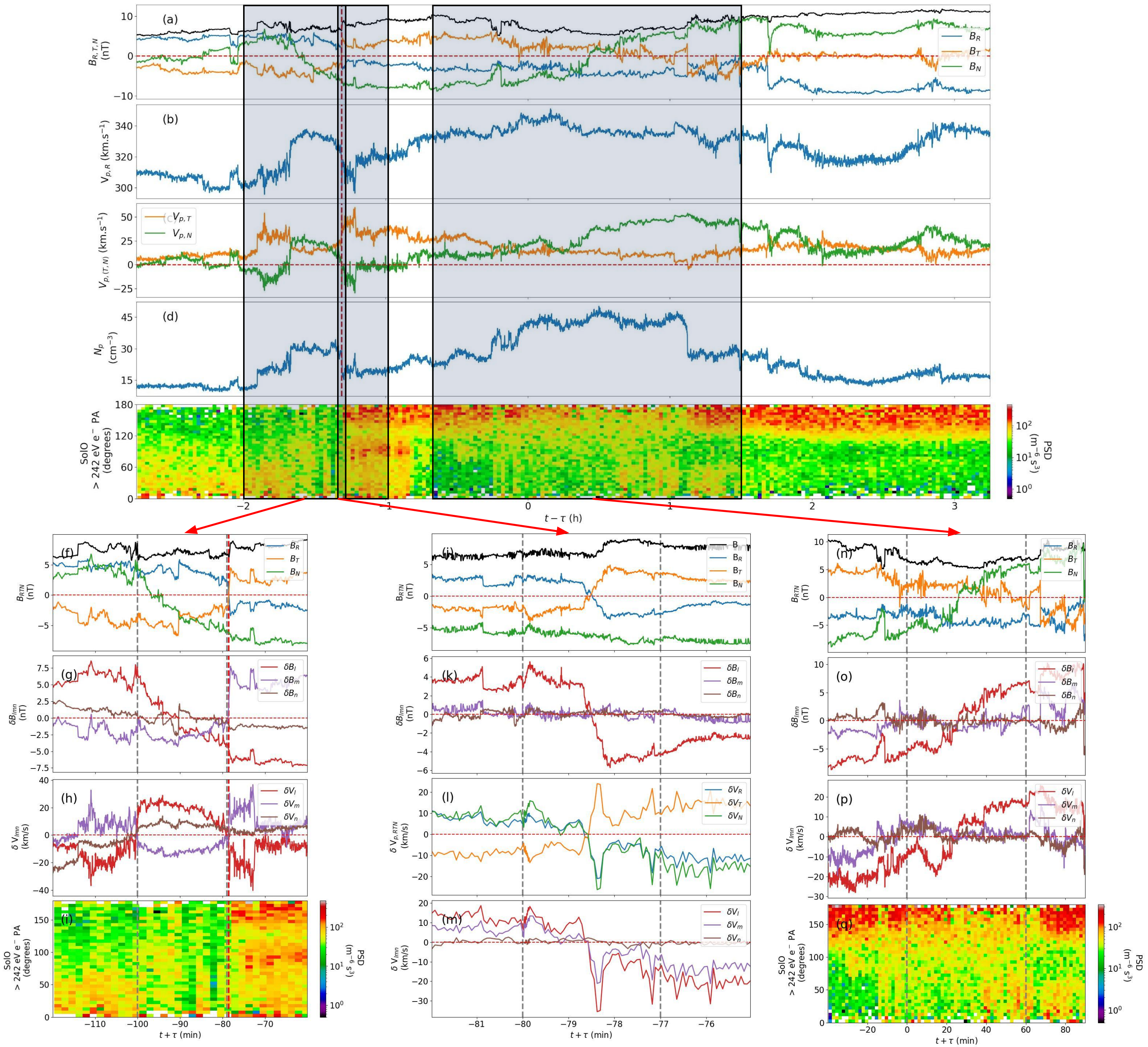






Large Rotation





(a)
$B_{R,T,N}$ (nT)
B_R
B_T
B_N
(b)
$V_{p,R}$ (km.s^{-1})
$V_{p,T}$
$V_{p,N}$
$V_{p,(T,N)}$ (km.s^{-1})
(d)
N_p (cm^{-3})
SolO > 242 eV e$^-$ PA (degrees)
PSD (m^{-6} s^3)
$t-\tau$ (h)
(f)
B_{RTN} (nT)
(g)
δB_l
δB_m
δB_n
δB_{lmn} (nT)
(h)
δV_l
δV_m
δV_n
δ V_{lmn} (km/s)
(i)
$t+\tau$ (min)
(k)
(l)
δV_R
δV_T
δV_N
δ $V_{p,RTN}$ (km/s)
(m)
(n)
(o)
(p)
(q)