Utilizing galactic cosmic rays to understand the Sun-to-Earth evolution of CMEs

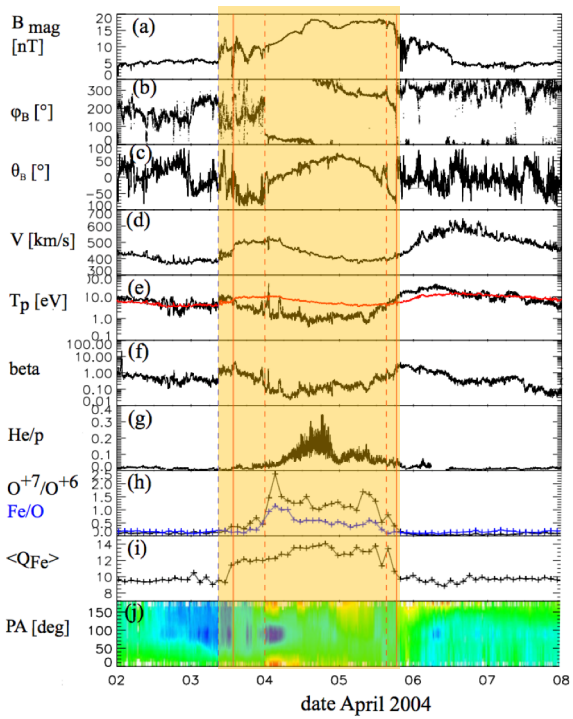
Mateja Dumbovic[1, 2]

1-Hvar Observatory, University of Zagreb, Croatia

2-Institute of Physics, University of Graz, Austria

EU Horizon 2020 MSCA grant agreement No 745782 (project ForbMod).

Interplanetary *in situ* CME signatures



Enhanced (+ smoothly rotating) **magnetic field**

Expanding **plasma** flow speed profile (linear trend)

Low **plasma** temperature

Low **plasma** beta

Elevated ion charge states (**plasma**)

Bi-directionality of **suprathermal** (>100eV) **electrons**

(adapted from Kilpua+2017)

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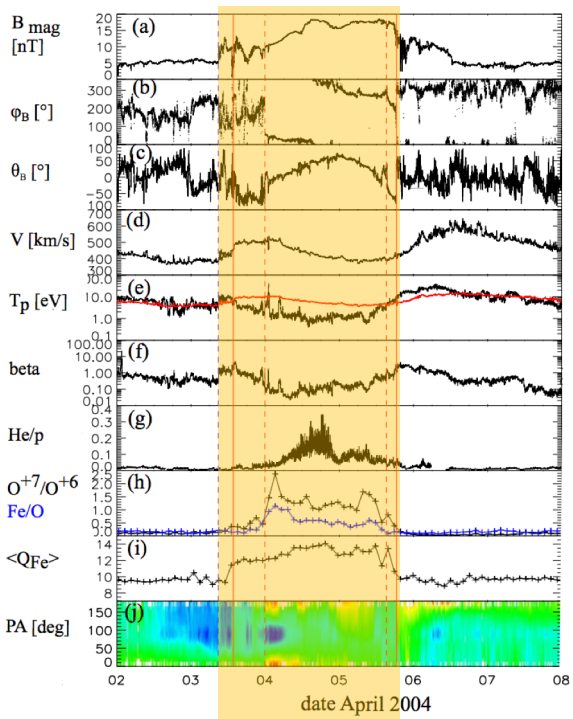

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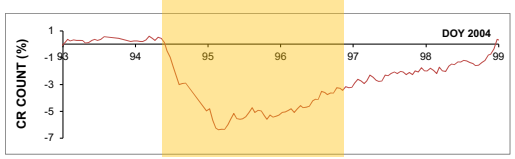


Enhanced (+ smoothly rotating) **magnetic field**

➡ Expanding **plasma** flow speed profile (linear trend)

➡ Low **plasma** temperature

➡ Low **plasma** beta

Elevated ion charge states (**plasma**)

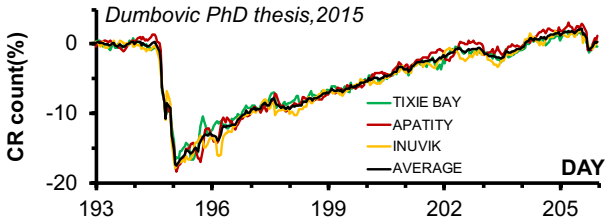
➡ Bi-directionality of **suprathermal** (>100eV) **electrons**

➡ Depression of the galactic cosmic ray (GCR) flux (**energetic protons**, i.e. **FORBUSH DECREASE**)

Forbush decreases

= short term decreases in galactic cosmic ray GCR count

(*Forbush, 1937 and Hess & Demmelmair, 1937; overviews by Lockwod, 1971; Cane, 2000; Belov, 2009*)



duration - several days
amplitudes - several %

… depending where they are observed
and with what detector!

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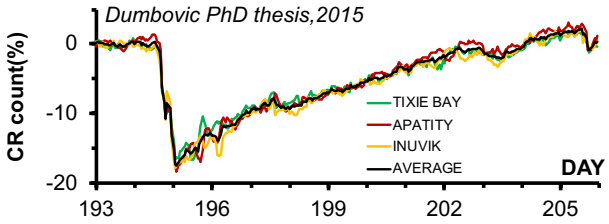

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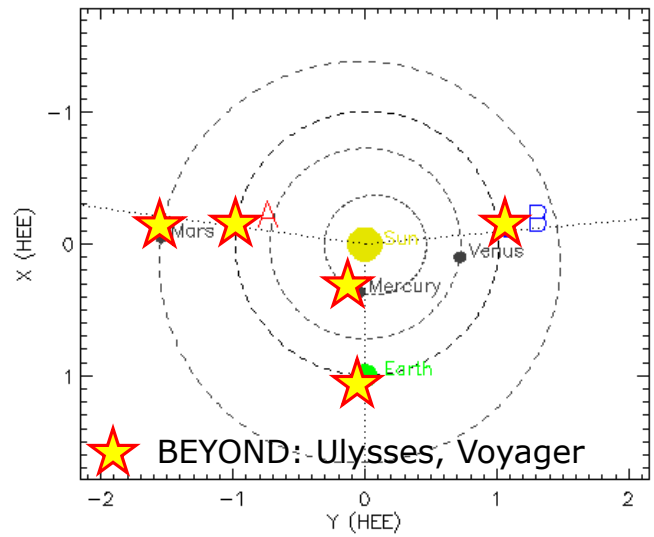


DETECTORS: spacecraft particle detectors, neutron monitors, muon detectors, dosimeters..

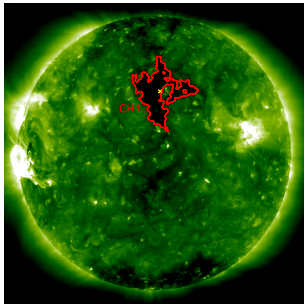
DETECTION PREREQUISITE: good statistics (count/time) + 'SEP unsensitivity'

WHY: interaction of protons with SW flow and IMF

different interplanetary structures → different Forbush decreases

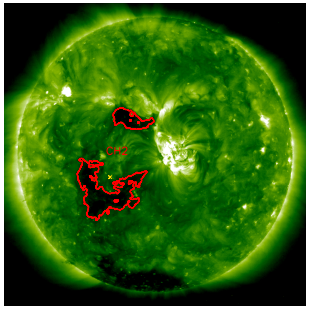
Stream interaction regions (SIRs)

REMOTE OBSERVATION

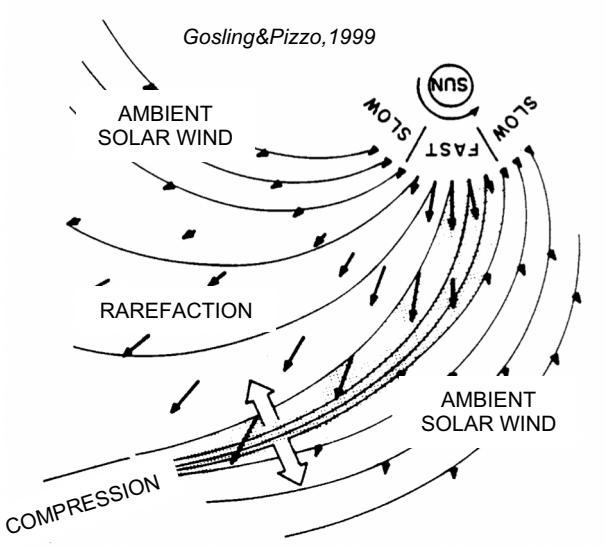


CH in STEREO-A EUVI 2017 July 23 (up) and 2017 July 29 (down) in 195 A

CH area extracted using the "Collection of Analysis Tools for Coronal Holes (***CATCH***)" tool (Heinemann+2019, in prep)



IP SPACE – EQUATORIAL (xz) PLANE



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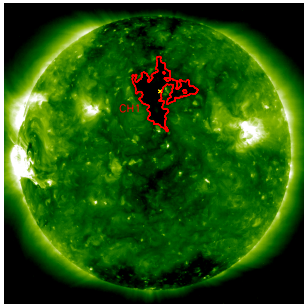

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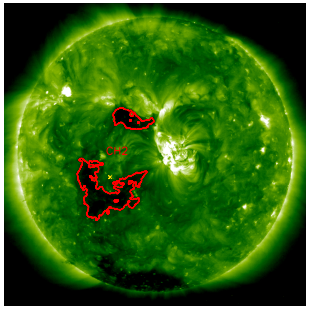

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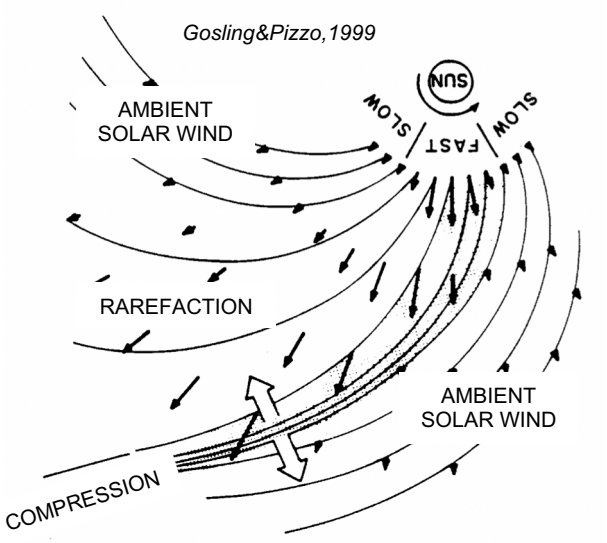

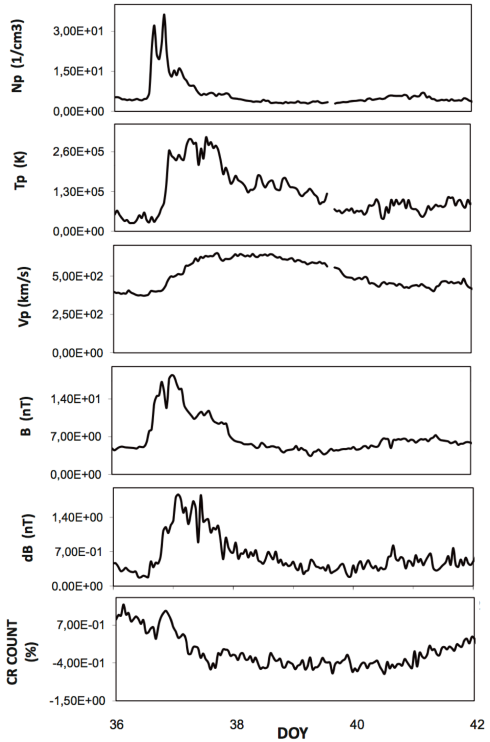

adapted from Dumbovic+,2012

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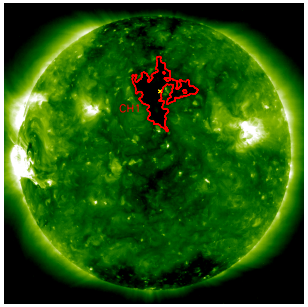

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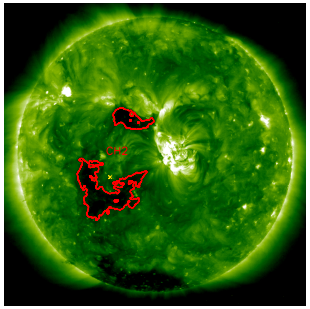

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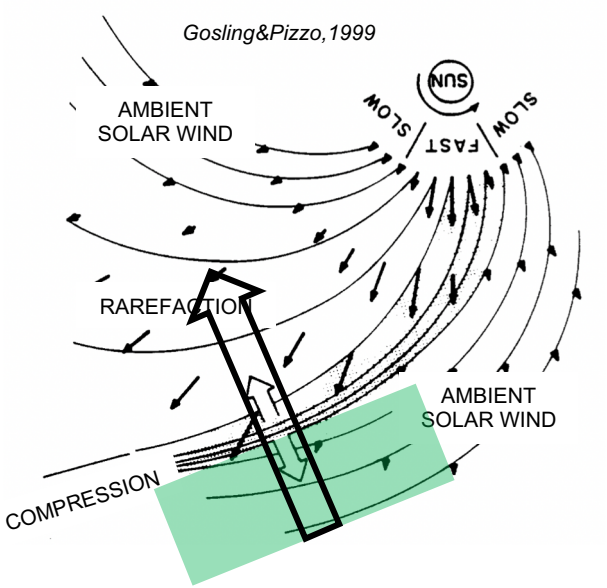

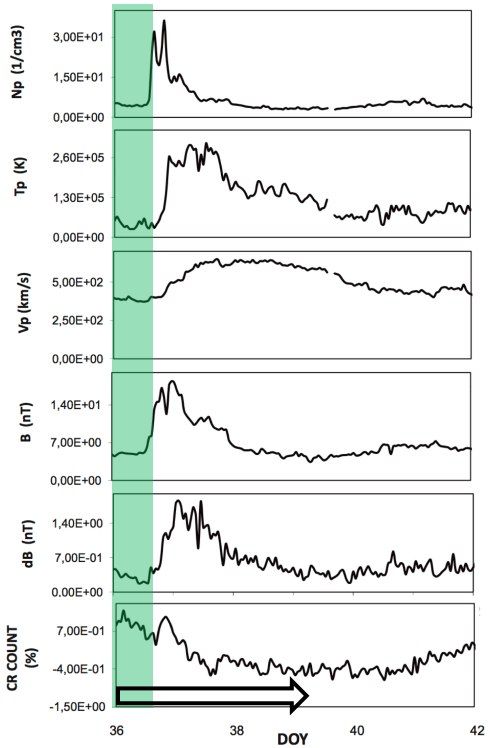

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1-SLOW WIND

Stream interaction regions (SIRs)

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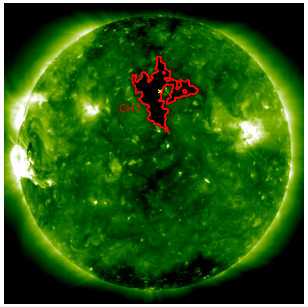

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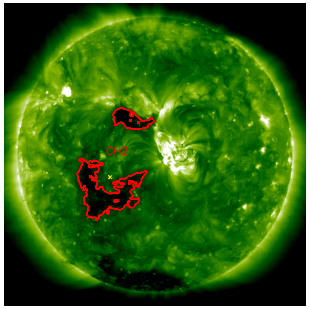

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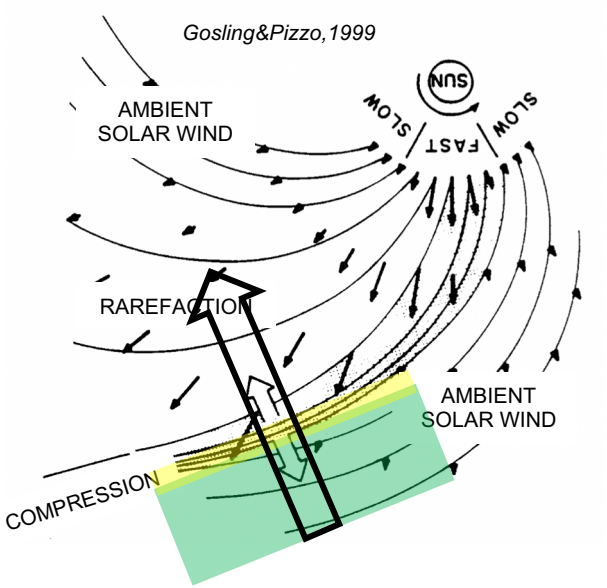

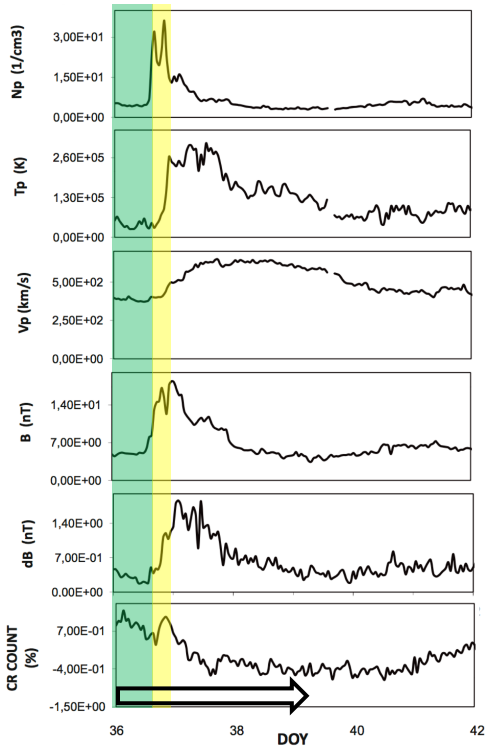

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1-SLOW WIND

2-COMPRESSION REGION

Stream interaction regions (SIRs)

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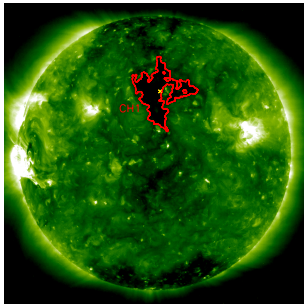

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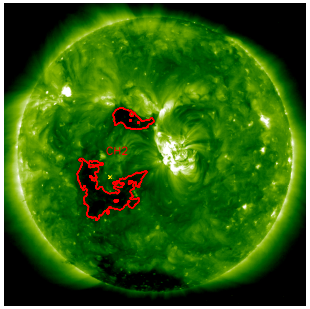

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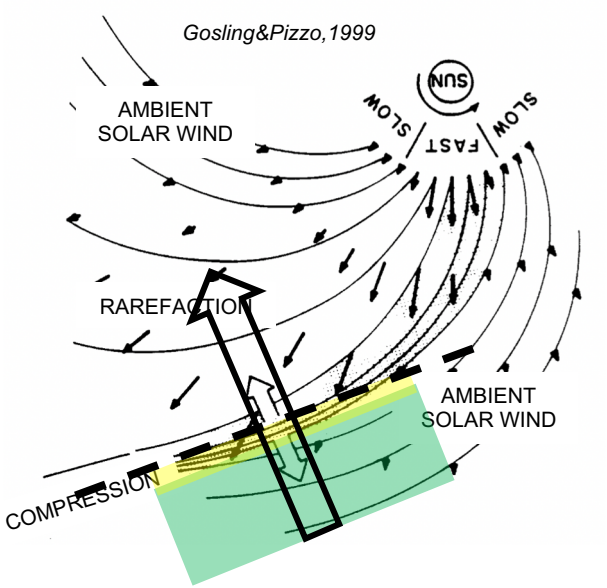

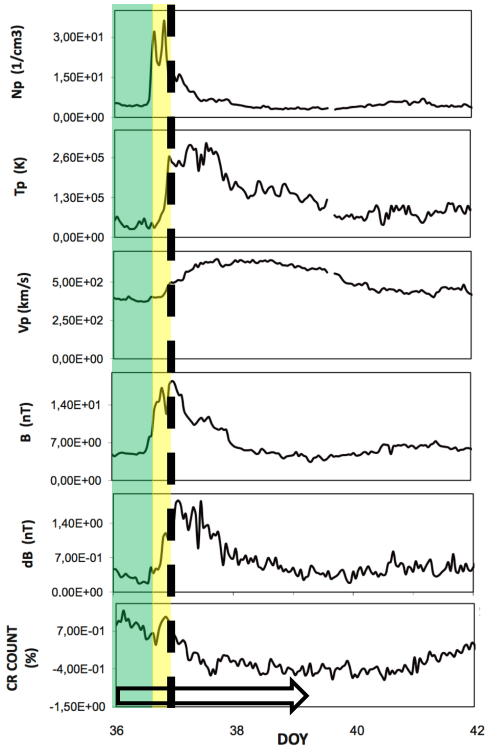

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1-SLOW WIND

2-COMPRESSION REGION

3-STREAM INTERFACE

Stream interaction regions (SIRs)

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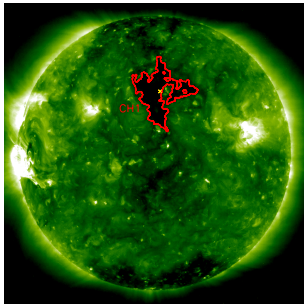

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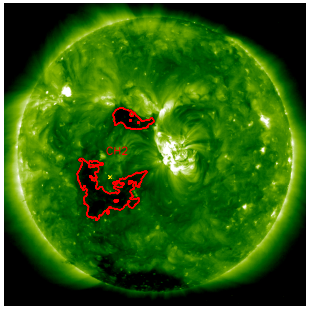

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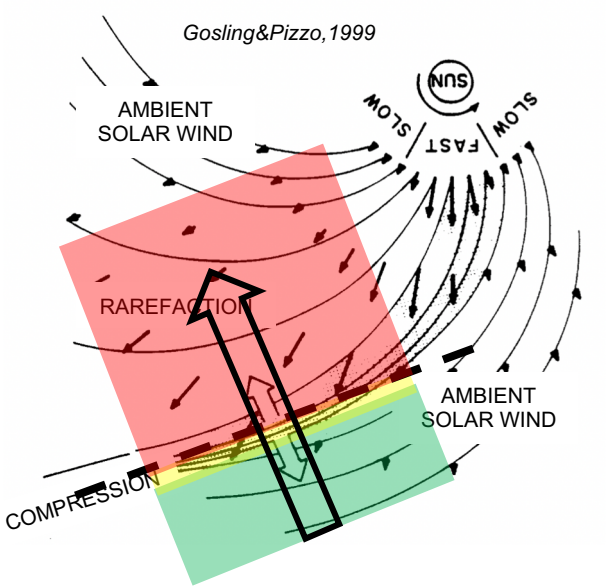

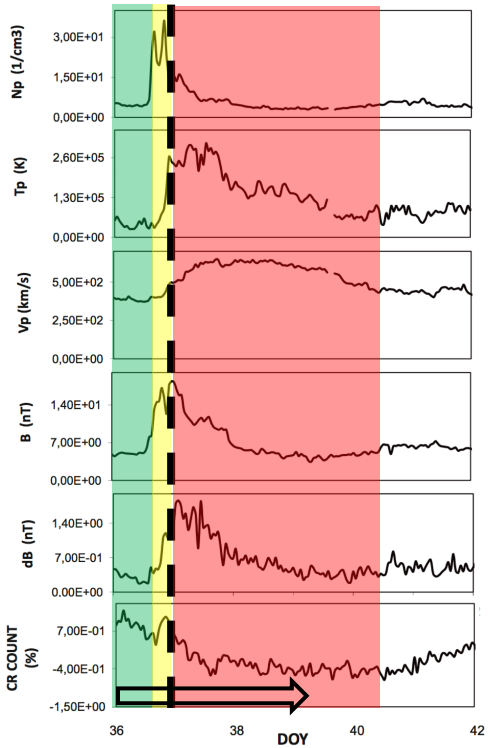

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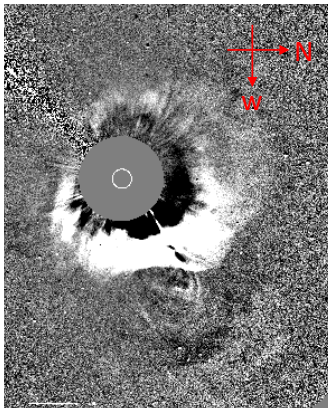
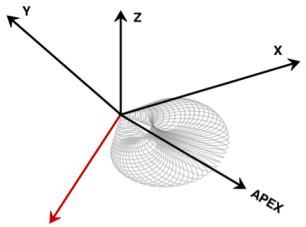
1-SLOW WIND **2-COMPRESSION REGION** **3-STREAM INTERFACE** **4-HIGH SPEED STREAM**

CMEs in interplanetary space

REMOTE OBSERVATION



CME in SOHO/LASCO C3
16 Sept 2000 06:18 UT
First C2 detection at 05:18



3D flux rope based on croissant model (GCS, Thernisien+2006,2009; Thernisien2011)

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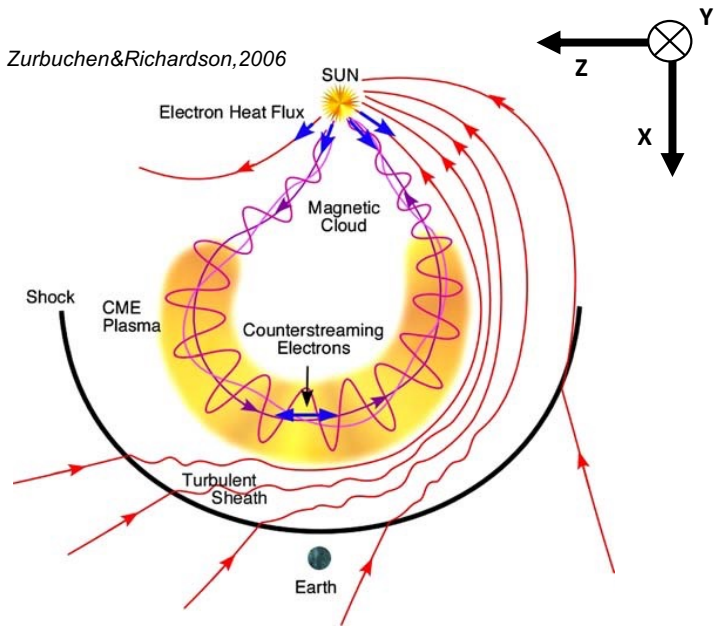

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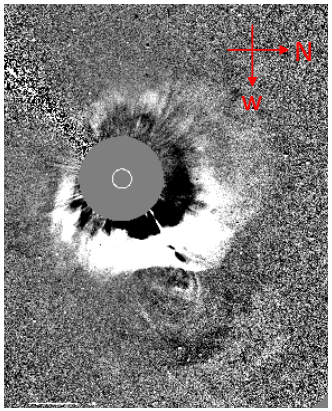

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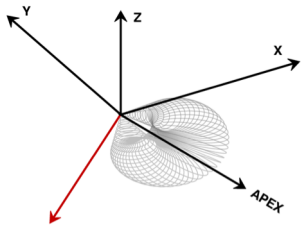

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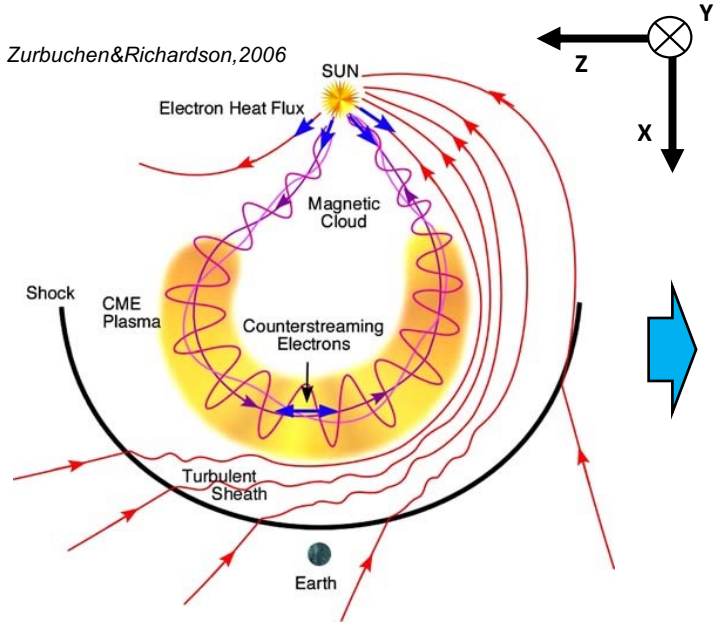

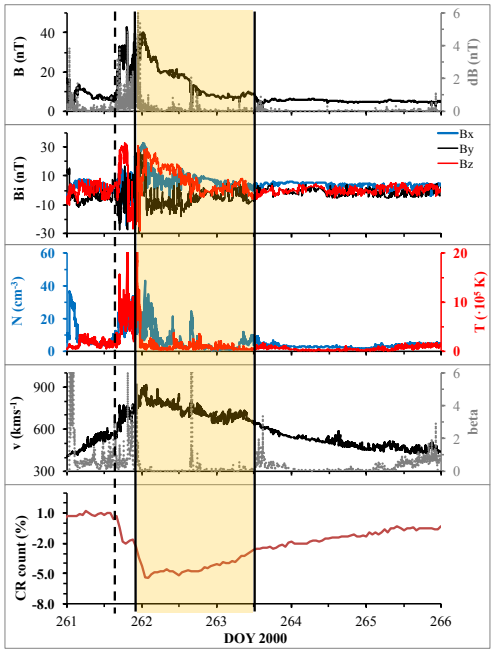

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CMEs in interplanetary space

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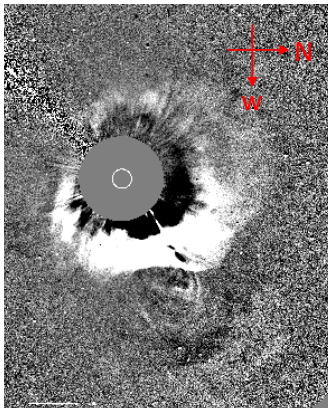

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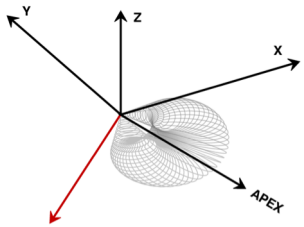

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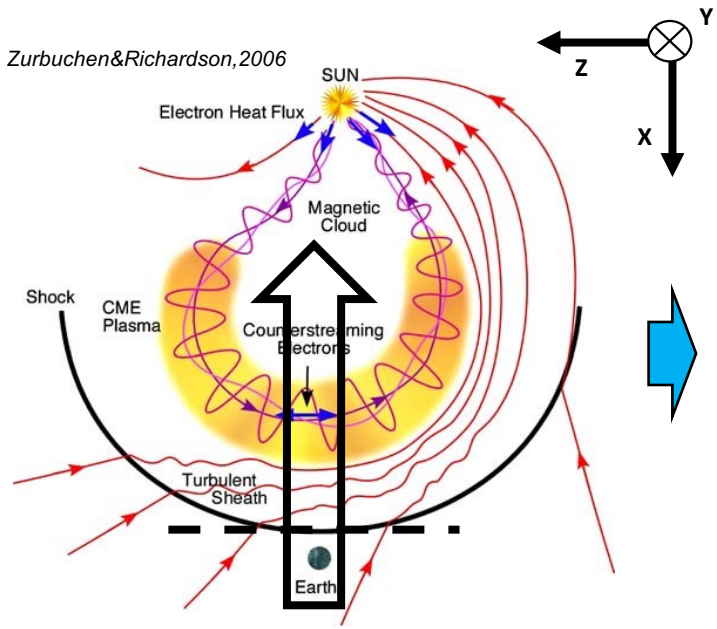

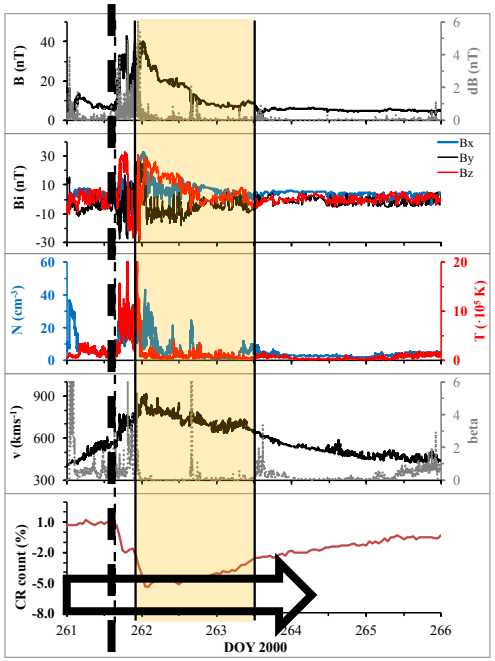

adapted from Dumbovic+,2012

1-SHOCK

CMEs in interplanetary space

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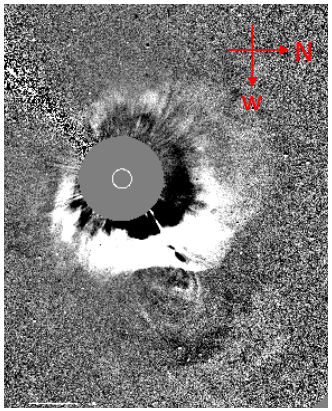

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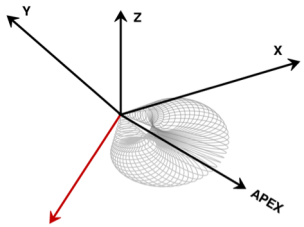

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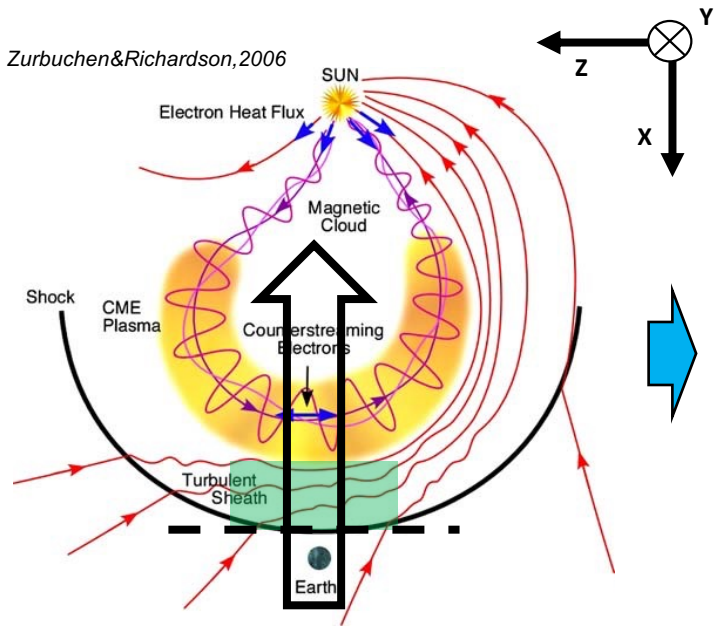

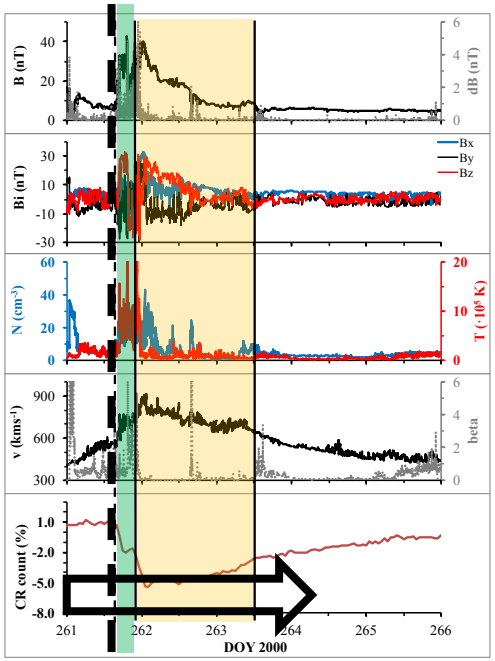

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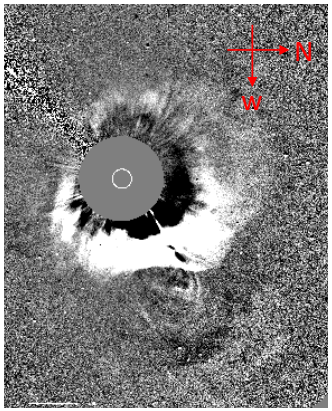
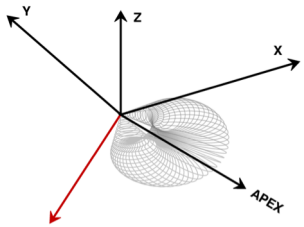
1-SHOCK **2-SHEATH**

CMEs in interplanetary space

REMOTE OBSERVATION

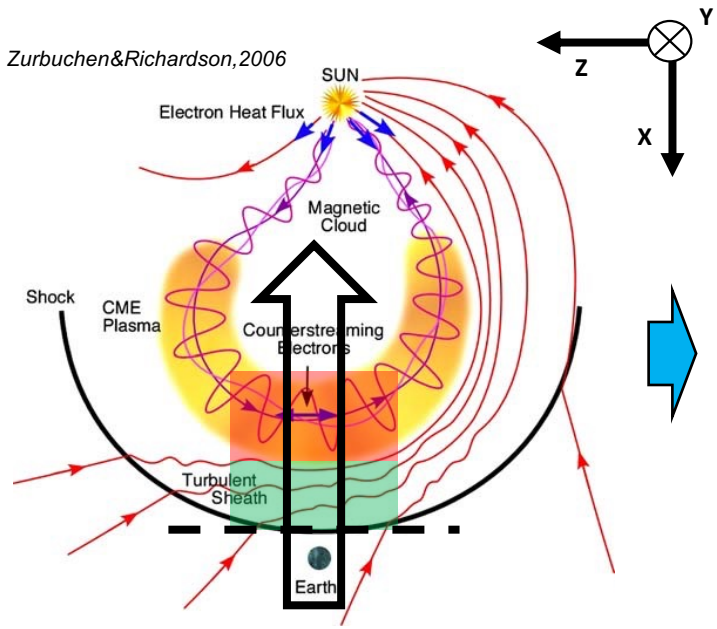


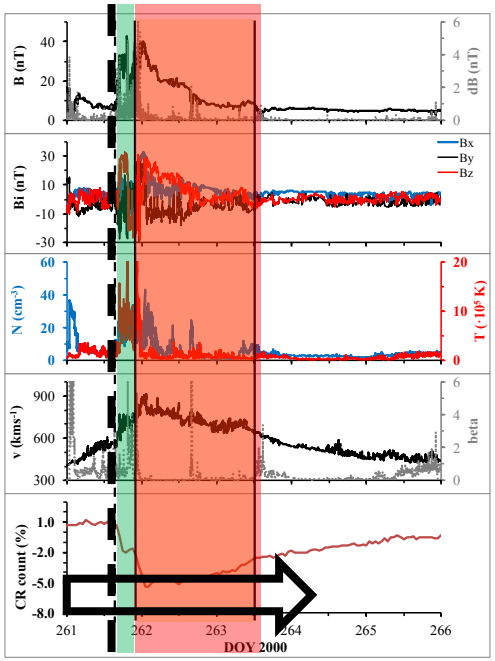
CME in SOHO/LASCO C3
16 Sept 2000 06:18 UT
First C2 detection at 05:18



3D flux rope based on croissant model (GCS, Thernisien+2006,2009; Thernisien2011)

IP SPACE – EQUATORIAL (xz) PLANE



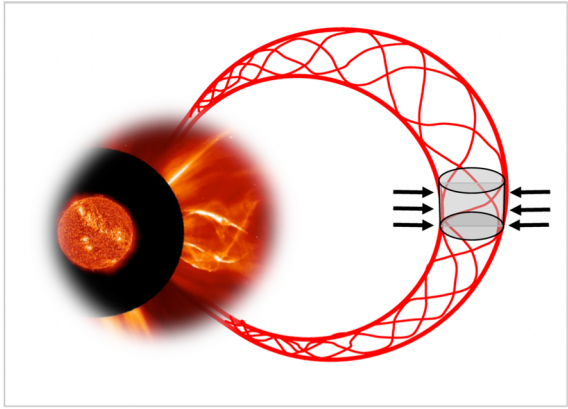


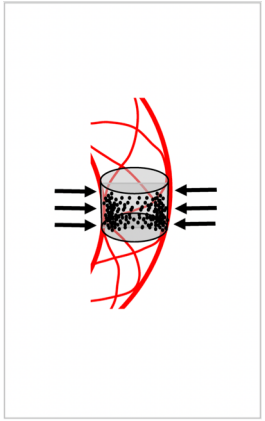
adapted from Dumbovic+,2012

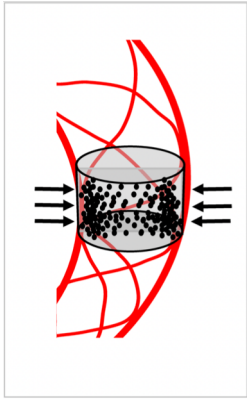
1-SHOCK **2-SHEATH** **3-MAGNETIC STRUCTURE (FLUX ROPE)**

Interaction of GCR with flux ropes

Dumbovic+2018, ApJ







->a closed magnetic structure

->Initially empty of GCR

->Locally of cylindrical form

->Moves with constant velocity

- particles enter by perpendicular diffusion and slowly fill the structure

FR expands (self-similarly): Volume increases magnetic field drops

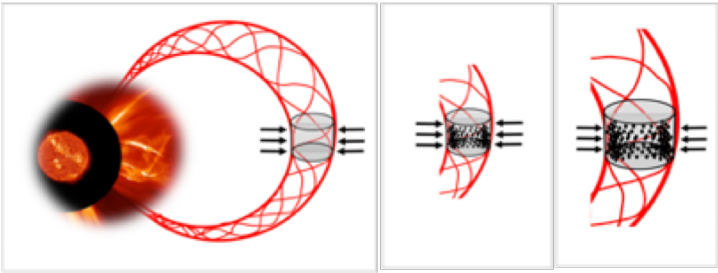
First proposed by Morrison, 1956

Similar to e.g. Cane+, 1995; Quenby+, 2008

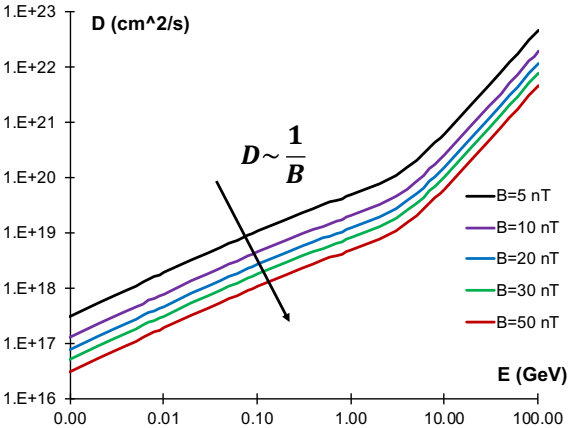
Similar to e.g. Munakata+, 2006; Arunbabu+, 2013

FR-related Forbush decrease: *ForbMod*

Dumbovic+2018, ApJ

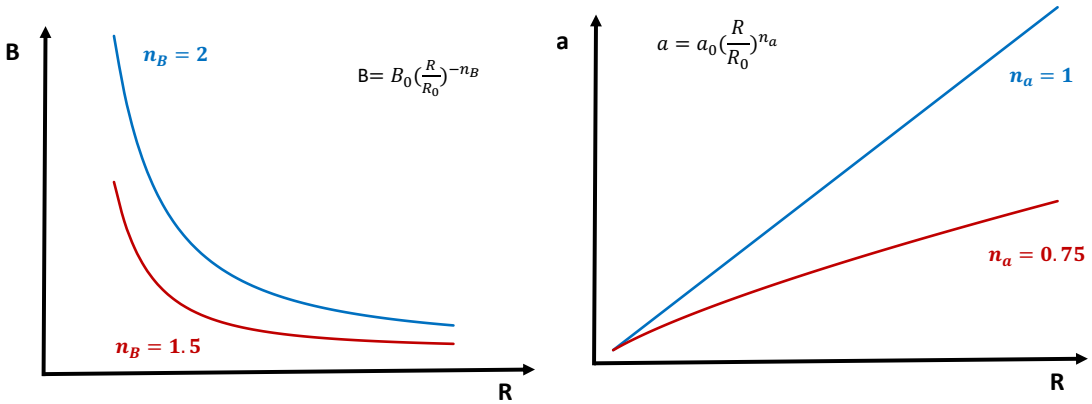


DIFFUSION



Based on Potgieter, Living reviews in SolPhys, 2013

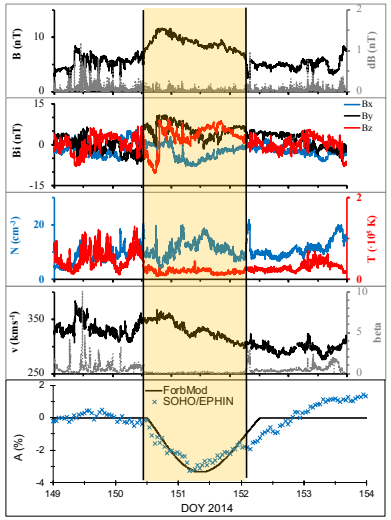
EXPANSION



Based on Demoulin et al., 2008

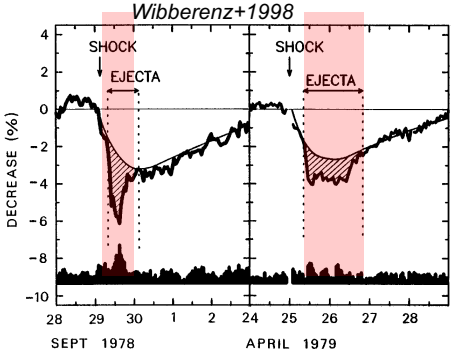
ForbMod: model *vs* observation

Dumbovic+2018, ApJ



Morphology:
Symmetric, MC borders

Wibberenz+1998



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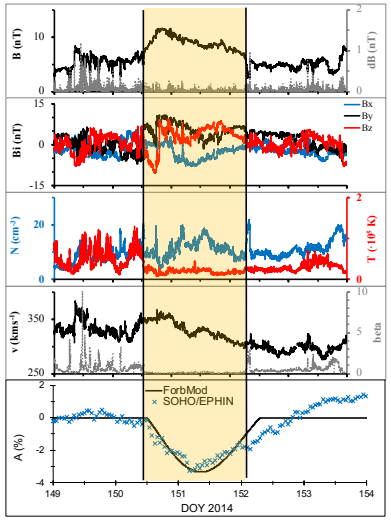
Dumbovic+2018, ApJ



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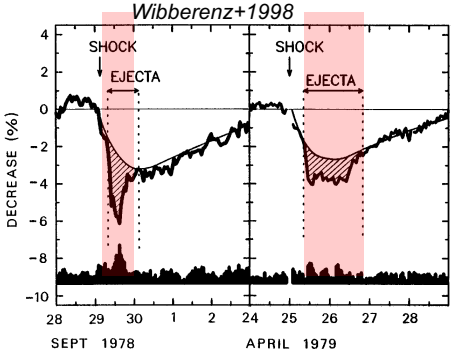
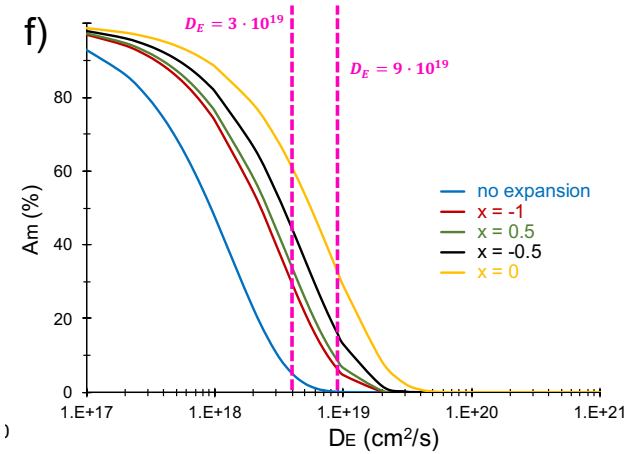
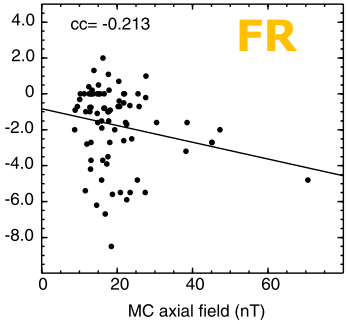


Diffusion coefficient:

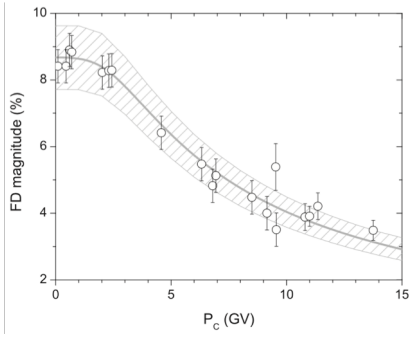


$B \nearrow \longrightarrow D \searrow \longrightarrow A \nearrow$

$E \nearrow \longrightarrow D \nearrow \longrightarrow A \searrow$



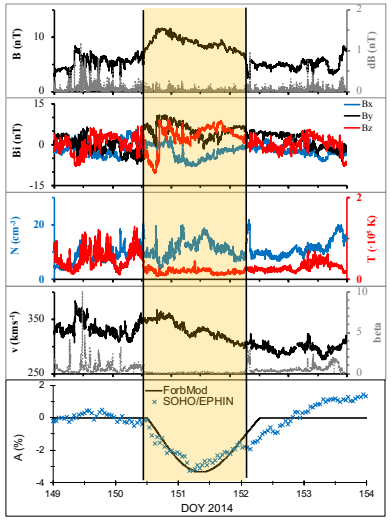
Richardson&Cane(2011)



Usoskin+(2015)

ForbMod: model *vs* observation

Dumbovic+2018, ApJ



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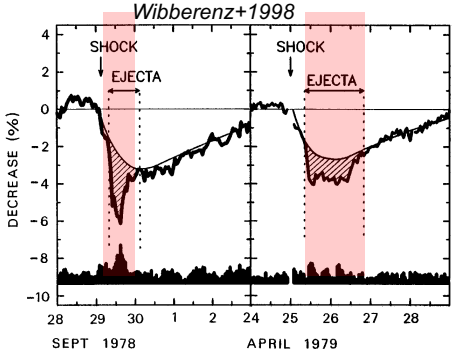

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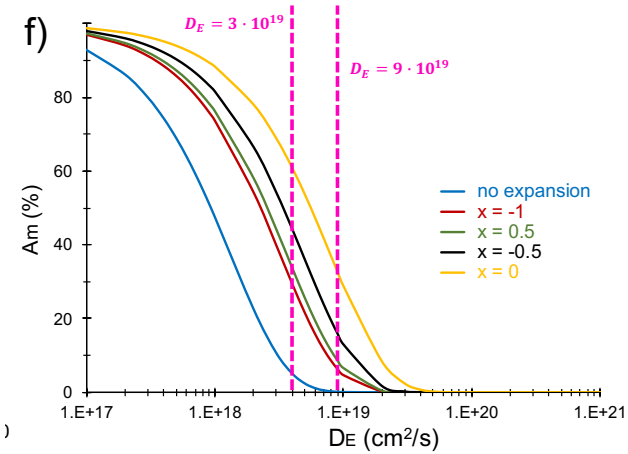
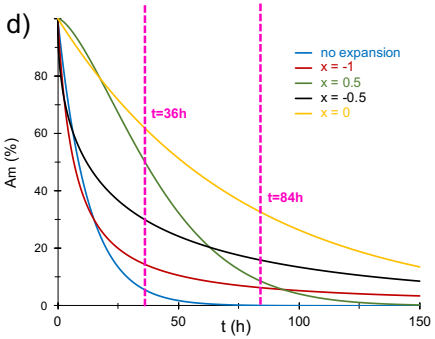
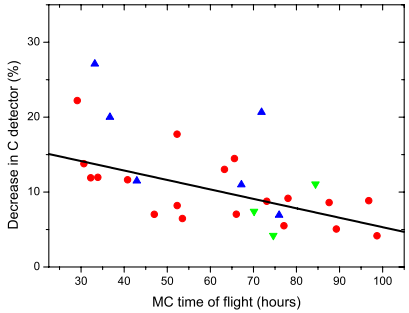


$B \nearrow \longrightarrow D \searrow \longrightarrow A \nearrow$

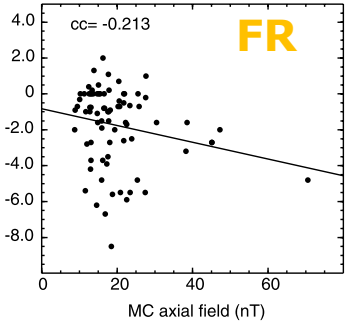
$E \nearrow \longrightarrow D \nearrow \longrightarrow A \searrow$

Time evolution:





Blanco+(2013)



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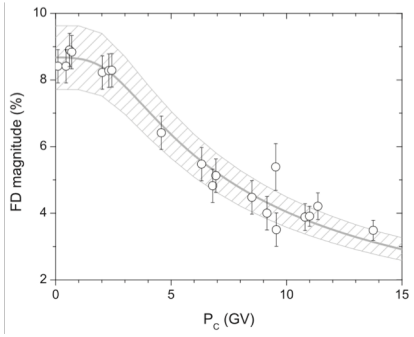
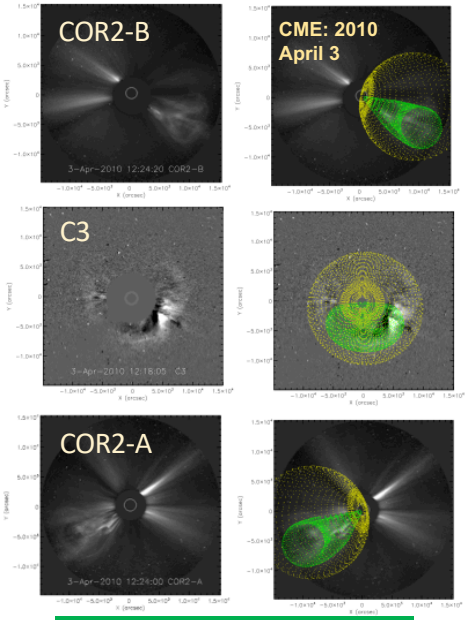


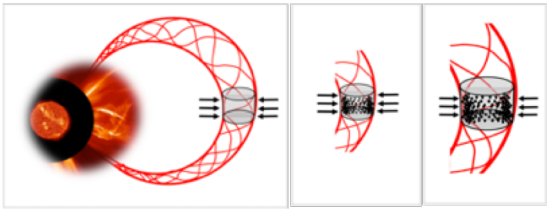
Usoskin+(2015)

ForbMod: reverse modeling

Rodari+2019

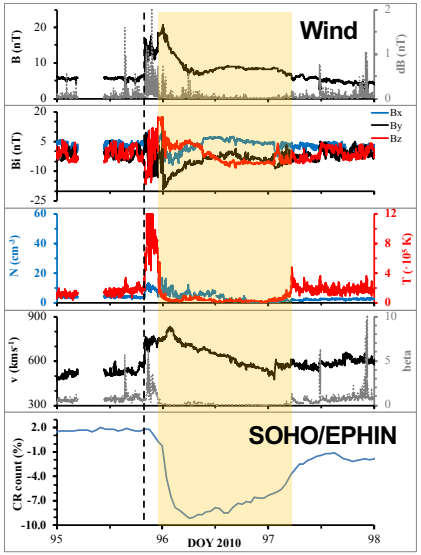


GCS reconstruction



$$|FD| = f(a_0, R_0, t, n_a, n_B, R_{FIN}, D_{FIN})$$

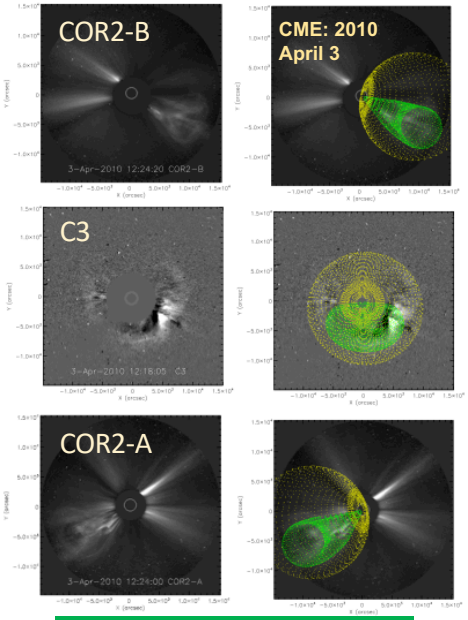
ICME & FD: 2014 May 30



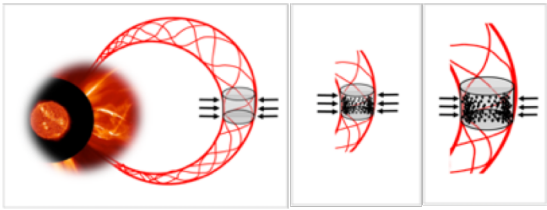
***In situ* measurements**

ForbMod: reverse modeling

Rodari+2019



GCS reconstruction



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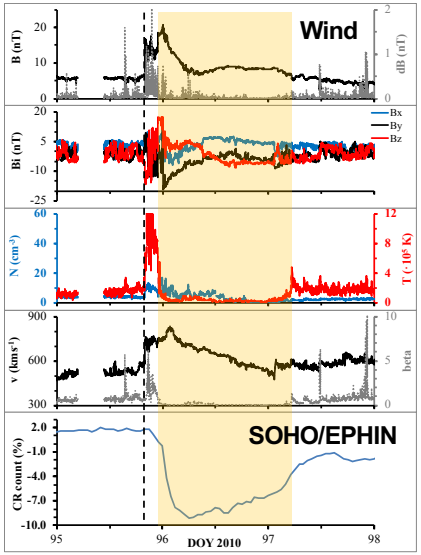

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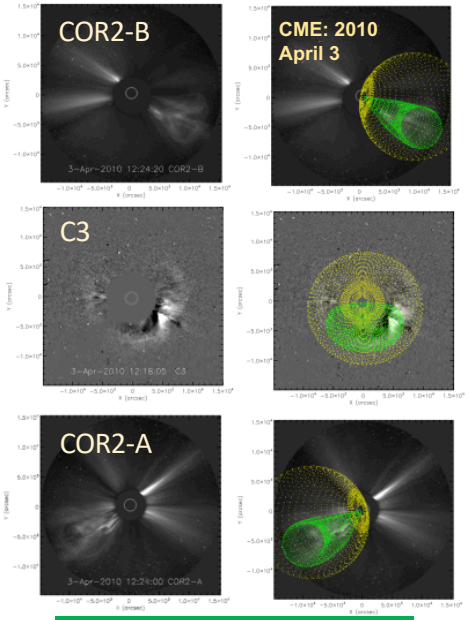

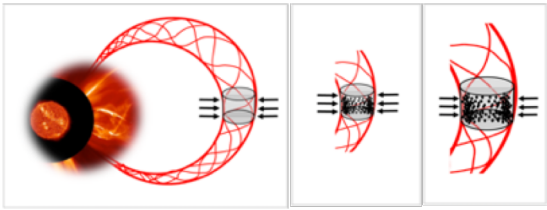

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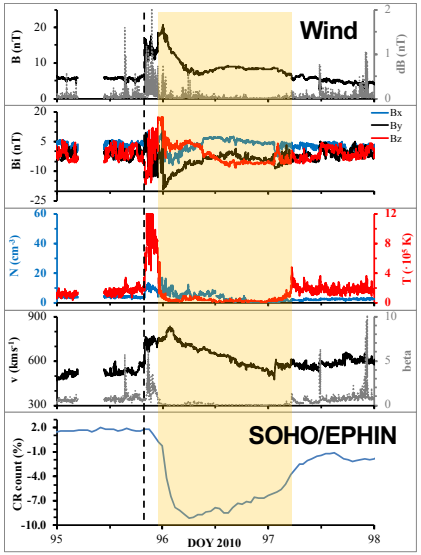

GCS reconstruction

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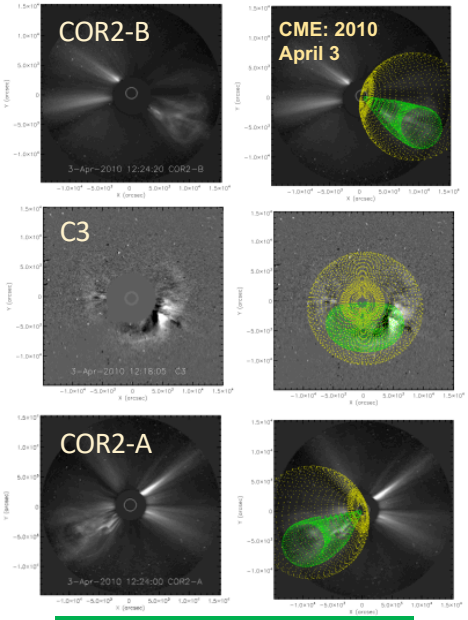
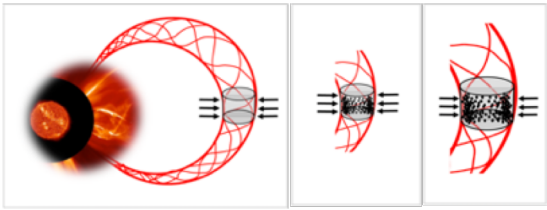
Rodari+2019





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GCS reconstruction

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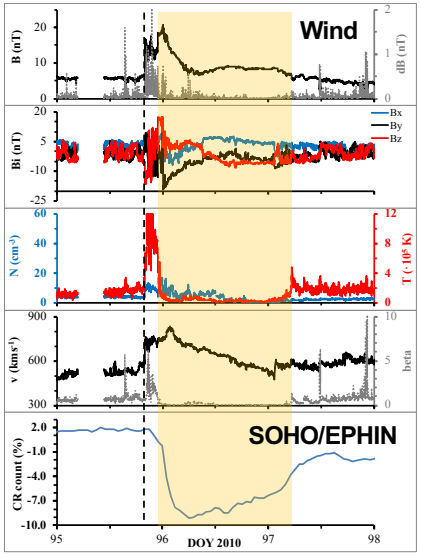

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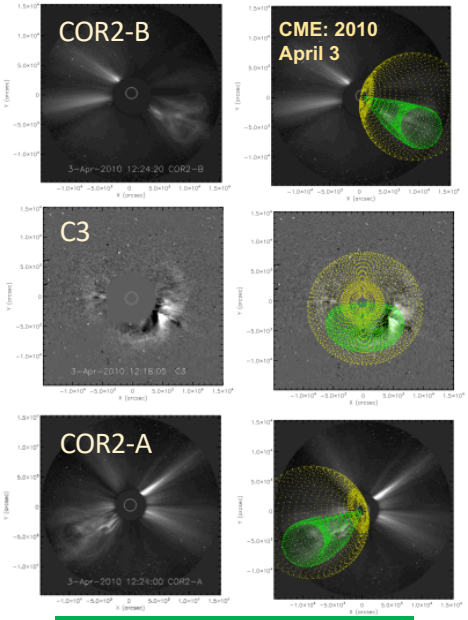

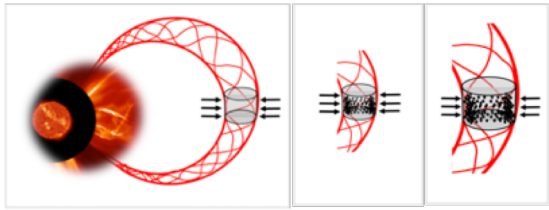

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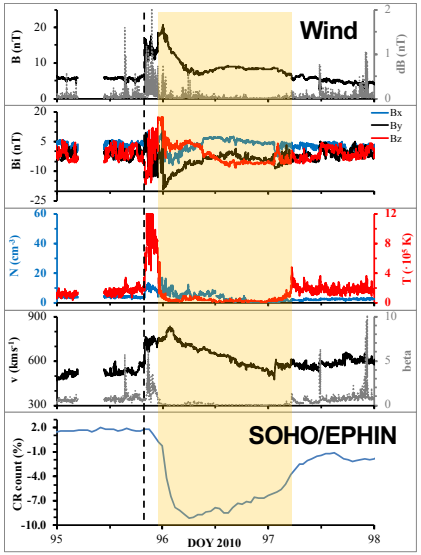

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GCS reconstruction

***In situ* measurements**

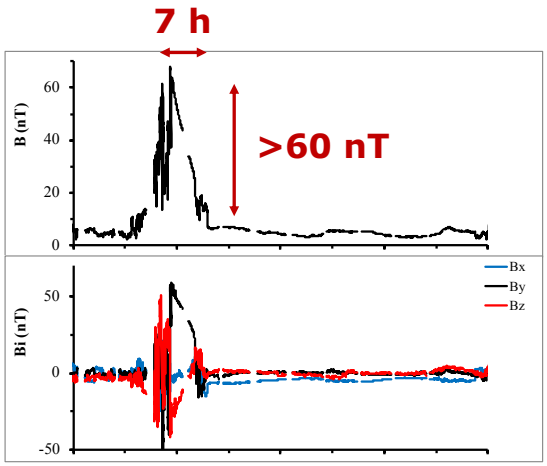
$$B(t) = B_0 \left(\frac{R(t)}{R_0} \right)^{-n_B}$$

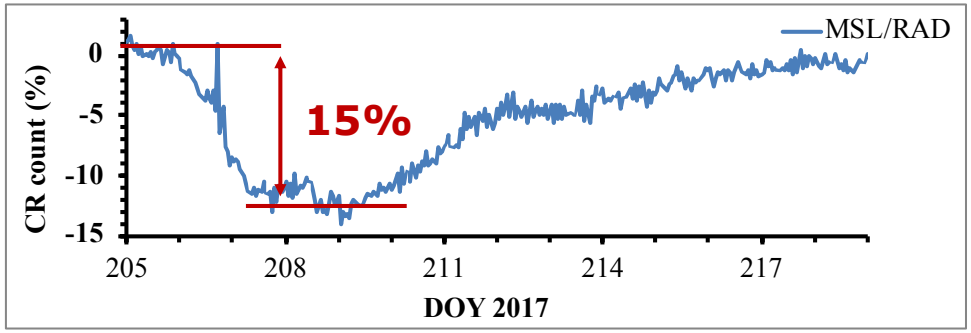
	1st method	*2nd method*
n_a	0.98 ± 0.03	0.99 ± 0.02
a_0	$(3.4 \pm 0.5) R_\odot$	$(3.3 \pm 0.4) R_\odot$
n_B	1.6 ± 0.3	1.6 ± 0.2
$x = n_B - 2n_a$	-0.4	-0.4
B_0	(0.01 ± 0.007) G	(0.009 ± 0.005) G
$\Phi_{ax} = 1.4\ B_0\ r_0^2$	$\sim 4.98 \cdot 10^{20}$ Mx	$\sim 4.86 \cdot 10^{20}$ Mx
B_0	0.010 - 0.018 (0.013) G	
a_0	0.5 - 3.1 (1.2) $R_\odot$	

Comparable:
DeVore,2000

ForbMod application: case study July 2017 events

Dumbovic+2019, ApJ





25.07.2017. Frobush decrease @ Mars:
one of the largest recorded by MSL/RAD
onboard Curiosity rover

24.07.2017.
Magnetic cloud @ ST-A:

B: 6x stronger than average @ 1AU
(acc. Richardson &Cane, 2010)

dT: 4x shorter than average @ 1AU
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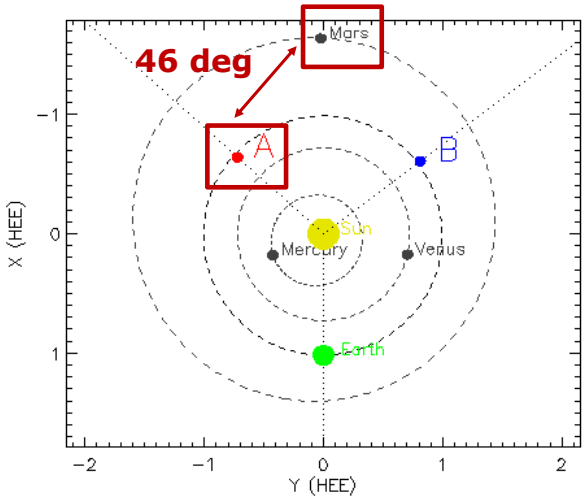
Liu+2019,ApJ:
modelled Dst index -600 nT



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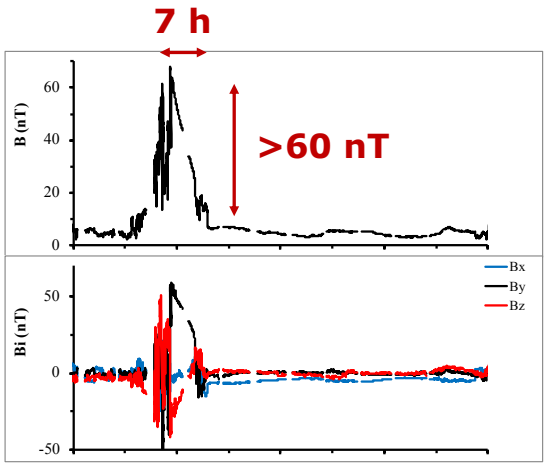
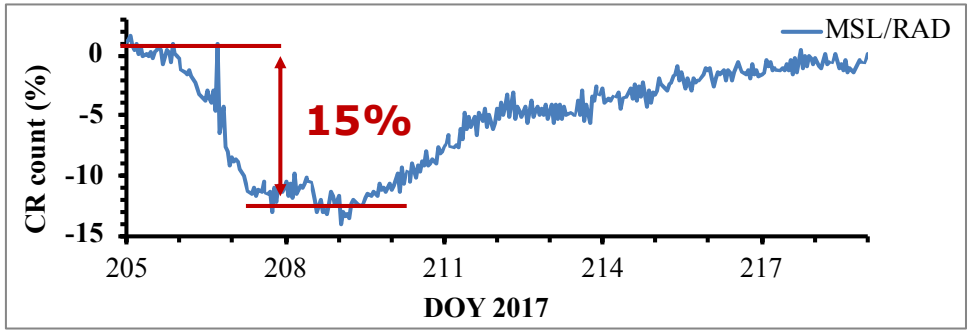
Dumbovic+2019, ApJ





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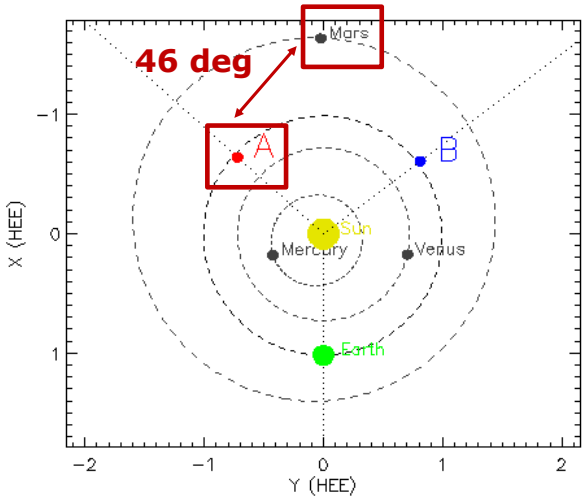


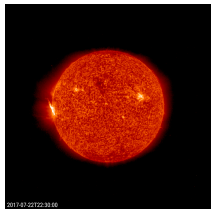
INTERPRETATION:

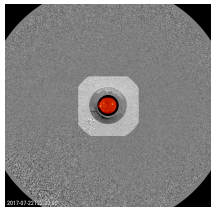
CME-CME
INTERACTION
+
PARTLY
INHIBITED
EXPANSION

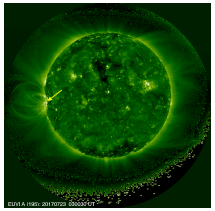
ForbMod application: case study July 2017 events

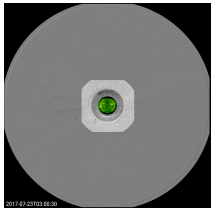
Dumbovic+2019, ApJ

REMOTE OBSERVATION

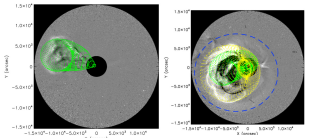






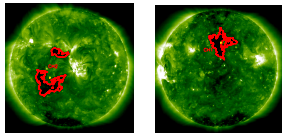


IP SPACE



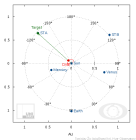
Graduated cylindrical shell model GCS

(Thernisien+2006, 2009; Thernisien, 2011)



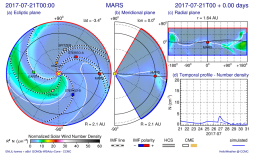
Collection of Analysis Tools for Coronal Holes CATCH

(Heinemann+2019, in prep)



Drag-based (ensemble) model DB(E)M

(Vrsnak+2013,2014, Zic+2015, Dumbovic+2018)

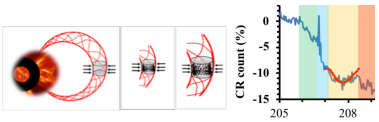


WSA+ENLIL+Cone (ensemble) model

(Odstrcil2003; Odstrcil+2004,2005; Mays+2015)

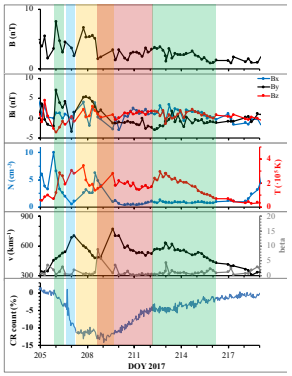
Lundquist fitting

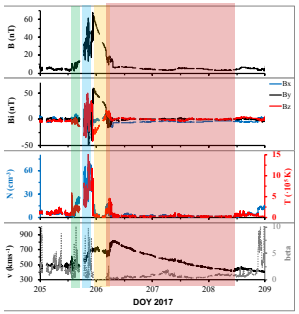
(Lundquist, 1951; Leitner+2007)



Forbush decrease model (ForbMod)

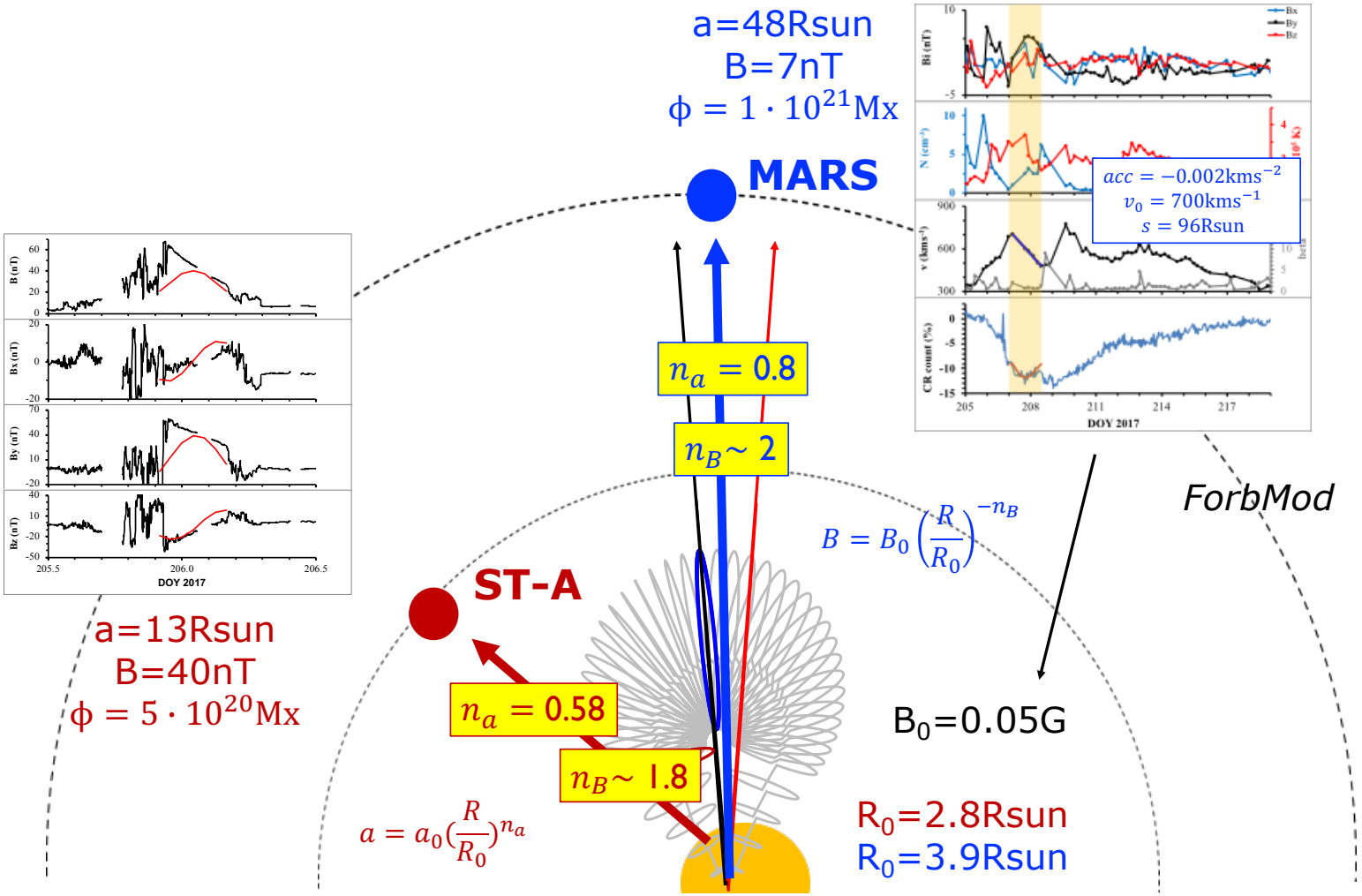
(Dumbovic+2018,ApJ)





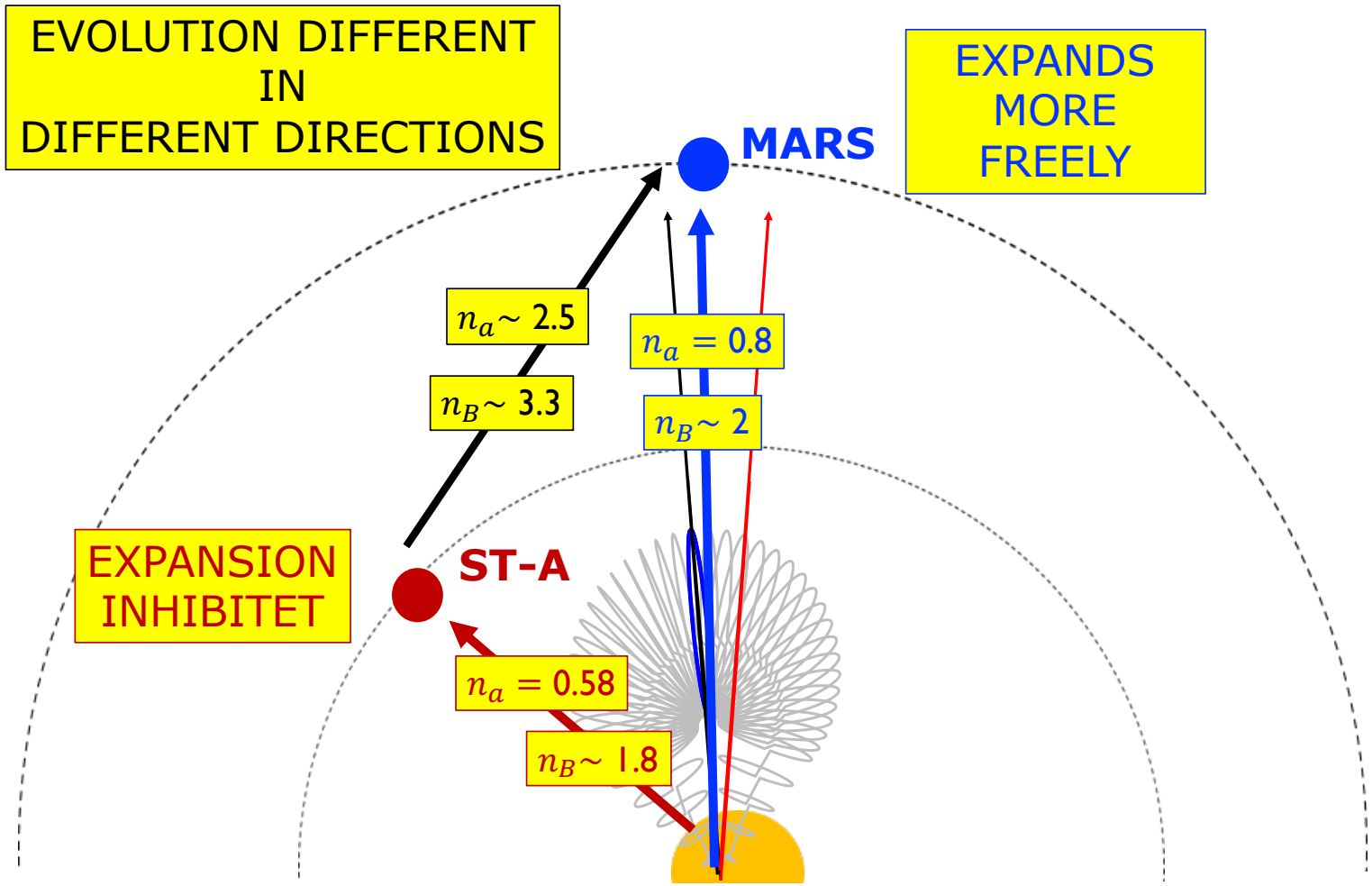
ForbMod application: case study July 2017 events

Dumbovic+2019, ApJ



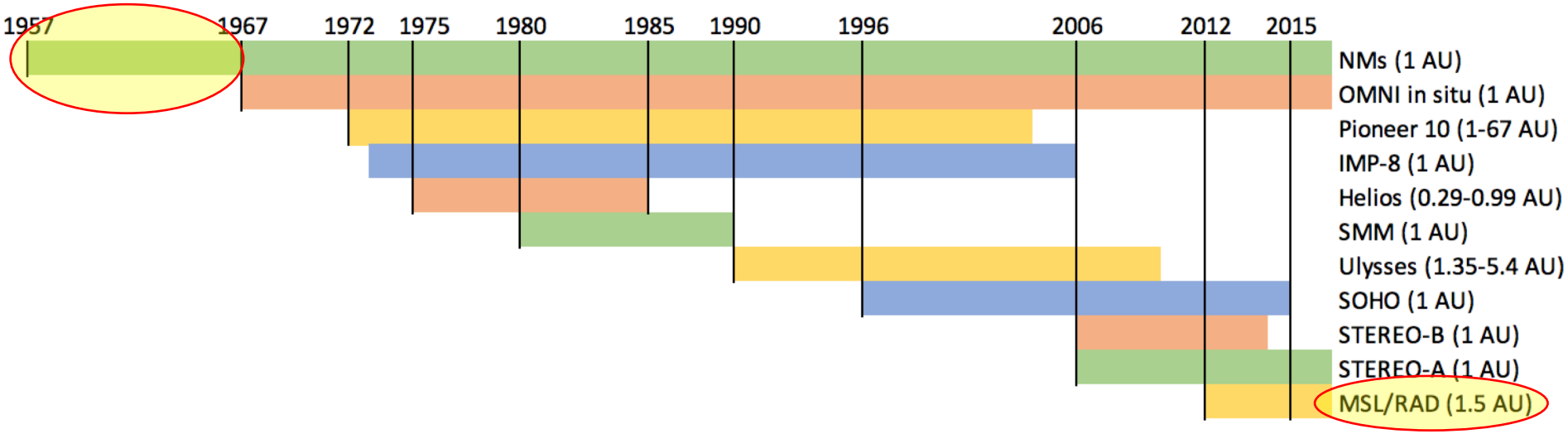
ForbMod application: case study July 2017 events

Dumbovic+2019, ApJ



Take home message:

GCRs can be (very effectively) used as probes of CMEs



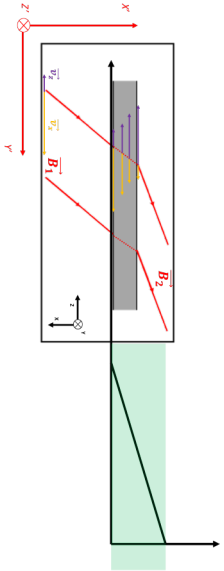
…especially when/where other measurements lack.

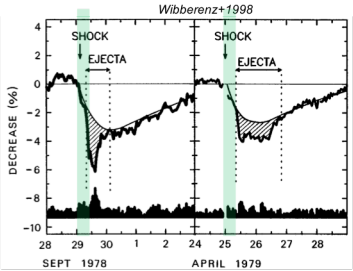
Thank you for your attention!

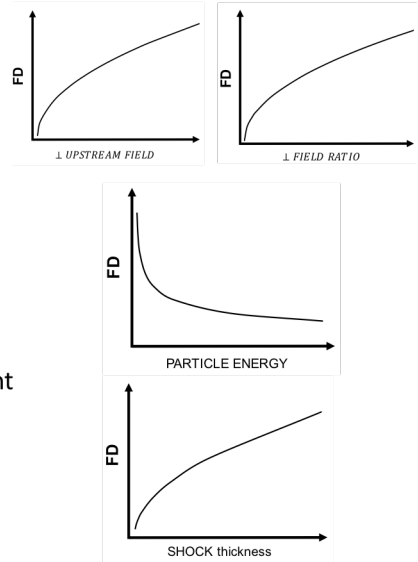
Check out:

Dumbovic+2018, ApJ (on arXiv!)
Rodari+,2019, CEAB, in press (on arXiv!)
Dumbovic+2019, ApJ, in press (on arXiv!)

Next…







Qualitative agreement:
fast drop across the shock front
B dependence
Energy dependence
Shock thickness dependence

Kirin+2019, in prep.

…shock-related Forbush decreases!