Evolution of coronal mass ejections and the corresponding Forbush decreases: modelling *vs* multi-spacecraft observation

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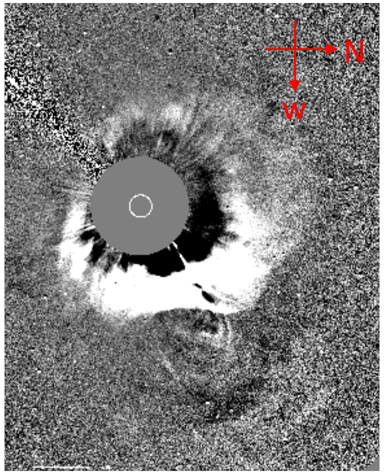
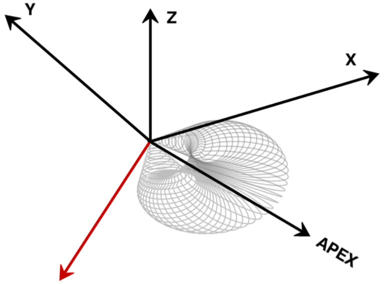
Introduction

REMOTE OBSERVATION

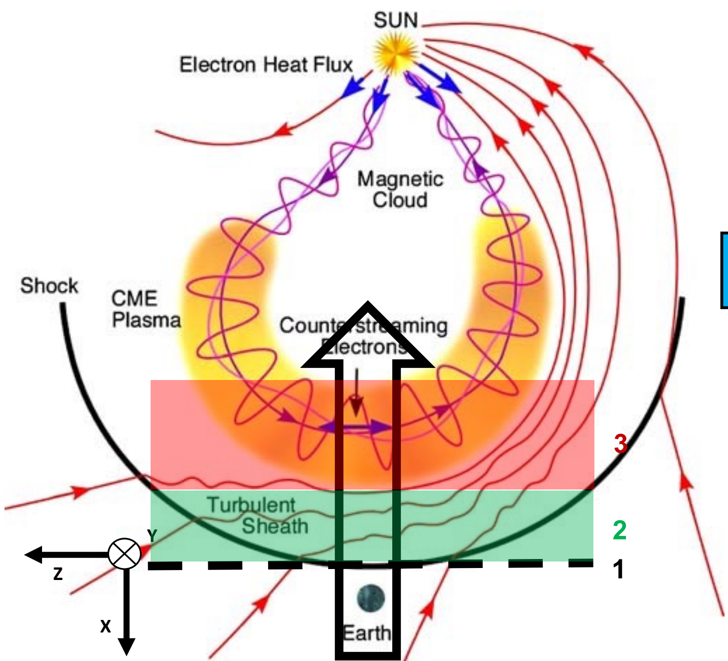


CME in SOHO/LASCO C3
2000 September 16 06:18 UT
First C2 detection at 05:18

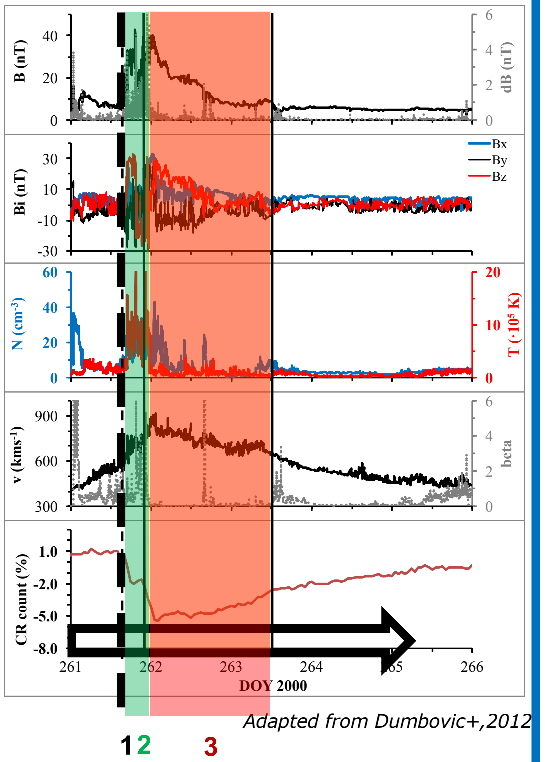


A sketch of a 3D flux rope based on croissant model (GCS; Thernisien+2006)

IP SPACE – EQUATORIAL (xz) PLANE



Zurbuchen&Richardson,2006

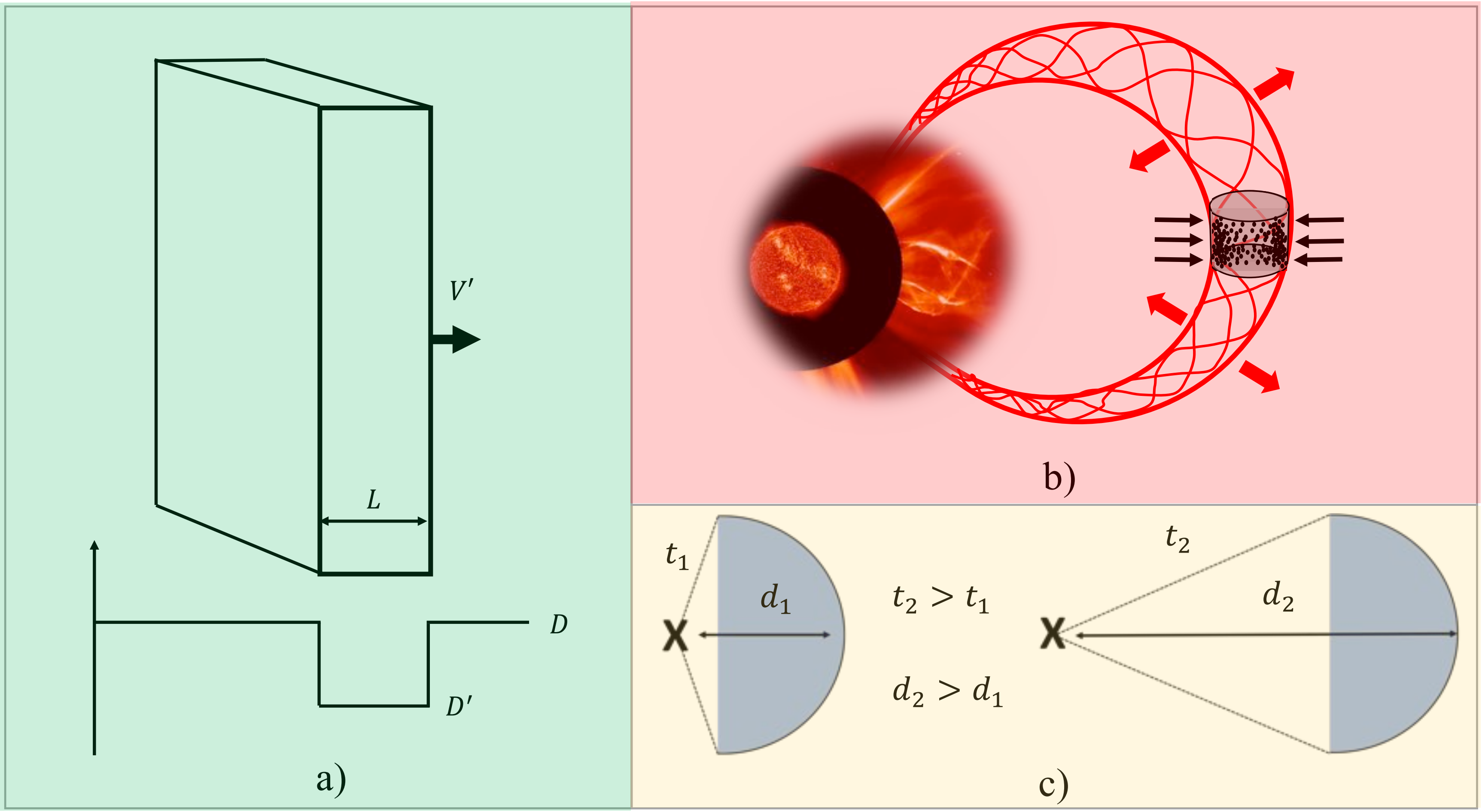


Adapted from Dumbovic+,2012

1-SHOCK **2-SHEATH** **3-FLUX ROPE**

One of the very common *in situ* signatures of interplanetary coronal mass ejections (ICMEs) are Forbush decreases (FDs), i.e. short-term reductions in the galactic cosmic ray (GCR) flux (bottom panel on the right). A two-step FD is often regarded as a textbook example, which presumably owns its specific morphology to the fact that the measuring instrument passed through the ICME head-on, encountering first the shock front, then the sheath and finally the flux rope. The interaction of GCRs and the shock/sheath region as well as the flux rope occurs all the way from Sun to Earth, therefore, FDs are expected to reflect the evolutionary properties of CMEs and their sheaths.

Forbush decrease (FD) modelling

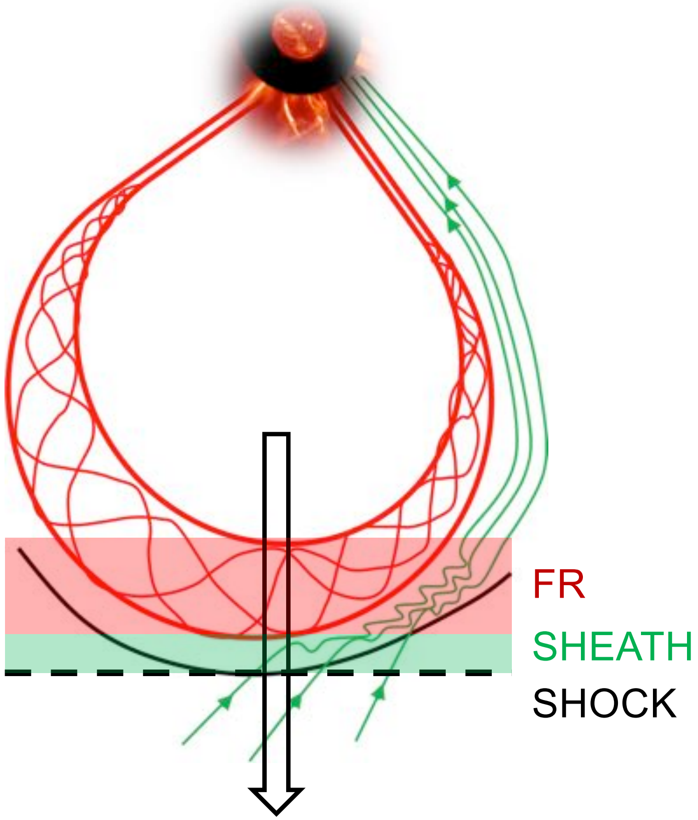


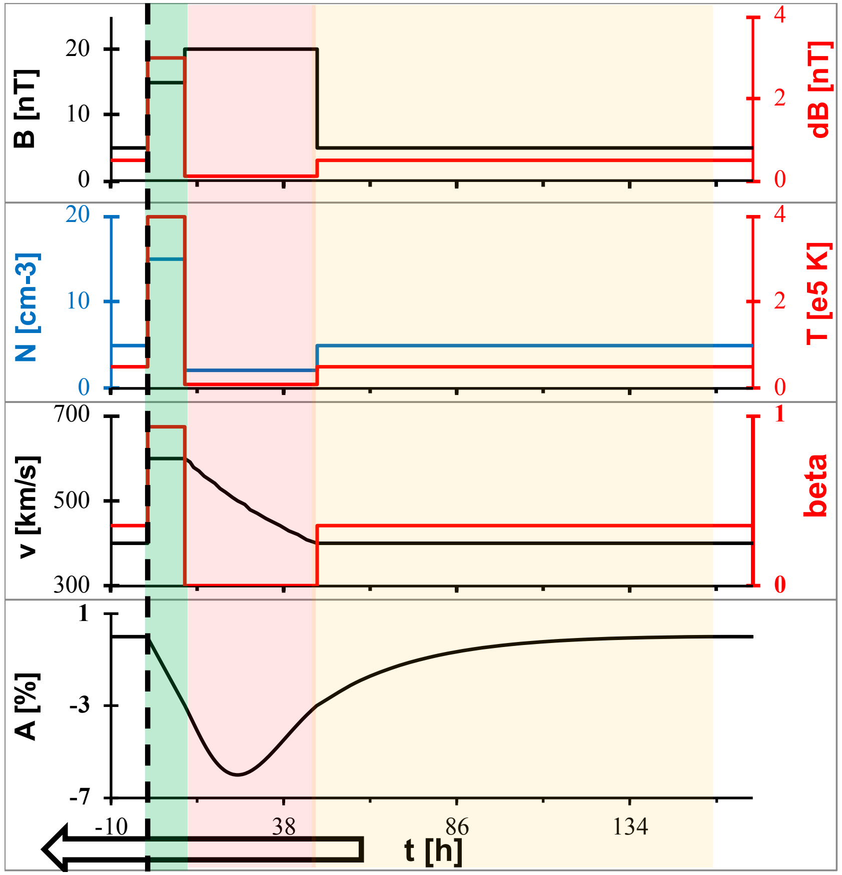
a) propagating diffusive barrier (PDB, Wibberenz+1998) – FD model for the sheath: the sheath is represented by a shell of thickness L, with constant flow speed, V′, and decreased constant diffusion coefficient, D′;

b) ForbMod (Dumbovic+2018) – FD model for the FR: FR is locally represented by a self-similarly expanding cylinder, GCRs (black arrow) diffuse into the expanding flux rope (red arrows);

c) shadow effect of the shock (Lockwood+1986) – FD model for the recovery phase: after the passage shock 'casts' larger shadow at the observer at time t1 when it is closer to the observer, resulting in an exponential recovery

Forbush decrease (FD) generic profile

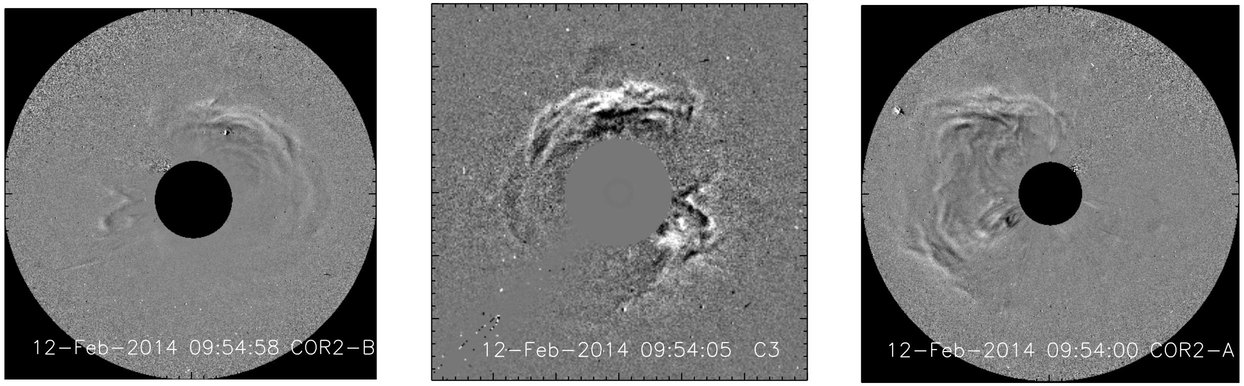


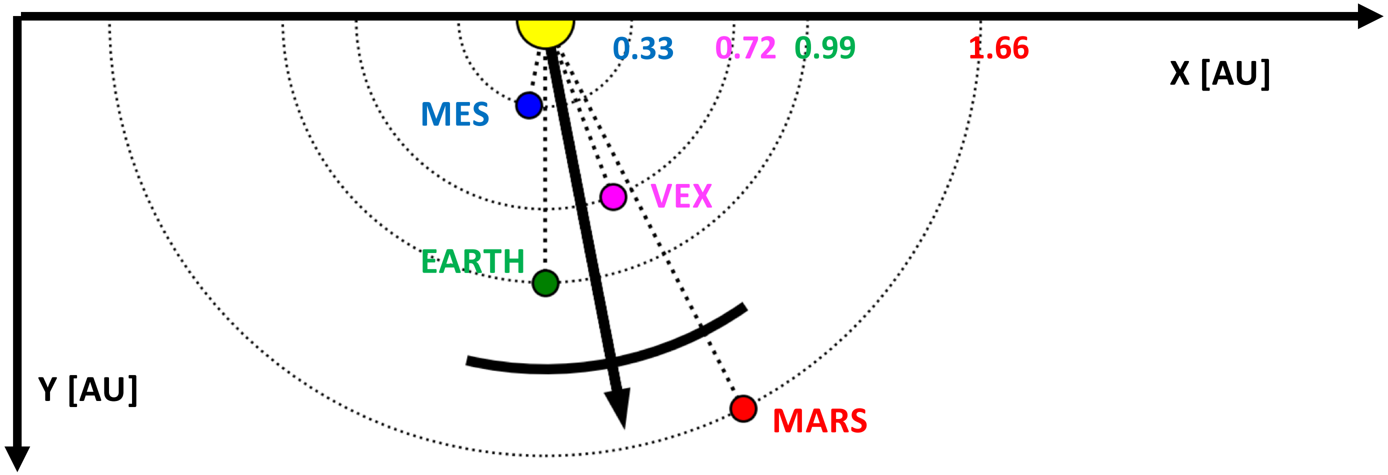


left: A sketch of ICME with shock (black line), sheath (green) and FR (red);
right: sketch of the assumed solar wind plasma parameters, top to bottom: magnetic field strength, B and fluctuations, dB; plasma density, N and temperature, T; plasma speed, v and beta parameter; and a generic profile of a two-step FD for particles of energies > 50 MeV. Shock arrival is marked by the black dashed line, sheath region is highlighted green, magnetic structure is highlighted red and the recovery phase is highlighted yellow. The passage of the ICME over the observer is marked by an arrow in both sketches.

The relative GCR density drop, *A*, in the sheath is modelled with PDB model and is a linear function of the sheath thickness; *A* in the FR is modelled by ForbMod and is given by a symmetric Bessel function of the radial distance from the FR axis; *A* in the recovery phase is given by the modified exponential function

Multi-spacecraft observations





Observations of the event reported throughout the inner heliosphere (Winslow+2018):

CME launch: 2014 February 12, 5:48 UT

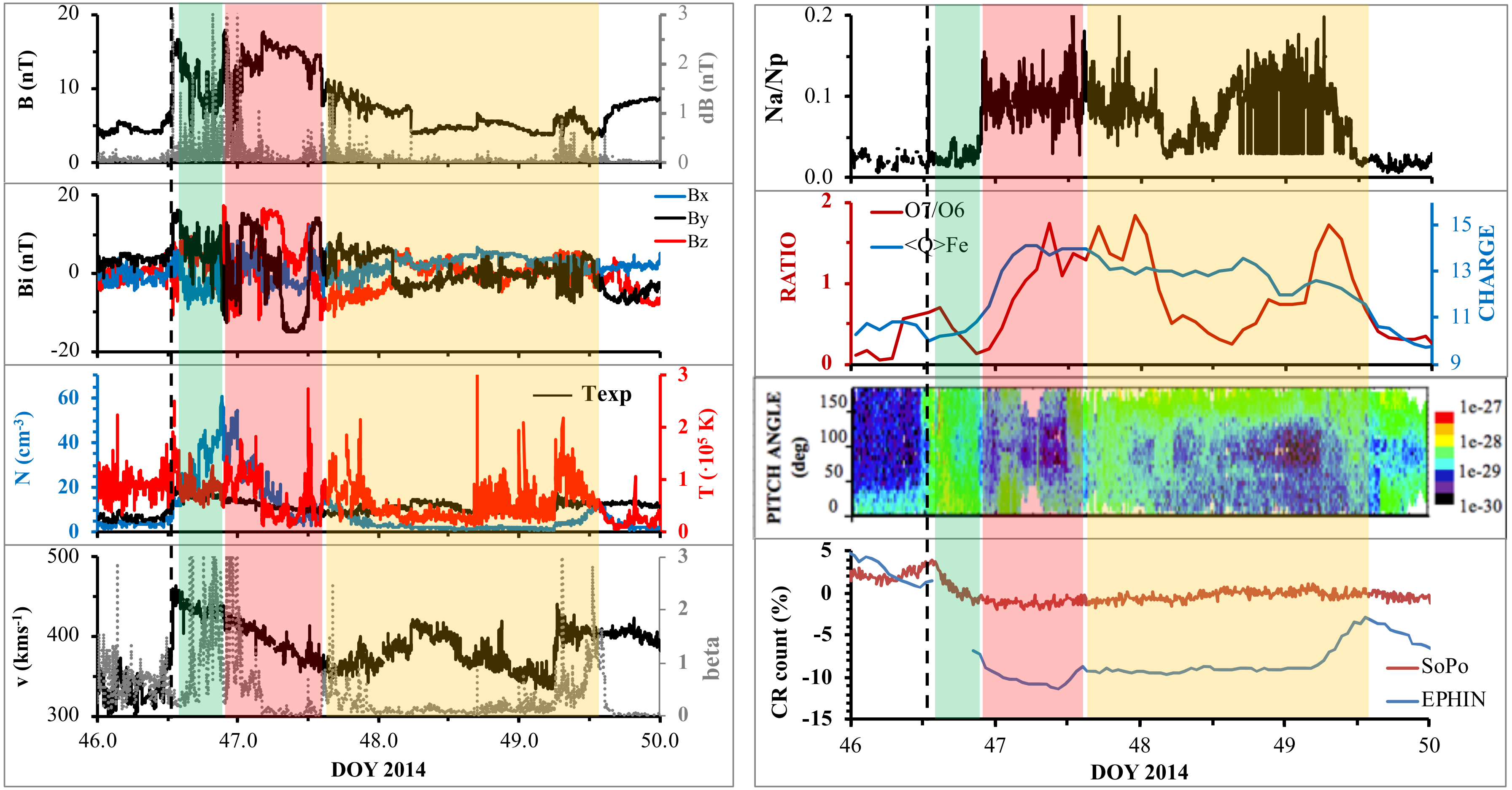
ICME arrival at Messenger (MES): 2014 February 13, 4:51 UT

ICME arrival at Venus Express (VEX): 2014 February 14, 10:35 UT

ICME arrival at Earth: 2014 February 15, 12:35 UT

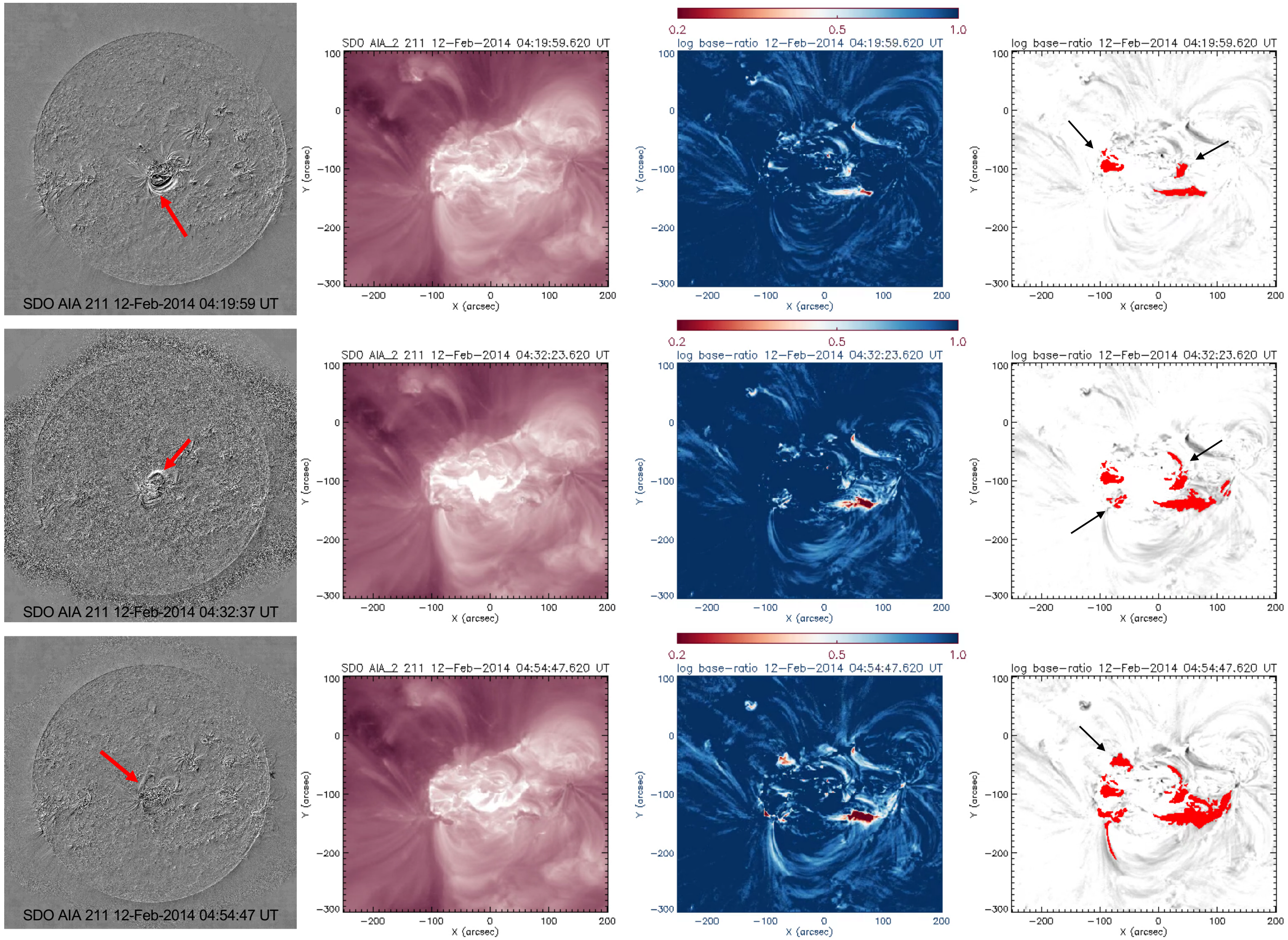
ICME arrival at Mars: 2014 February 18, 3:24 UT

In situ measurements at Earth



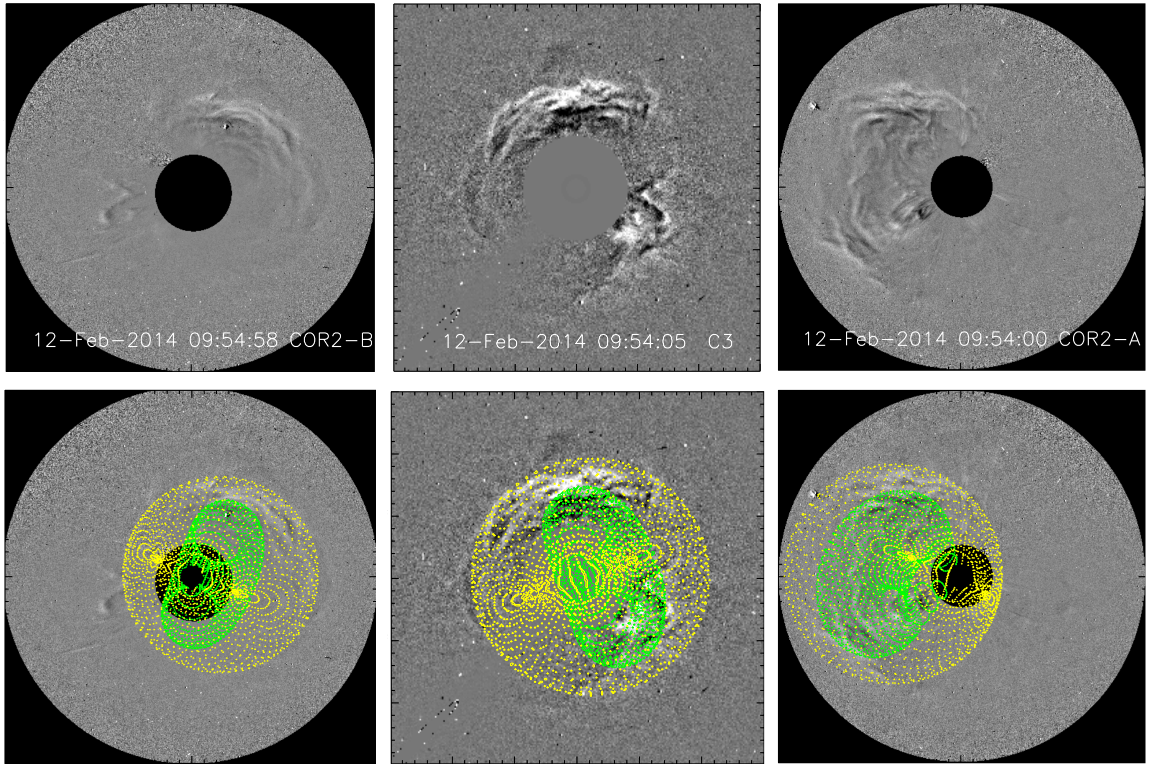
In situ measurements for the **2014 February 15 ICME** observed at Earth. Different panels show (top left to bottom right): (1) magnetic field strength, B, and fluctuations, dB; (2) GSE components of the magnetic field, Bi; (3) plasma density, N, and temperature, T; (4) plasma flow speed, v, and beta; (5) alpha to proton ratio, Na/Np; (6) Iron charge states, < Q >Fe, and oxygen charge states ratio, O7/O6; (7) suprathermal electron pitch angle distribution (for E=116,1 eV); (8) relative CR count for South Pole neutron monitor (geomagnetic rigidity cutoff 0.10 GV, altitude 2820 m) and SOHO/EPHIN F-detector (>50 MeV). The black line marks the shock and the sheath is shaded green. The region containing magnetic cloud signatures is shaded red and the region with compound stream signatures is shaded yellow, where the borders of both regions are defined based on the 2nd and 3rd depression as observed by SOHO/EPHIN.

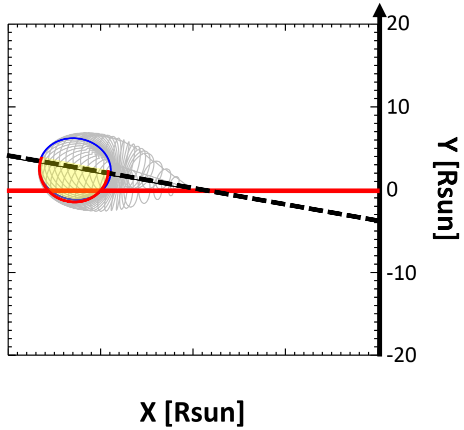
Low coronal signatures

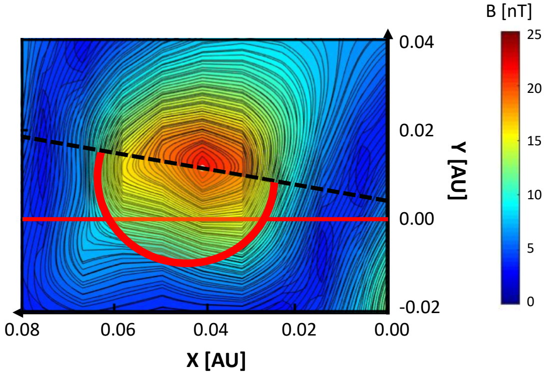


Low coronal signatures of the 2014 February 12 CME: a multi-step eruption is observed with three sub-eruptions from the same active region followed by dimmings at ~04:20 UT (upper panels), ~04:30 UT (middle panels), and ~04:55 UT (bottom panels). On the left a full disc images of SDO AIA 211 in running difference are presented with arrows pointing at the eruptive loop. On the right a zoom-in on the active region is shown in the same wavelength, together with log-base ratio and highlighted dimmings in the log-base ratio, where the black arrows point to dimmings corresponding to different stages of the eruption

3D reconstruction of the FR







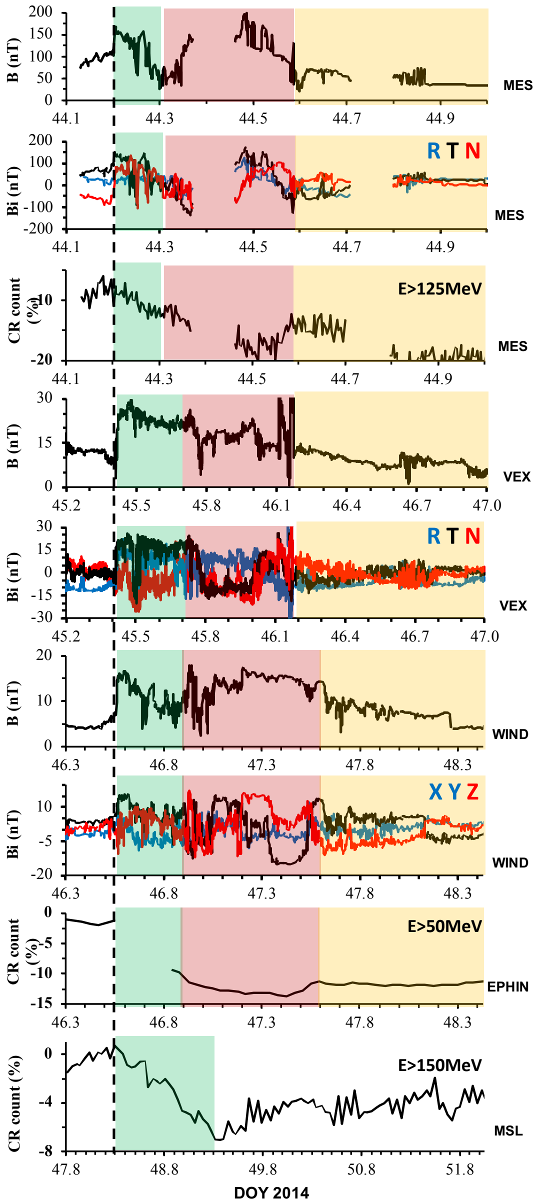
Left: 3D CME reconstruction using the Graduated cylindrical shell (GCS) model of the CME FR (green mesh) corresponding mainly to the first eruption and of the shock (yellow mesh), using STEREO A&B/COR2 and LASCO C3. FR is represented as a hollow croissant with its origin at Sun center;

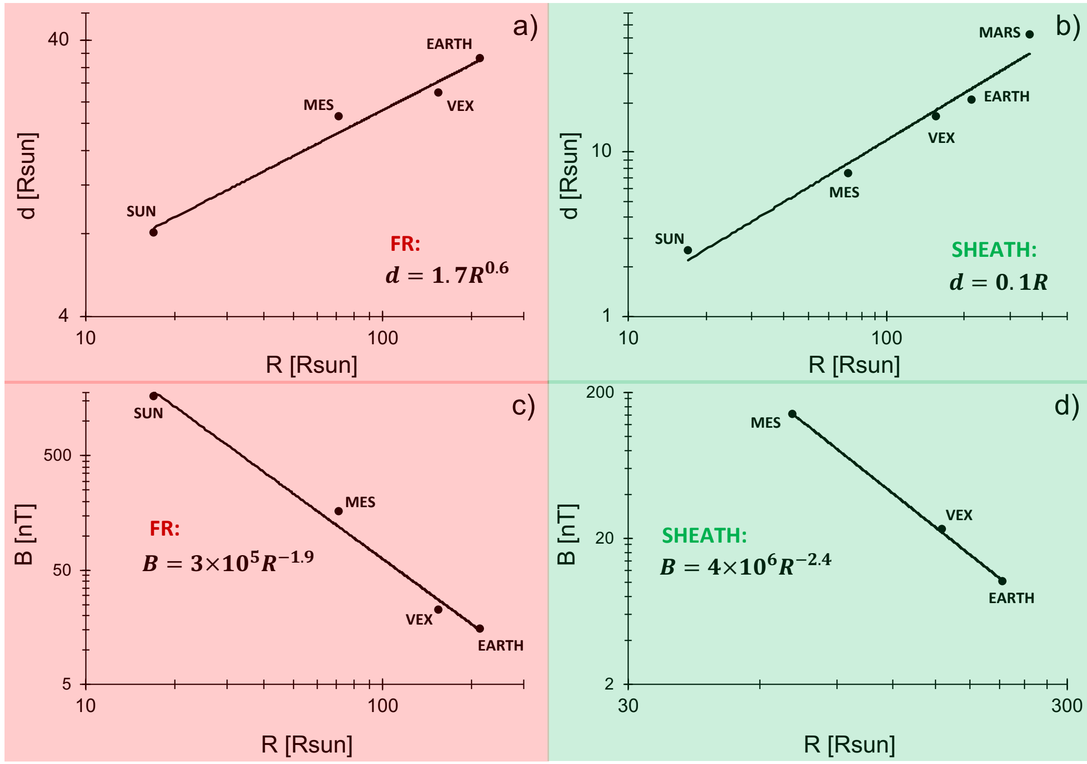
Upper right: GCS reconstruction projected onto the solar equatorial plane, with the black dashed line showing the direction of the apex, the red line showing the Sun-Earth line and the red semicircle outlining the cross-section of the croissant in the solar equatorial plane;

Bottom right: comparison of the FR orientations obtained by GCS reconstruction and Grad-Shafranov (GS) reconstruction (bottom). The GCS results are overlaid on the GS reconstruction image showing a magnetic field contour plot in the plane of the flux rope cross section as determined by the GS method, which is practically perpendicular to the solar equatorial plane. GS reconstruction was performed for the structure corresponding to the 2nd step of the FD observed by SOHO/EPHIN. The goodness of the fit, measured by the minimum of fitting residues is Rf=0.2 which is a borderline solution (Hu+2017).

The orientation of the two reconstructions are in agreement (GCS tilt angle is −70◦ and GS tilt angle is −75◦).

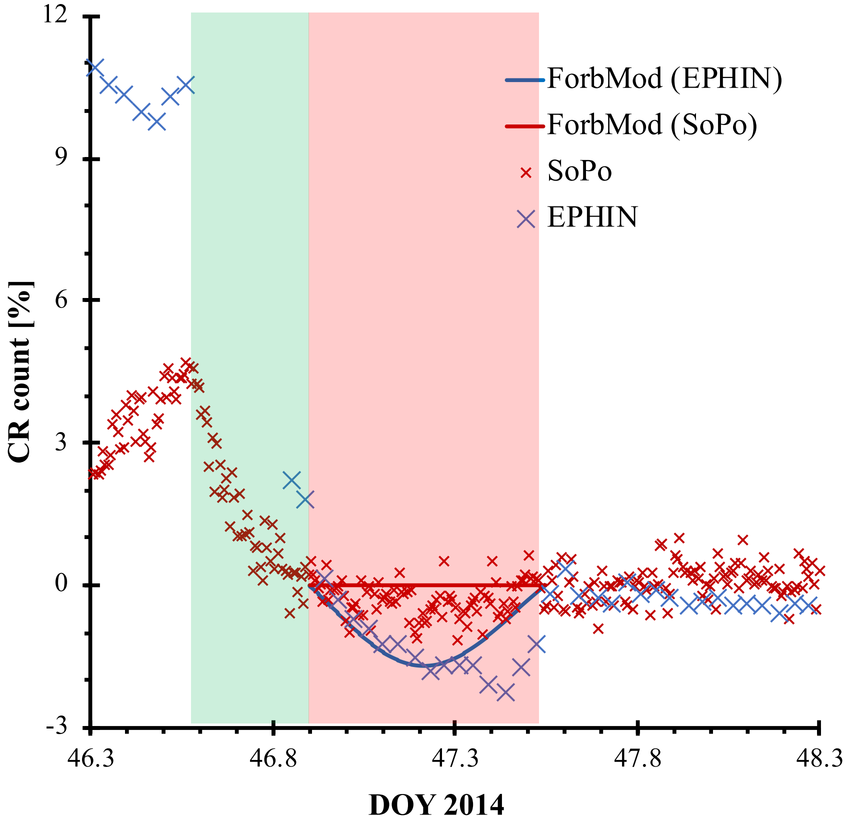
Multi-spacecraft in situ measurements





Multi-spacecraft in situ measurements for the 2014 February 12 CME and evolution of the size, *d*, and the magnetic field strength, *B*, in the FR (red) and sheath (green). The two magnetic structures as identified at Earth based on SOHO/EPHIN are identified at MES and VEX and highlighted red and yellow, respectively (note that the time scales at different spacecraft are not the same and the second magnetic structure is not encompassed at all spacecraft due to visualization purposes, i.e. to focus on the sheath and FR). At Mars we observe only one decrease, and we assume that the entire main phase of the FD (from onset to the minimum) corresponds to the shock/sheath region. The size at the Sun is calculated based on GCS reconstruction and the magnetic field strength is estimated based on the dimming flux, as a proxy of the magnetic flux contained within the magnetic structure (Dissauer+2018). Evolution of the size and the magnetic field is characterized by power-law fits: a) FR size; b) sheath size; c) FR magnetic field; d) sheath magnetic field).

Forbush decrease: modelling vs observation



Based on the derived evolutionary properties of CME we calculate FD amplitude and profile taking into account also the energy dependence. SOHO/EPHIN and South Pole neutron monitor (SoPo) observe different energy ranges and not all energies contribute equally to the observed GCR count rate. In both cases the shape of the curve is given by the symmetric Bessel function of the zero order. The calculated FD amplitude in the SOHO/EPHIN (based on its energy range and response function) is 1.7 %, and in SoPo 0% (i.e. we do not expect to see any effect). We conclude that the effect is seen in SOHO/EPHIN because it responds to particles of lower energies compared to SoPo. At Mars, based on ForbMod calculations, 2nd step is not expected to be observed. At Messenger, the ForbMod results are inconclusive because the energy dependence is unknown, however they are not in disagreement with observations.

modelling results show reasonable agreement with measurements near Earth, at Earth, and at Mars

one of the key factors in understanding the inner structure of the CME/ICME event was the FD substructure observed by SOHO/EPHIN

FD models not only offer an opportunity to understand the variability of FDs detected in the heliosphere but also to gain insight into the CME evolution

Thank you for your interest in this display!

The research presented in this display is currently submitted to Solar Physics and will appear on arXiv soon.

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REFERENCES:

Dissauer+2018, ApJ, DOI: 10.3847/1538-4357/aaadb5
Dumbovic+2012, A&A, DOI: 10.1051/0004-6361/201117710
Dumbovic+2018, ApJ, DOI: 10.3847/1538-4357/aac2de
Hu+2017, SolPhys, DOI: 10.1007/s11207-017-1195-z
Lockwood+1986, JGR, DOI: 10.1029/JA091iA03p02851
Thernisien+2006, ApJ, DOI: 10.1086/508254
Wibberenz+1998, SSR, DOI: 10.1023/A:1005083109827
Winslow+2018, ApJ, DOI: 10.3847/1538-4357/aab098
Zurbuchen&Richardson2006, SSR, DOI: 10.1007/s11214-006-9010-4