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Identification of solar origins of geo-effective ICMEs by modeling of their ion composition

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Goal of the research

To develop methods for identification and parametrization coronal sources of the solar wind transients in order to improve forecasting their geoefficiency

Method:

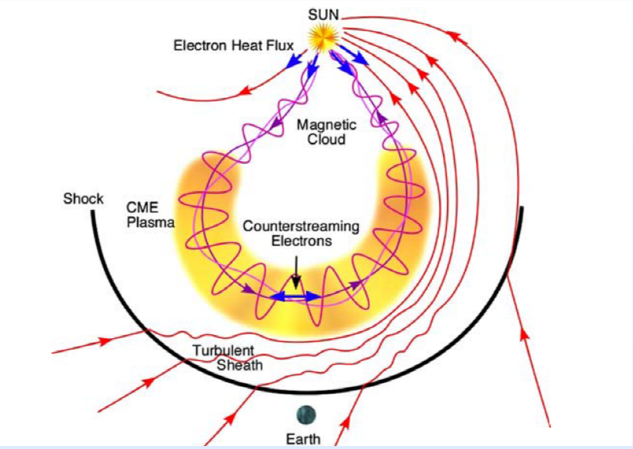
Study the link between measured “in situ” ion composition of geoeffective ICMEs and parameters of plasma in the supposed coronal sources, taking into account evolution of the SW plasma from the solar origin to the Earth

Advantages of ion composition as signatures of coronal sources over other parameters of SW

1. Ion charge composition is “**freesed**” in the lower corona below 5 Rsun and **stays practically unchanged** during the collisionless passage of SW through the heliosphere.
2. In contrary, **such parameters as Vp, np, Tp, plasma beta, magnetic field components may variate in the heliosphere** by interaction of different transients with each other or with background due to reconnection, compression, wave generation etc.
3. **An elevation of ion charge state above the background values unambiguously denotes a presence of hot plasma** in the SW forming below the freesing-in zone, so the **ion composition of SW represents a physically model-independent parameter** inherent in the type of the coronal source.
4. A **charge state distribution** of ions measured in situ bears information about **process of SW forming and heating in the corona**, thus can be used for verification of SW models
5. The **charge state of the SW ions can be modeled** using the parameters of plasma diagnostics – density and temperature of electrons, their energy distribution function, plasma mass velocity, which can be defined in the corona **from easily measured intensities of X-ray and EUV lines.**

The GMU ICME List (by Phillip Hess and Jie Zhang)

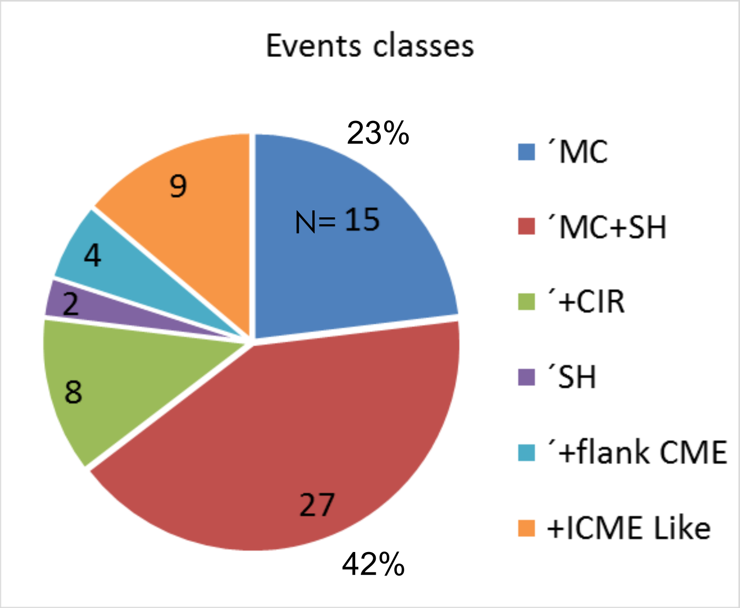
- 65 ICME events in Cycle 24 from 2007 to 2015
- Sources associated with AR - 44 events
- 38 events are geoeffective with Dst<-40 nT

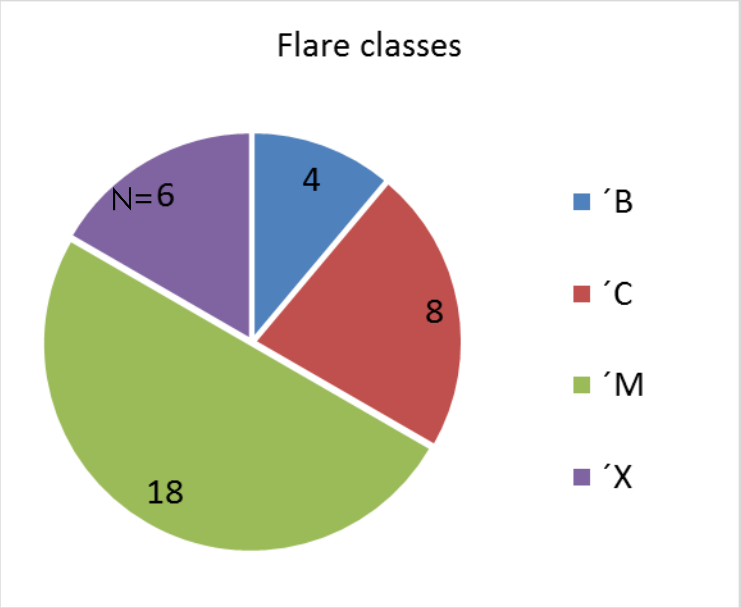


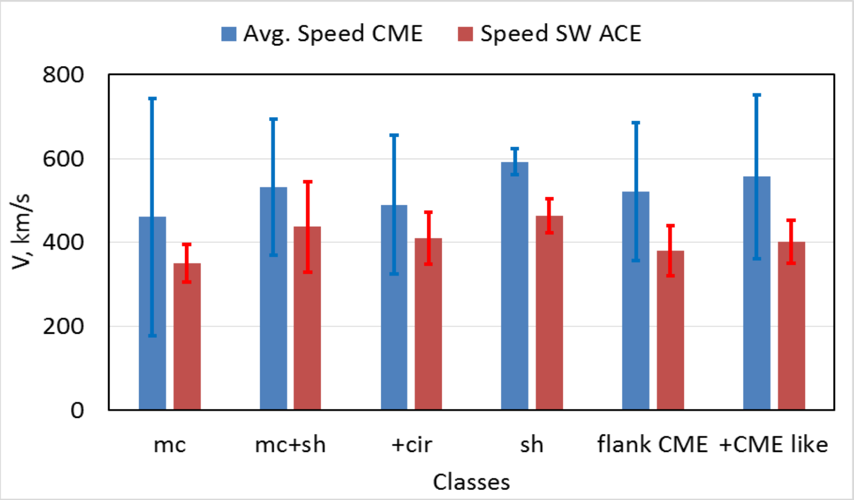
Zurbuchen&Richardson 2006

Classes of events	N	<Dst>±σ, nT	< -40nT	% of all/geoeff	Yermolaev et al. 2012 (1976-2000)
MC	15	63±12	7	**11/40**	2.6/54.5
MC+SH	27	85±27	21	**42/78**	13.4/63.3
+CIR	8	99±73	4	12/50	31.2/20.2
SH	2	99±(?)	1	**3/50**	20/30
+flank CME	4	137±(?)	1	6/25	24.8/21.2
+ICME Like	9	54±9	4	**14/44**	9.9/7.8

Statistics of the ICME types and geoefficiency in Cycle 24

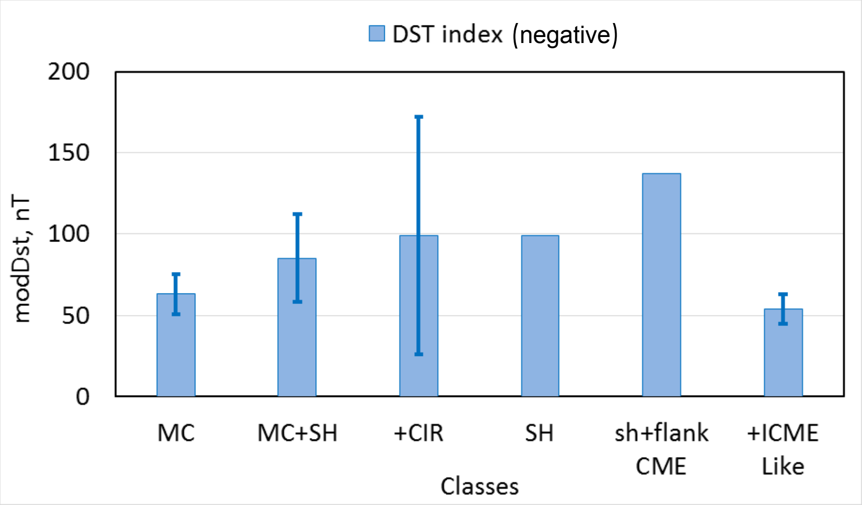






Total 65 events

Total 36 flares (57% of events)



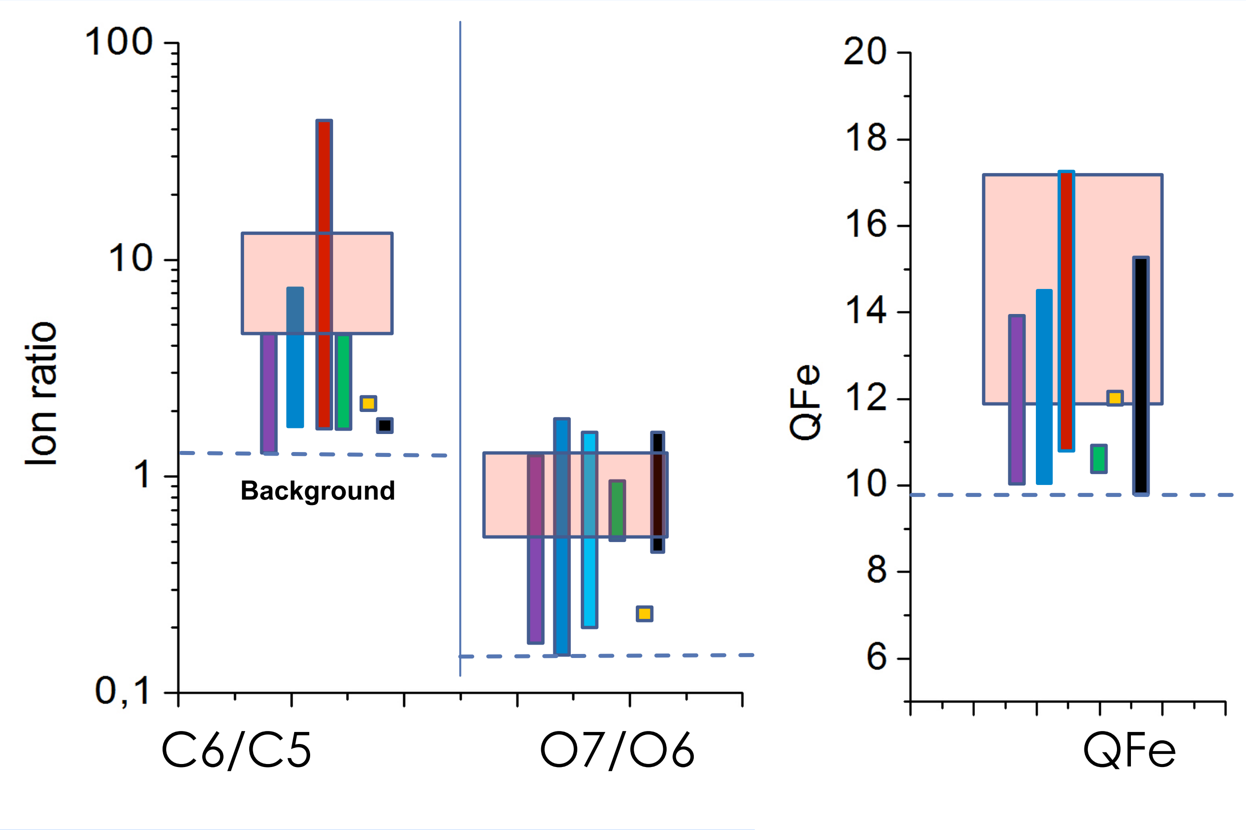
More than 70% of geoffective events associated with plasma ejections from ARs

In more than 30% events the sources were not identified by ordinary signatures (Vp, Tp, B, plasma β)

Ion composition of the geoeffective SW transients in 2007 - 2015

1 – MC
2 – MC+SH
3 - +CIR
4 – SH
5 - +flank CME
6 – ICME like
7 – range for 23d cycle

(Gopalswamy et al. 2013; von Steiger Springer book, 2008)



Except CIRs, coronal sources in Cycle 24 produce the SW transients with less enhanced ion composition than in the previous Cycle 23

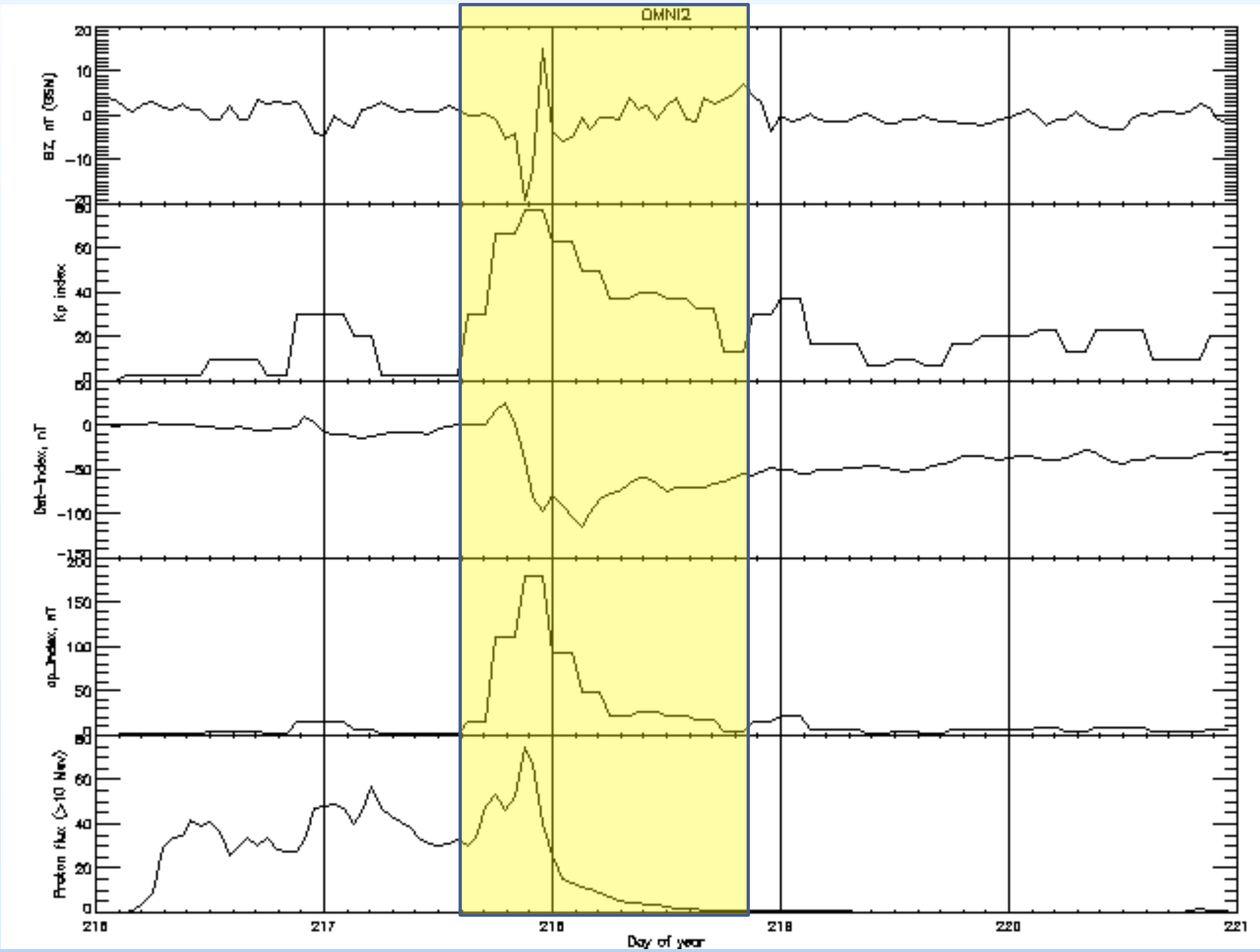
Case study: identification of coronal sources of the 5 – 8 August 2011 geomagnetic storm

Start of the storm:

Proton flux <10 MeV 4 Aug 05h
Main phase 5 Aug 14h
Dst peaks: (-100 nT) 5 Aug 22h
(-113 nT) 6 Aug 3h

End of the storm:

6 Aug 21h



Bz
Kp
Dst
Ap
Protons >10 MeV

4/08 5/08 6/08 7/08 8/08 2011

GMU ICME list

One flare event 4 Aug 03:41UT with CME produced at Earth a storm with Dst = -113 nT
ICME type – MC+SH

Singh et al. IJSRPAS 3, 2015

Two flare events 3 Aug 13:17UT and 4 Aug 03:41UT with Halo CME. Storm with Dst = -68 nT
ICME type – two IP Shocks

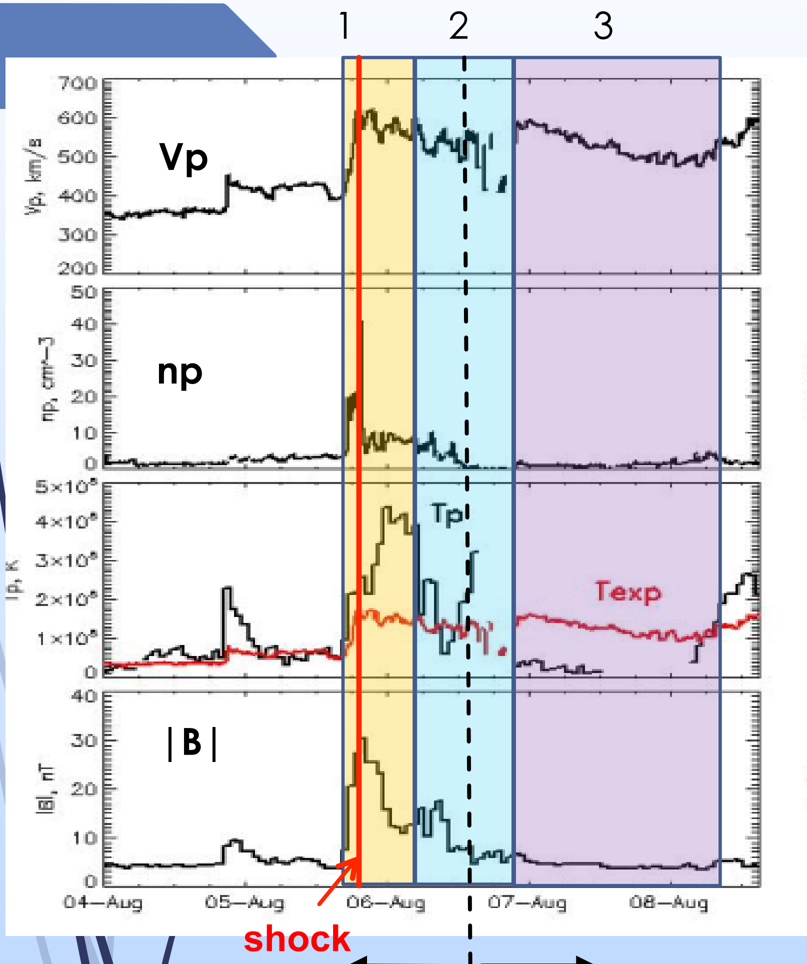
The ISEST Master ICME List

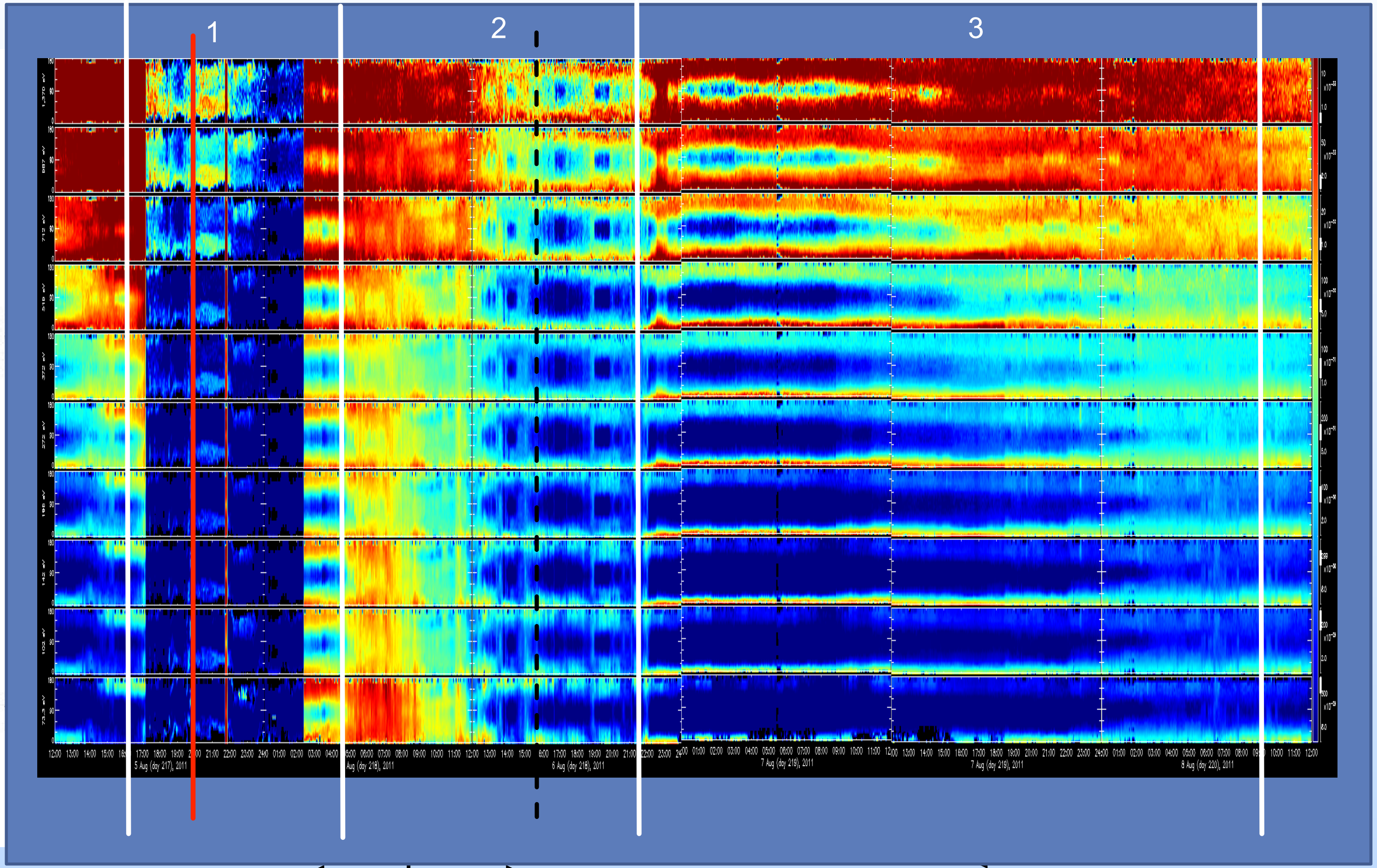
Flare M9 with Halo CME 4 Aug 03:41. Storm with Dst=-113.
ICME type - SH+CIR(?) +ICME like

Richardson&Cane ACE ICME data list

ICME with signatures of MC, **BDE** 05 Aug 17:51 – 06 Aug 22:00
(ion composition used)

In-situ ACE solar wind data for 04 – 08 August 2011





$B_x > 0$ $B_x < 0$

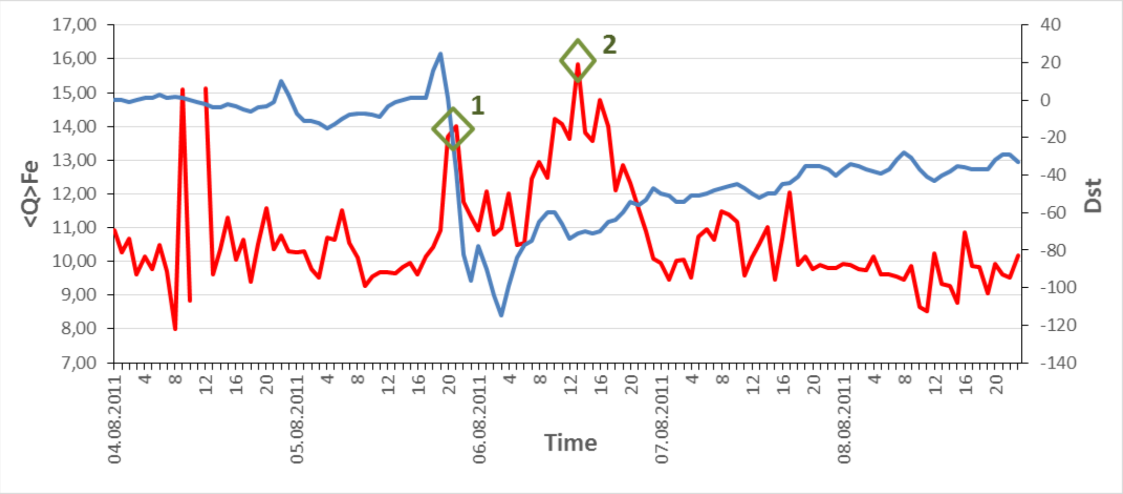
sector boundary

$B_x > 0$ $B_x < 0$

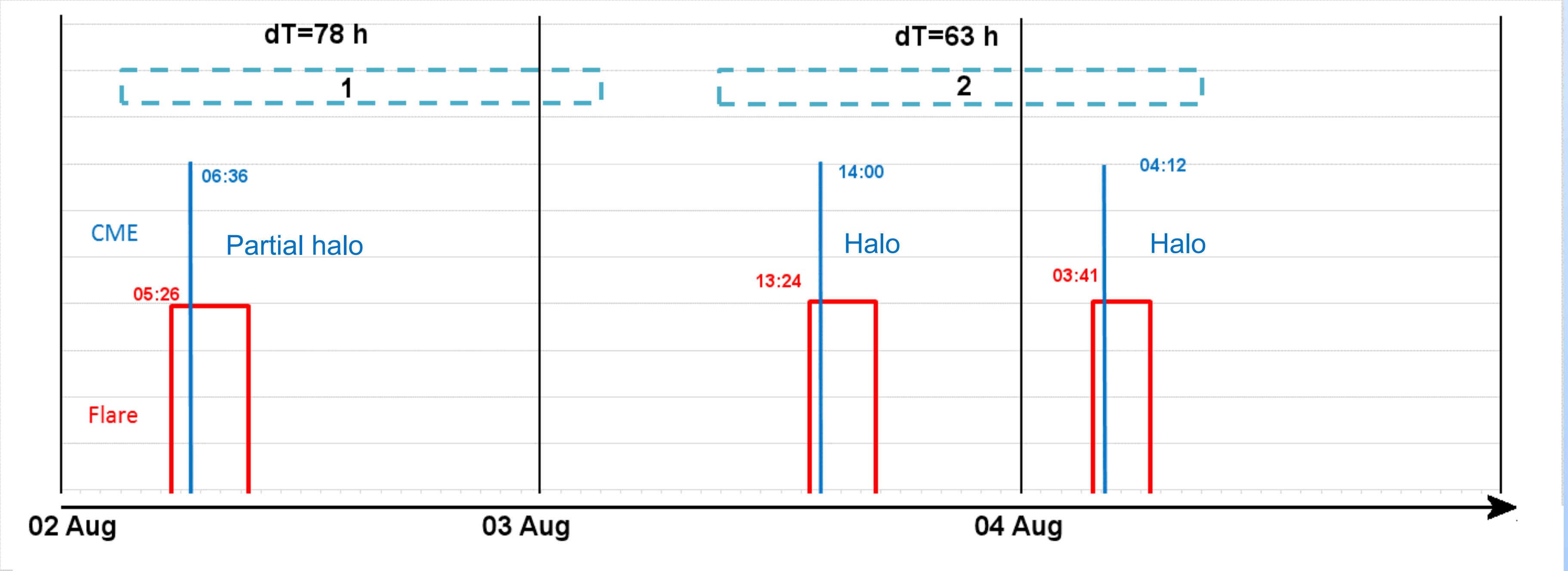
$B_x > 0$ $B_x < 0$

1. 5 Aug 17:00 – 06 Aug 05:00 – shock +sheath
2. 06 Aug 05:00 – 06 Aug 22:00 - small-sized MC (3h, 0.03 AU) + sector boundary
3. 06 Aug 22:00 – 08 Aug 09:00 - Non-cloud ICME (ejecta)

Bounding of SW ion disturbances with coronal sources using the ballistic model

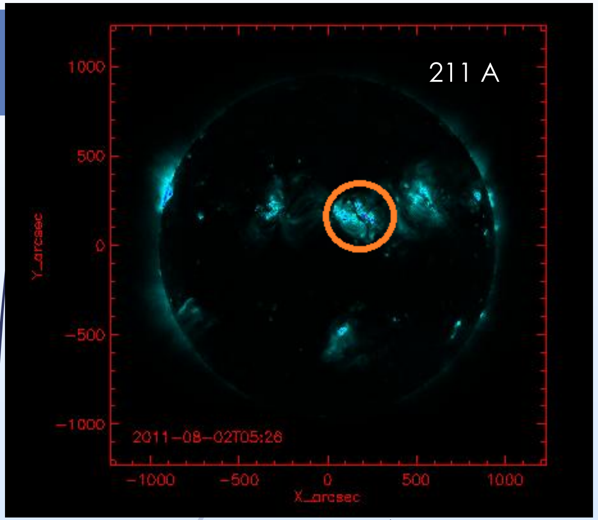


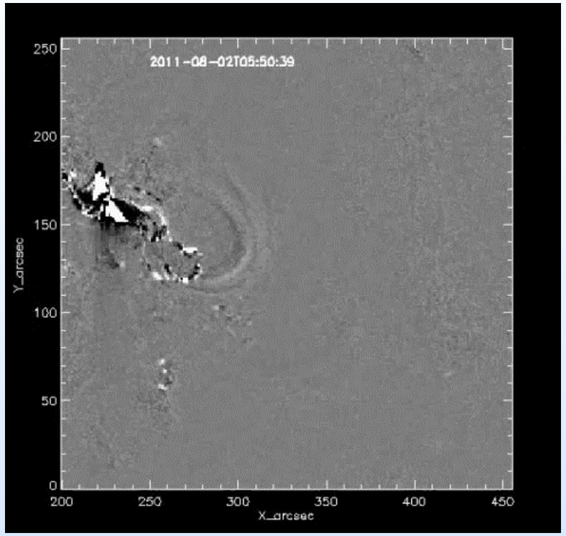
$dT = L_{SE} / \langle V_{CME} \rangle$

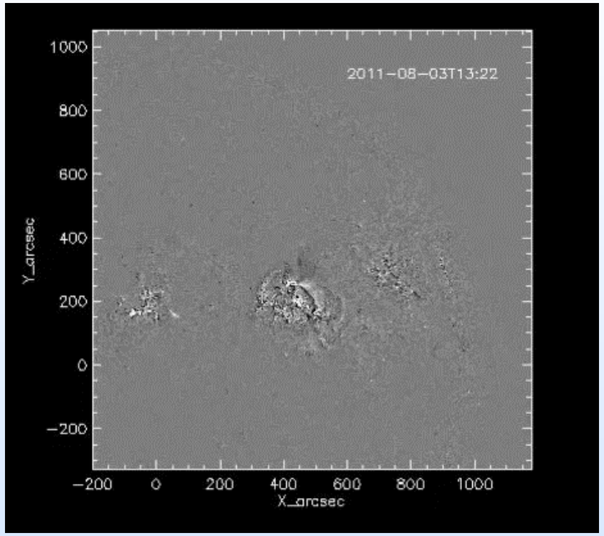


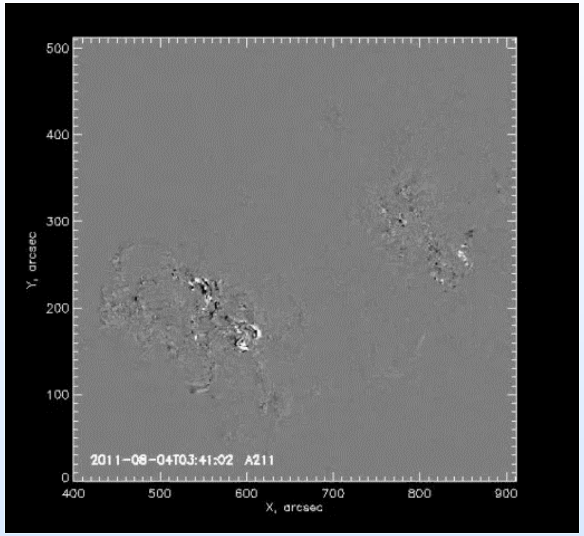
3 flares in AR 11261

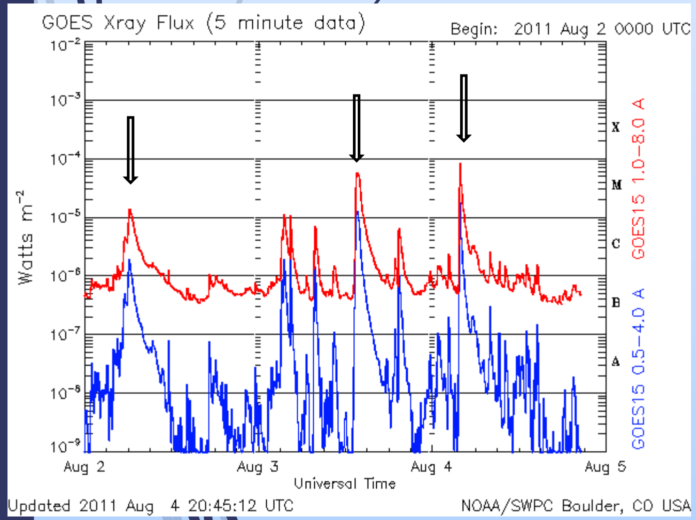
02 Aug 2011 03 Aug 2011 04 Aug 2011



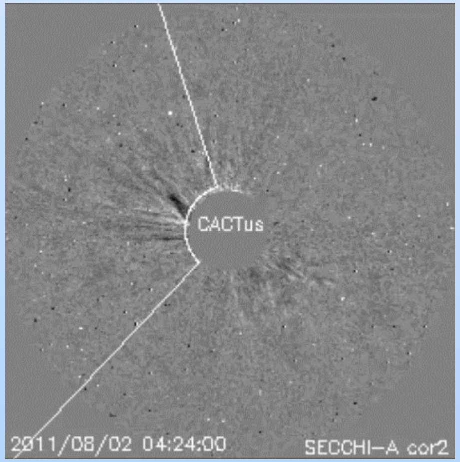


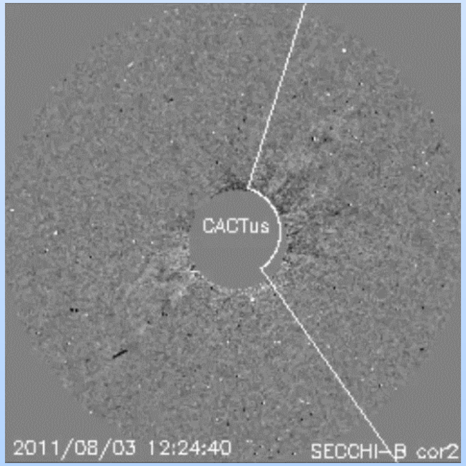


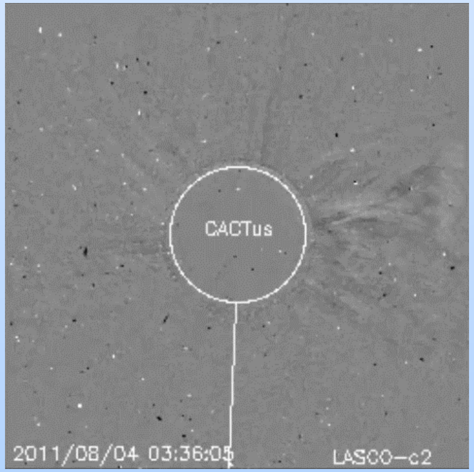




Flares 05:26UT M1 13:24 UT M6 03:41UT M9







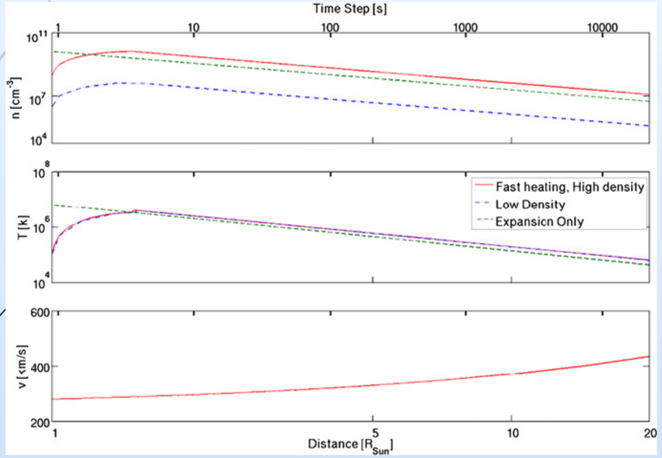
CME STA 02.08 06:36UT
(Cactus) Partial Halo

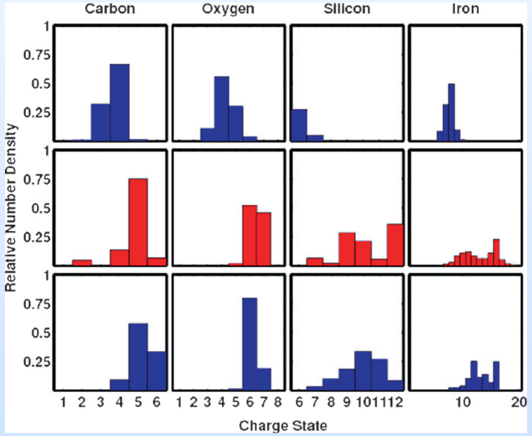
STB 03.08 14:00UT
Halo

LASCO 04.08 04:12UT
Halo

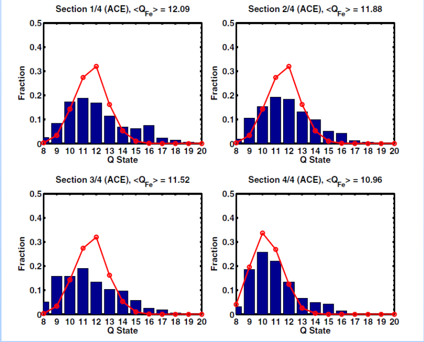
Models of the CME plasma evolution during the acceleration stage in the corona

Guesbeck et al. ApJ 2011: a model of CME evolution at 2 – 5Rsun: initial heating by compression of flare reconnection jets adiabatic expansion and cooling

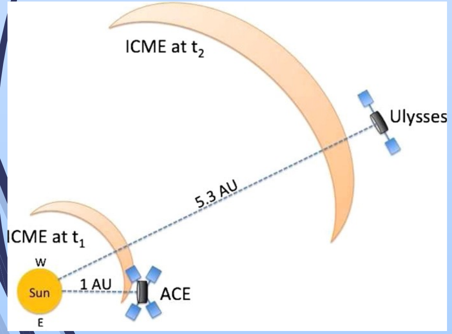




Fe ion state by ACE (bars) and model (red)

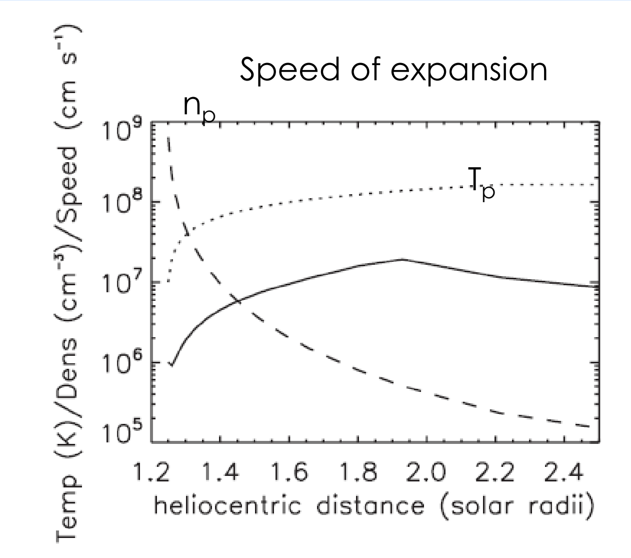


Lepri et al. ApJ 2012: modeling of the CME ion plasma composition in the event of January 21, 2005 observed by ACE at L1 and by Ulysses at 5.3 AU.



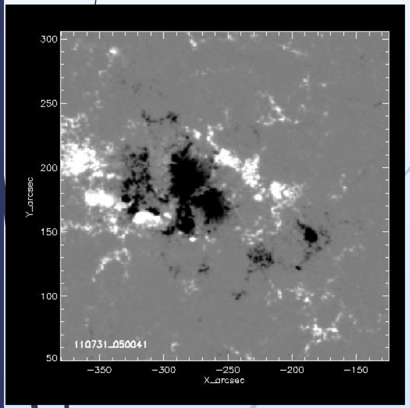
The heating flux is taken in proportion to the increase of kinetic energy with Q= 0.25 – 0.5

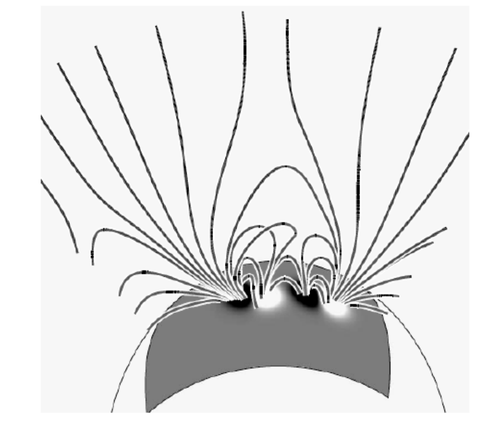
Laming (2004)
Laming, Lepri (2008)

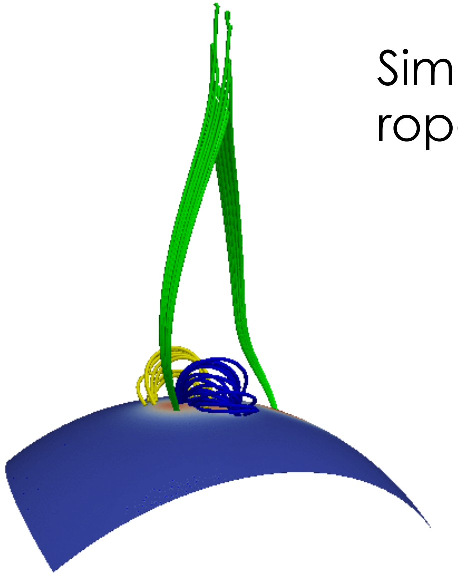


MHD modeling of flux rope

Global Non-Linear Force-Free Field (GNLFFF) model with MHD (MPI-AMRVAC) code







Simulation flux rope ejection

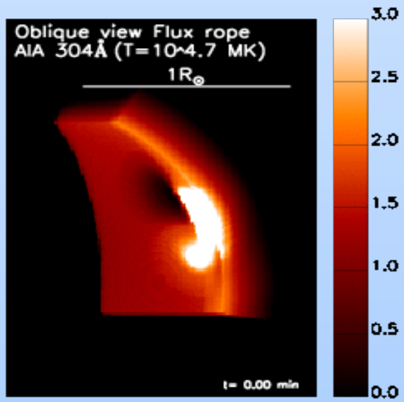
the GNLFFF model is based on the HMI map

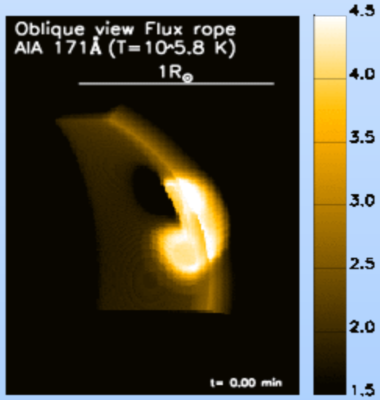
Pagano, P. et al., 2014,A&A,568A,120P

Pagano, P. et al., 2013,A&A,560A, 38P

Pagano, P. et al., 2013,A&A,554A, 77P

Testing of the model by synthesise AIA/SDO observations:





MHD Equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0,$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v}) + \nabla p - \frac{(\vec{\nabla} \times \vec{B}) \times \vec{B})}{4\pi} = +\rho \vec{g},$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{v} \times \vec{B}) = 0,$$

$$\frac{\partial e}{\partial t} + \vec{\nabla} \cdot [(e+p)\vec{v}] = \rho \vec{g} \cdot \vec{v} - \mathbf{n}^2 \chi(\mathbf{T}) - \nabla \cdot \vec{\mathbf{F}}_{\mathbf{c}},$$

$$\nabla \cdot \vec{B} = 0$$

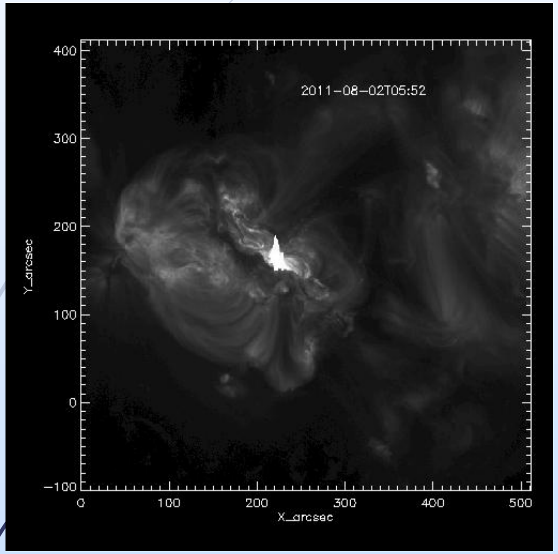
$$\frac{p}{\gamma - 1} = e - \frac{1}{2} \rho \vec{v}^2 - \frac{\vec{B}^2}{8\pi},$$

$$\vec{g} = -\frac{GM_\odot}{r^2} \hat{r},$$

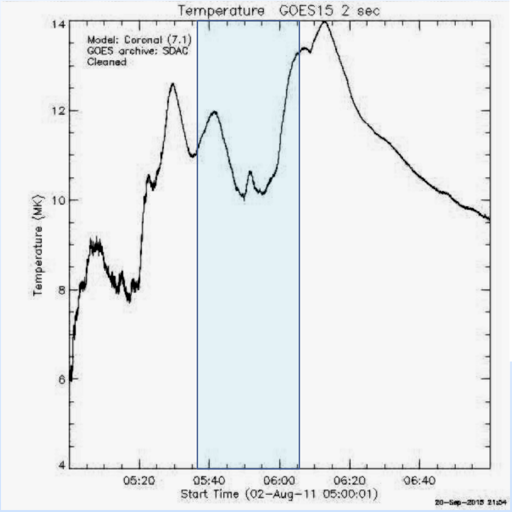
Diagnostics of plasma in the flare and ejecta

(2 August 2011)

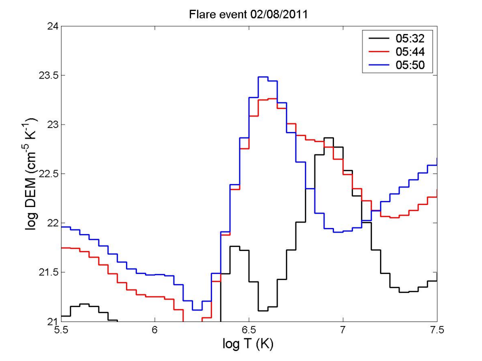
Flare 05:19 - 06:48UT



GOES temperature



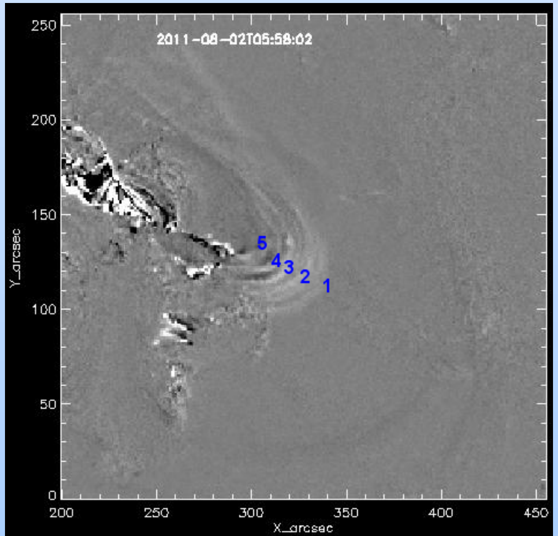
Diagnostics by EUV lines of AIA

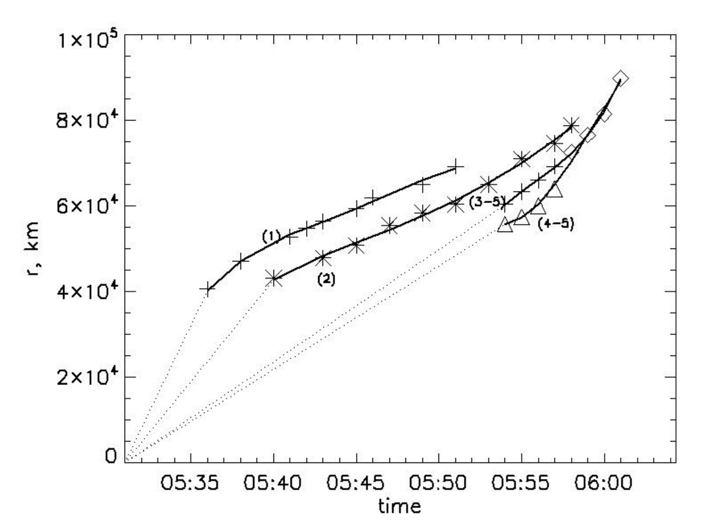


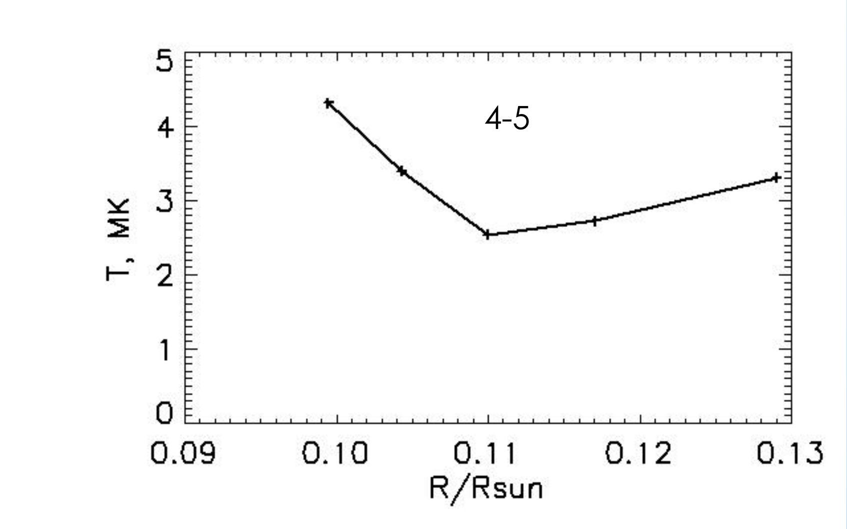
Time	Teff , MK	ne , cm^(-3)
05:32	9.12	1.53E9
05:44	7.31	2.48E9
05:50	7.19	2.40E9

$$F_i = \int_{\Delta T} R_i(T) \cdot DEM(T) dT$$

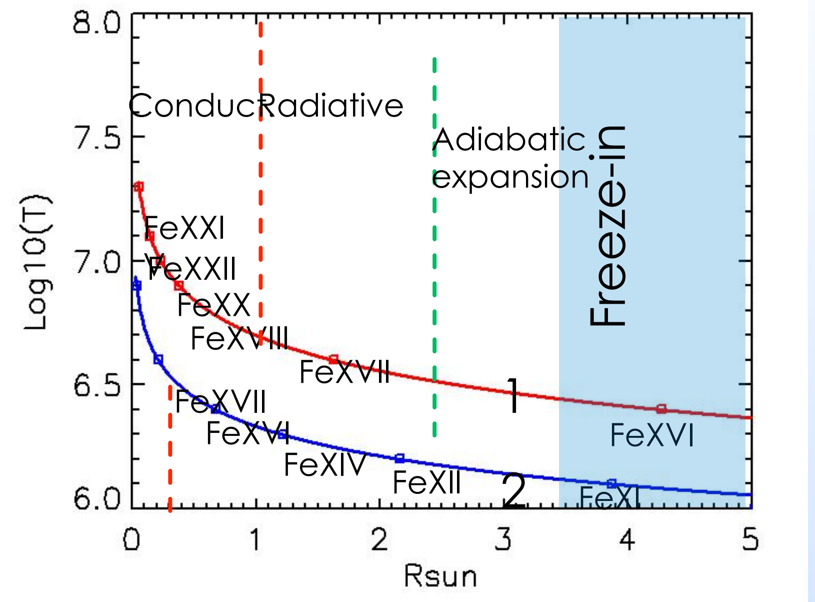
$$T_{eff} = \frac{\int_{\Delta T} T \cdot DEM(T) dT}{\int_{\Delta T} DEM(T) dT}$$

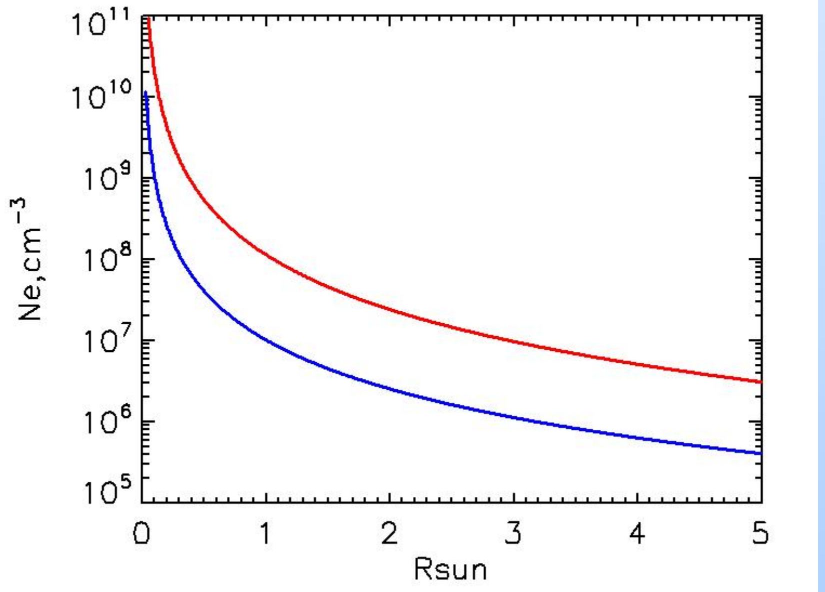






Evolution of the Fe ion charge state of SW transients in the corona





Distance from the solar surface

1) medium flare+CME event

T_{max}=20 MK, $N_{e\ max}=10^{11} cm^{-3}$, V_{CME}=1000 km/s

2) small-scale flare +CME event

T_{max}=10MK, $N_{e\ max}=10^{10} cm^{-3}$, V_{CME}=100 km/s

Model

1. $\tau_{recomb} < \tau_{cooling}$
2. $N_e \sim 1/R^2$
3. $t_{exp} \approx L_{freeze\text{-}in} / \langle V_{CME} \rangle$ (boundary $t = L_{SE}/V_{SW}$)
4. Plasma move in the corona with constant acceleration

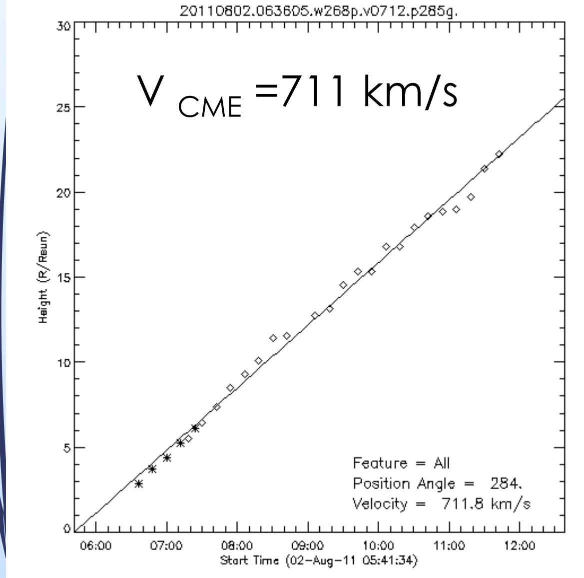
Cooling processes

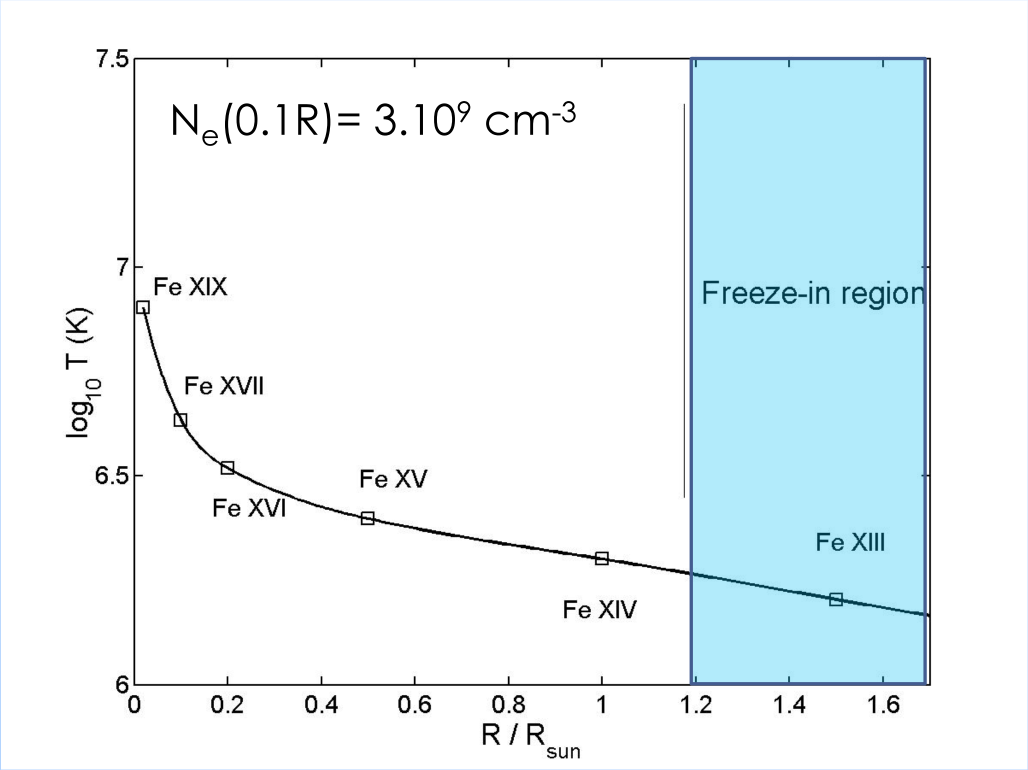
conductive $T(t)=T_1(1+t/\ \tau_{cond})^{-2/5}$, $\tau_{cond} \sim Ne/T^{5/2}$

radiative $T(t)=T_1(1-t/\ \tau_{rad})^{3/5}$, $\tau_{rad} \sim T^{5/3}/Ne$

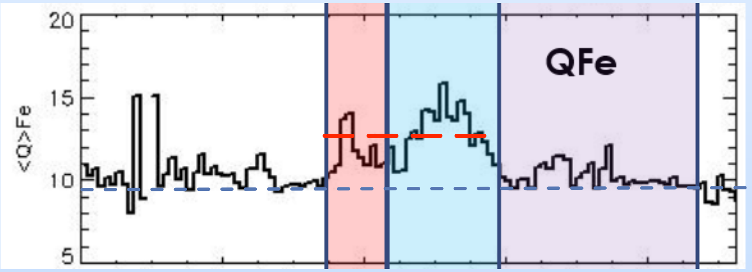
adiabatic expansion $T \sim N_e^{\gamma-1} = 1/R^2 = (\int V(t)dt)^{2(1-\gamma)}$

Evolution of the Fe-ion charge state in the plasma of forming CME of 2 August 2011





In situ
<Qfe> ≈ 13



$$R_{Freeze} \propto \sqrt{\frac{n_0 \sigma_{rec}}{V_{CME}}}$$

Conclusions

1. In the current Cycle 24 coronal sources of the most frequent and geoeffective ICMEs are associated with flares and CMEs from ARs (SW types MC, MC+SH, SH) providing more than 70% events with Dst <-40 nT.
2. In Cycle 24 the ion charge ratios C6/C5, O7/O6 and QFe in ICMEs are less than in Cycle 23 due to colder coronal plasma.
3. Analysis of ion composition is very important because it enables to link physically the SW disturbances with their coronal sources, thus, providing new possibilities for the earliest forecast of geomagnetic storms.

Future tasks

Implementation the MHD simulation the flux robe/ejecta propagation in the corona for the August 2011 event

- Simulation the ion charge distributions and comparison with the measurements in situ
- Analysis of the ion composition for all ICMEs of Cycle 24 from the ISEST Master list