HORIZON 2020 'HESPERIA' Project: High-Energy Solar Particle Events Forecasting and Analysis

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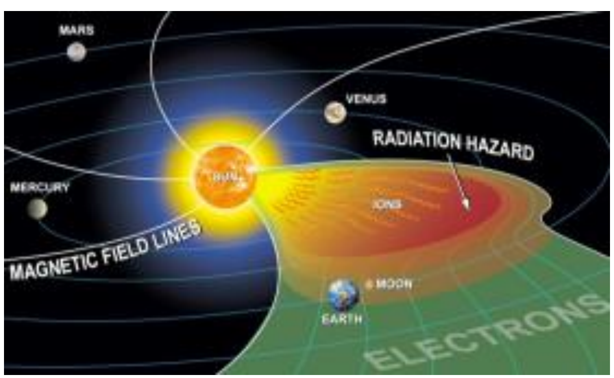

The 12th Hellenic Astronomical Conference

SEPServer: Data Services and Analysis Tools for SEP Events and Related EM Emissions

COMESEP: Coronal Mass Ejections and Solar Energetic Particles: Forecasting the Space Weather Impact

National Observatory of Athens (NOA)

INSTITUTE FOR ASTRONOMY, ASTROPHYSICS, SPACE APPLICATIONS & REMOTE SENSING
(formerly INSTITUTE OF ASTRONOMY & ASTROPHYSICS)
National Observatory of Athens

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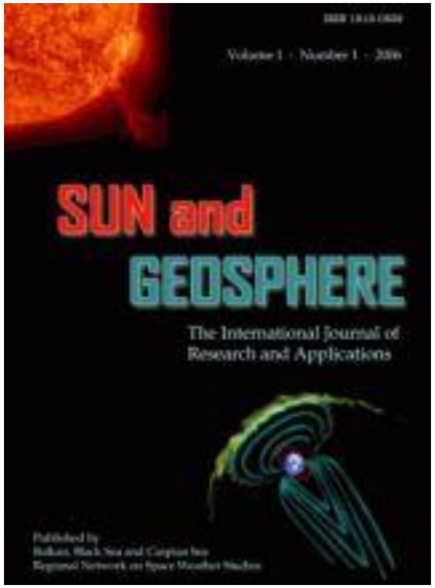
Review of Space Weather research – SEP Perspective- at NOA in Greece within SEPServer & COMESEP

Olga E. Malandraki,
Sun and Geosphere, 10, 21-30, 2015



Balkan, Black Sea and Caspian Sea Regional Network for Space Weather Studies (BBC SWS Regional Network)

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Space Weather Research in Greece: The Solar Energetic Particle Perspective

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Abstract. Space Weather Research carried out in the National Observatory of Athens (NOA), within the SEPServer and COMESEP projects under the Seventh Framework Programme (FP7-SPACE) of the European Union (EU) is presented. Results and services that these projects provide to the whole scientific community as well as stakeholders are underlined. NOA strongly contributes in terms of crucial Solar Energetic Particle (SEP) dataset provided, data analysis and SEP catalogue items provided as well as comparative results of the various components of the project server, greatly facilitating the investigation of SEPs and their origin. SEP research highlights carried out at NOA are also presented, used to test and validate the particle SEP model developed and incorporated within the SEP forecasting tools of the COronal Mass Ejections and Solar Energetic Particles (COMESEP) Space Weather Alert System, i.e. the First European Alert System for geomagnetic storms and SEP radiation hazards.

Keywords: Solar eruptive events, Solar Energetic Particles, Coronal Mass Ejections, solar flares, Space Weather Alerts

Introduction

Solar Energetic Particle (SEP) events are a key ingredient of solar-terrestrial physics both for fundamental research and space weather applications. SEP events, are the defining component of solar radiation storms, contribute to radio blackouts in polar regions and are related to many of the fastest Coronal Mass Ejections (CMEs) driving major geomagnetic storms. In addition to CMEs, SEP events are also related to flares (e.g. Reames, 2013). The occurrence rate of large, space-weather relevant SEP events is about 100 per solar cycle, with a broad distribution in time that extends well into the declining phase of the activity cycle as traced by the sunspot index.

The SEPserver and COMESEP projects have been two three year collaborative projects funded under the Seventh Framework Programme (FP7-SPACE) of the European Union (EU) and coordinated by the University of Helsinki in Finland and the Belgian Institute for Space Aeronomy in Belgium, respectively. NOA in Greece participates as a Collaborating Partner in both the SEPServer and COMESEP projects.

The SEPServer project provides a new tool, which greatly facilitates the investigation of SEP events and their origin. This is achieved via an internet server (http://server.sepserver.eu) which gives access to a large number of SEP datasets from different instruments onboard several missions, to Electromagnetic (EM) observations related to the events identified from the SEP data and to state-of-the art analysis tools that can be used to infer the solar SEP emission time profiles and events. It also led to better understanding of the particle acceleration and transport processes at the Sun and in the inner heliosphere, resulting to SEP events that form one of the key elements of space weather.

The COronal Mass Ejections and Solar Energetic Particles (COMESEP) project has developed tools for forecasting geomagnetic storms and SEP radiation storms. By analysis of historical data, complemented by the extensive data coverage of solar cycle 23, the key ingredients that lead to magnetic storm and SEP events and the factors that are responsible for false alarms have been identified. The structure, propagation and evolution of CMEs have been investigated, enhancing our understanding of the 3-D kinematics and interplanetary propagation of CMEs. In parallel, the sources, acceleration and propagation of SEPs have been examined and modelled. COMESEP is a unique cross-collaboration effort and bridges the gap between the SEP, CME and terrestrial effects scientific communities.

In this paper, we present a review of the Space Weather research, results and contributions from the SEP perspective, carried out at NOA in Greece within the SEPServer and COMESEP projects.

SEPServer SEP Data, Catalogs and Research

In coordination with the Principal Investigator (PI) teams in the US and Europe, NOA directly contributes to SEPServer the electron, ion and heavy ion datasets of the Electron, Proton, and Alpha Monitor (EPAM) (Gold et al., 1998) and the Solar Isotope Spectrometer (SIS) (Stone et al., 1998) instruments onboard the Advanced Composition Explorer (ACE), the particle

HESPERIA

PROTEC-1-2014 'Space Weather'
High Energy Solar Particle Events Forecasting and Analysis

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

✓ **Solar energetic particles (SEPs)** are of prime astrophysical interest, but are also a space weather hazard motivating the development of predictive capabilities.

✓The project is funded through the **European Union's HORIZON 2020** research and Innovation Programme (Contract No 637324) and coordinated by the National Observatory of Athens in Greece **(Project Coordinator: Dr. Olga Malandraki**) .

✓It will combine data and knowledge from **9 European partners** and several collaborating parties from US and Russia.

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ISNet Intelligent Systems Networks

HESPERIA

Team Members

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  Project Coordinator
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- **Rami Vainio [Turun Yliopisto, UTU, Finland]**
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- Galina Bazilevskaya [Lebedev Physical Institute of Russian Academy of Sciences, Moscow, Russia]
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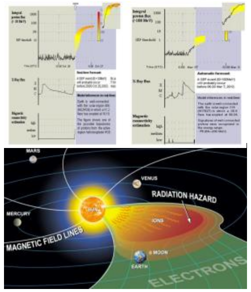
HESPERIA

WP1

leader NOA

MANAGEMENT

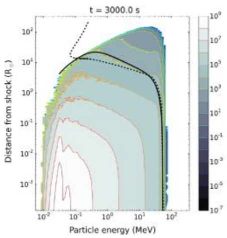
WP2



leader UMA

FORECASTING OF SOLAR RADIATION STORMS

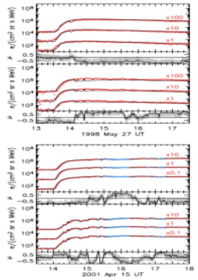
WP3



leader UTU

MODELING OF SHOCK-ACCELERATED EVENTS

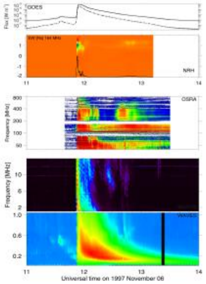
WP4



leader UB

INVERSION METHODS

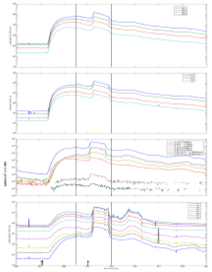
WP5



leader OBSPARIS

SCIENTIFIC DATA ANALYSIS: GAMMA-RAYS, RADIO SEPS

WP6



leader NOA

SEP RADIATION IMPACT

WP7

leader ISNet

SERVER DEVELOPMENT

WP8

leader NOA

DISSEMINATION AND EXTERNAL COORDINATION

The HESPERIA 'High Energy Solar Particle Events Forecasting and Analysis' project will:

✓ **produce two novel forecasting tools** based upon proven concepts **(UMASEP, REleASE).**

✓ **advance our understanding of the physical mechanisms** that result into high-energy solar particle events (SEPs) exploiting novel datasets **(FERMI/LAT/GBM; PAMELA; AMS)**

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Facts & Figures:

✓ The project has just started on **May 1, 2015** and will last **24 months**.

The most significant milestones are planned as follows:

- **The first forecasting results published via the Consortium Server in May 2016**
- **The results on the SEP simulation modelling for Fermi/LAT events as well as the inversion software for GLE events will be posted online in October 2016.**
- **The web-based front-end of the four SEP prediction tools will be released in the HESPERIA Server in April 2017**

✓A **scientific Workshop**, open to the community, **on SEP event analysis** will be organised in Paris in Fall 2016

✓ In addition the consortium will provide **educational** and **outreach material** on solar eruptions and space environment on its website

‘HESPERIA’

Kick-Off Meeting, Athens 21-22 May 2015

HESPERIA team at NOA

- Prof. Kanaris Tsinganos, President of NOA
- Dr. Olga Malandraki, Member of staff , Scientist, (PI, Team Leader, Coordinator)
- Dr. Georgia Tsiropoula, Researcher A', Member of Staff
- Dr. Gerry Share, Research Associate
- Dr. Rositsa Miteva, Postdoctoral Researcher
- Vangelis Argoudelis, financial-legal support manager
- Nikolaos Milas, Research Support Dept. (server)
- Eleni Christia, Dissemination & Public Outreach (WP8)

HESPERIA Overall Objectives

1. To develop two novel SEP forecasting systems based upon proven concepts (UMASEP, REleASE)

2. To develop SEP forecasting tools searching for electromagnetic proxies of the gamma-ray emission in order to predict large SEP events

3. **To perform systematic exploitation of the novel high-energy gamma-ray observations of the FERMI mission together with in situ SEP measurements near 1 AU**

HESPERIA Overall Objectives

4. To provide for the first time publicly available software to invert neutron monitor observations of relativistic SEPs to physical parameters that can be compared with the space-borne measurements at lower energies.

5. To perform examination of currently unexploited tools (e.g. Radio emission)

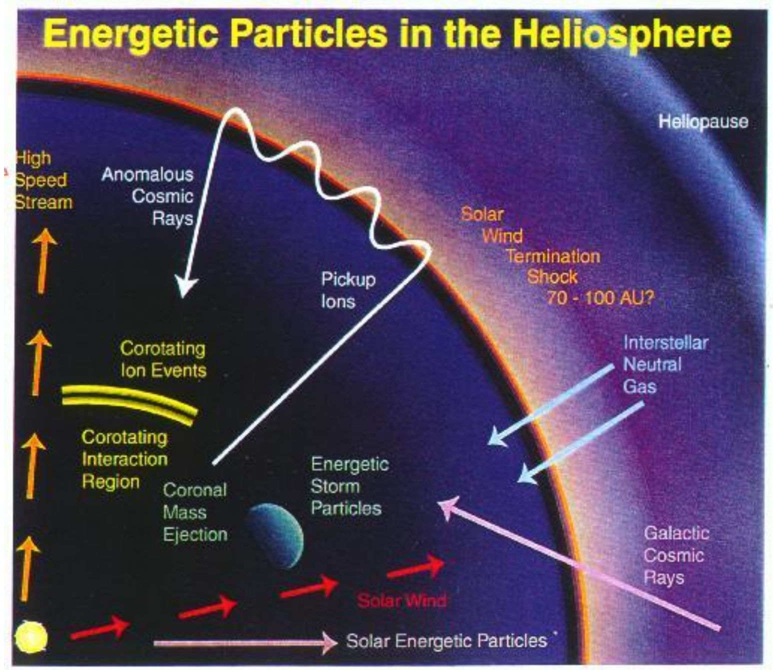
6. To design recommendation for future SEP forecasting systems.

All results will be openly accessible to the public through the dedicated web interface of HESPERIA

Acknowledgement:

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 637324.

On the role of local CIR-associated particle acceleration in the formation of time-intensity profiles of suprathermal particle fluxes



Collaborators

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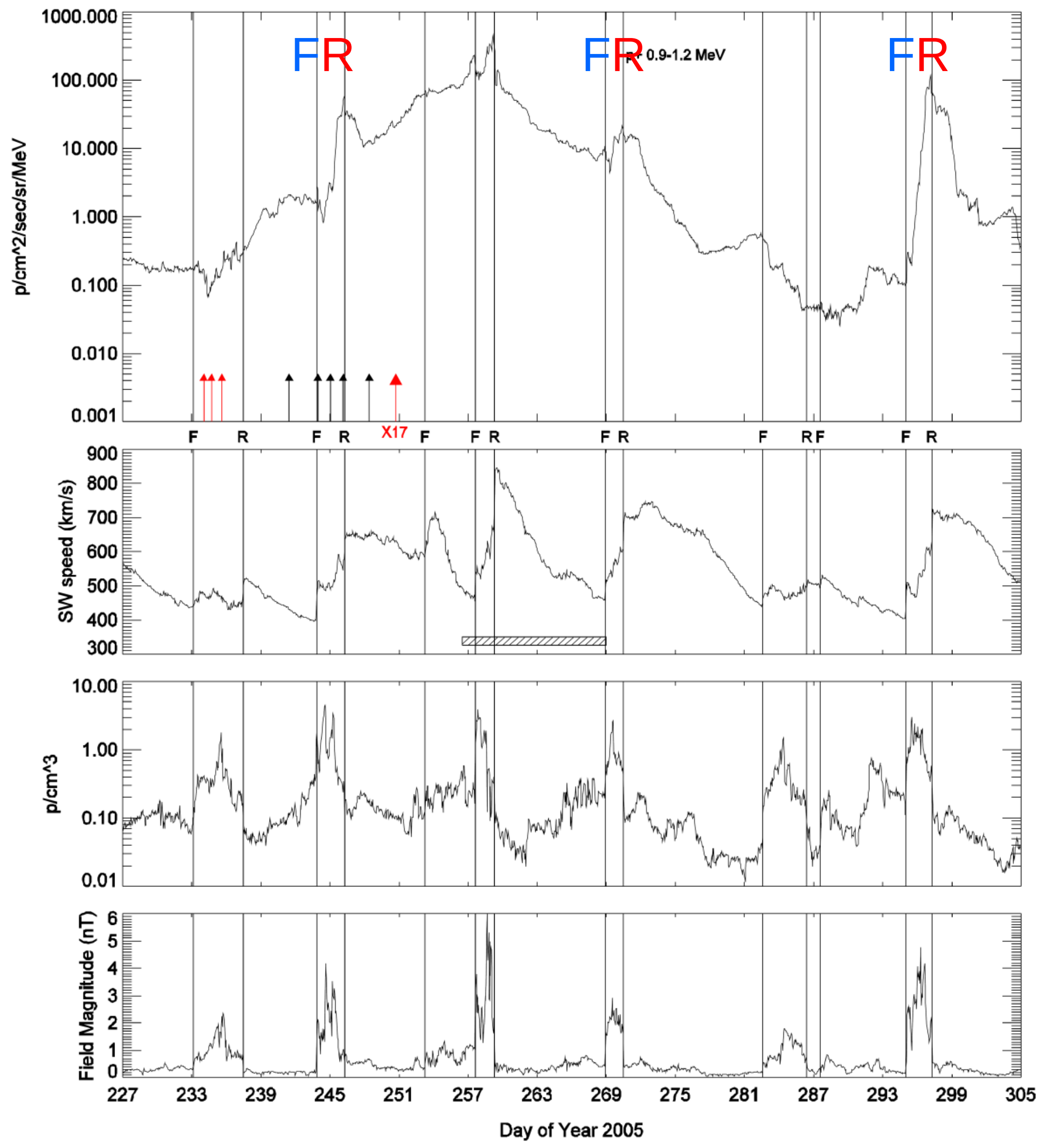
Ulysses @~ 5 AU near the ecliptic plane

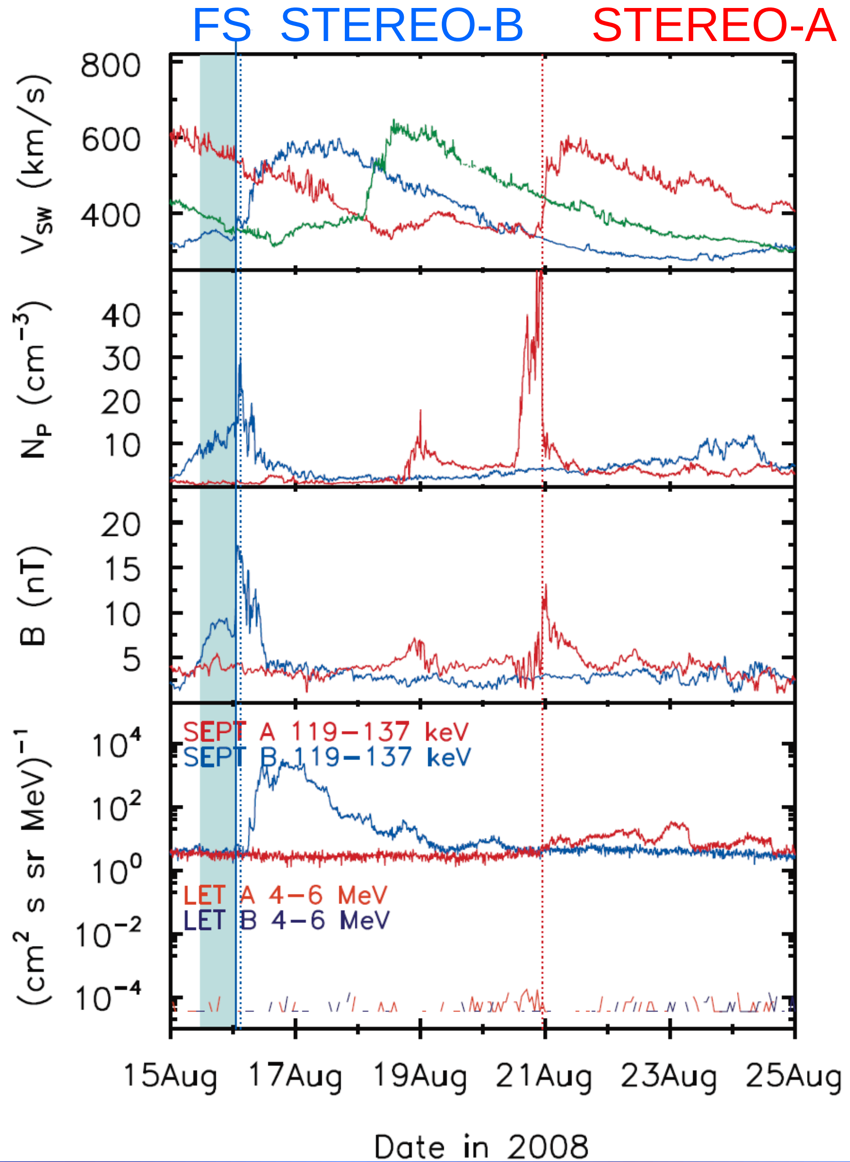
The more intense and longer duration CIR MeV/n ion enhancements typically associated with the REVERSE SHOCK

Malandraki et al. 2008, Ann. Geophys.



STEREO-B & STEREO-A

CIR observations in August 2008



Shock fronts of CIRs:
Main source of energetic particle enhancements observed at 1 AU

Observations also showed evidence for particle acceleration in the vicinity of the s/c @ 1 AU

Gomez-Herrero, Malandraki, et al. 2011, JASTP

In this work:

- ***We explore the role of local CIR-associated particle acceleration in the formation of time-intensity profiles of suprathermal particle fluxes***

- ***We investigate whether the bounding of the Heliospheric Current Sheet (HCS)- associated <u>magnetic islands</u> by the HCS from one side and the CIR front from the other side (which also contains <u>local current sheets</u>) may produce significant particle acceleration***

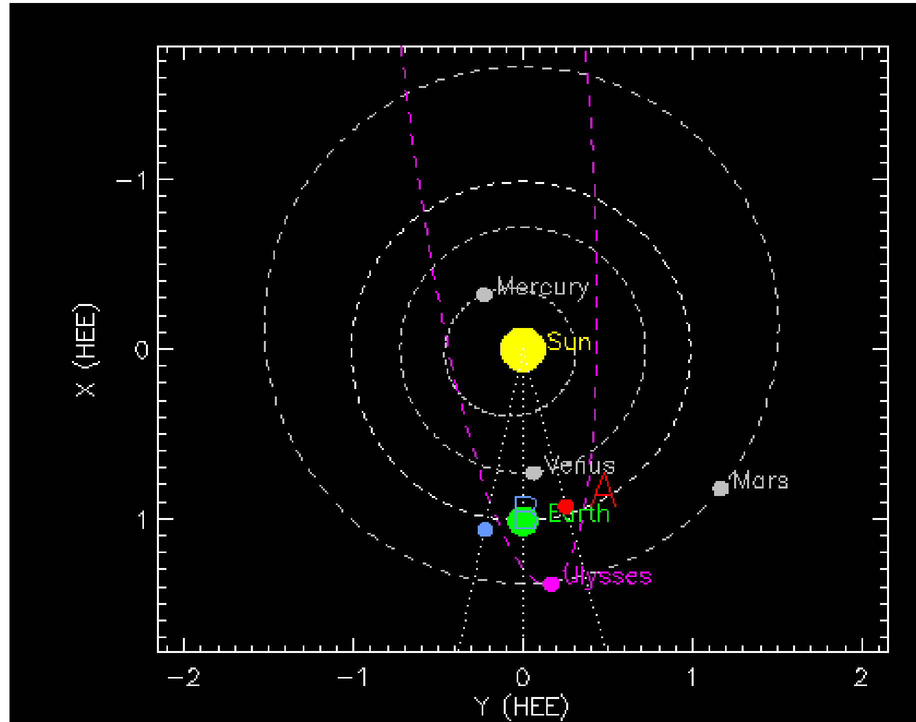
Analysis of the CME- and coronal hole-originating CIRs interaction with the HCS on 25 August – 2 September, 2007 from five(!) spacecraft (STEREO A and B, Wind/ACE and Ulysses).

Coordinates of **STEREO A, B** are given in the figure; **Ulysses** was at 1.4AU, ~10 deg. above the ecliptic plane

The sequence of the HCS crossings was as follows:

STEREO-B – WIND/ACE – STEREO A - Ulysses

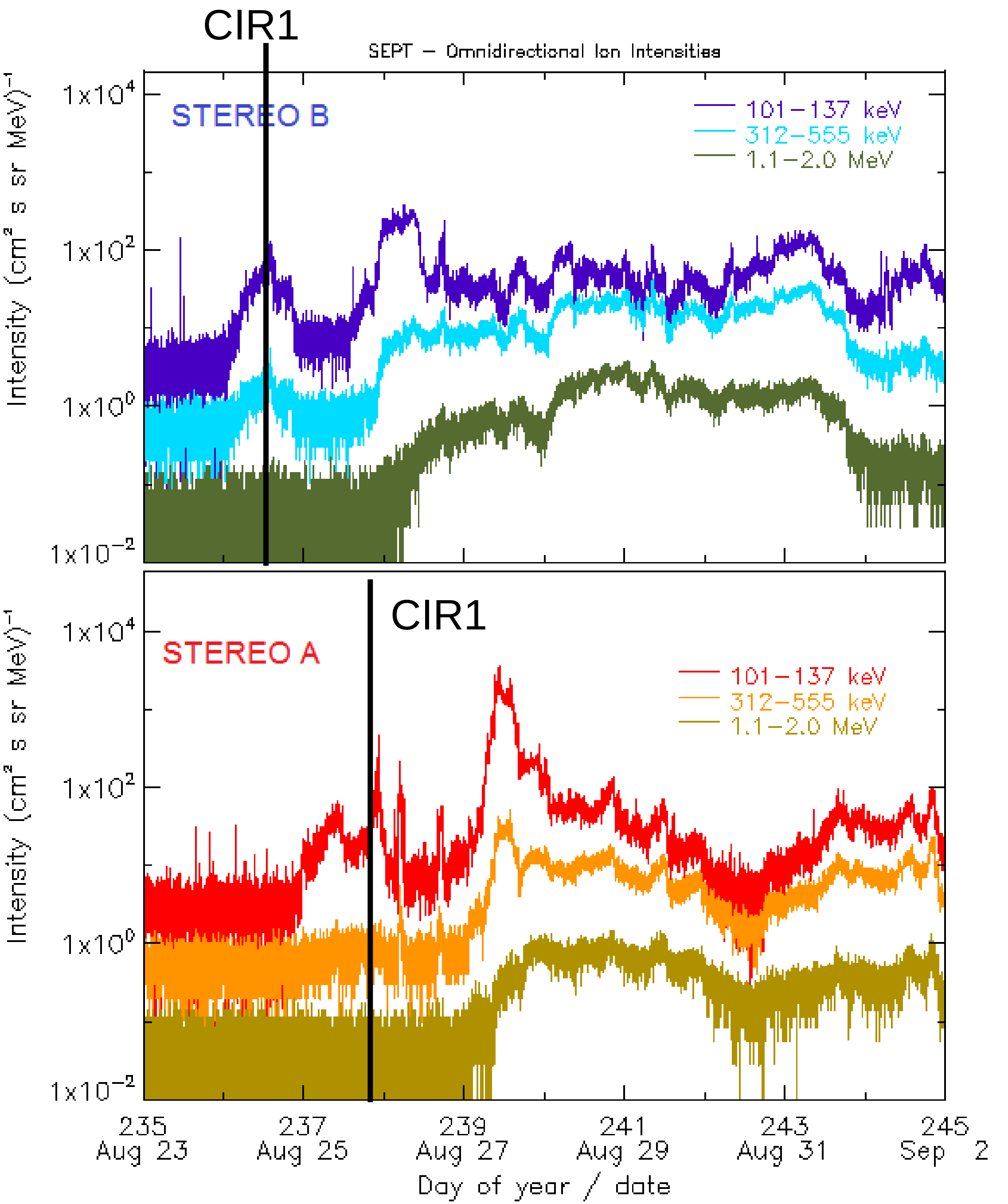
STEREO A: one ICME *http://www-ssc.igpp.ucla.edu/~jlan/STEREO/Level3/STEREO_Level3_ICME.xls*, but WIND and STEREO B observed a sequence of CIRs. Ulysses registered CIRs, with a shock ahead.



	STEREO-B	Earth	STEREO-A
Heliocentric distance (AU)	1.083854	1.010724	0.957888
Semidiameter (arcsec)	885.385	949.446	1001.816
HCI longitude	244.487	256.431	271.896
HCI latitude	6.470	7.052	7.339
Carrington longitude	197.356	209.299	224.765
Carrington rotation number	2060.452	2060.419	2060.376
Heliographic (HEEQ) longitude	-11.943	0.000	15.465
Heliographic (HEEQ) latitude	6.470	7.052	7.339
HAE longitude	320.427	332.301	347.646
Earth Ecliptic (HEE) longitude	-11.874	-0.000	15.345
Earth Ecliptic (HEE) latitude	-0.082	-0.000	0.091
Roll from ecliptic north	-0.387		-0.330
Roll from solar north	-3.504		-0.091
Light travel time to Earth (min)	1.901		2.229
Separation angle with Earth	11.874		15.346
Separation angle A with B		27.220	

The energetic particle flux increases observed by the STEREO pair looked different. These were not SEP events due to flares or ICMEs, **but flux enhancements related to CIRs**. As we will show later, CIRs originated from (1) long-lived low-latitude coronal hole, and (2) a weak CME that did not hit the Earth directly.

The interesting aspect of this event is that **the energetic particle flux enhancements were observed both before the first CIR's approach and between two CIRs.**

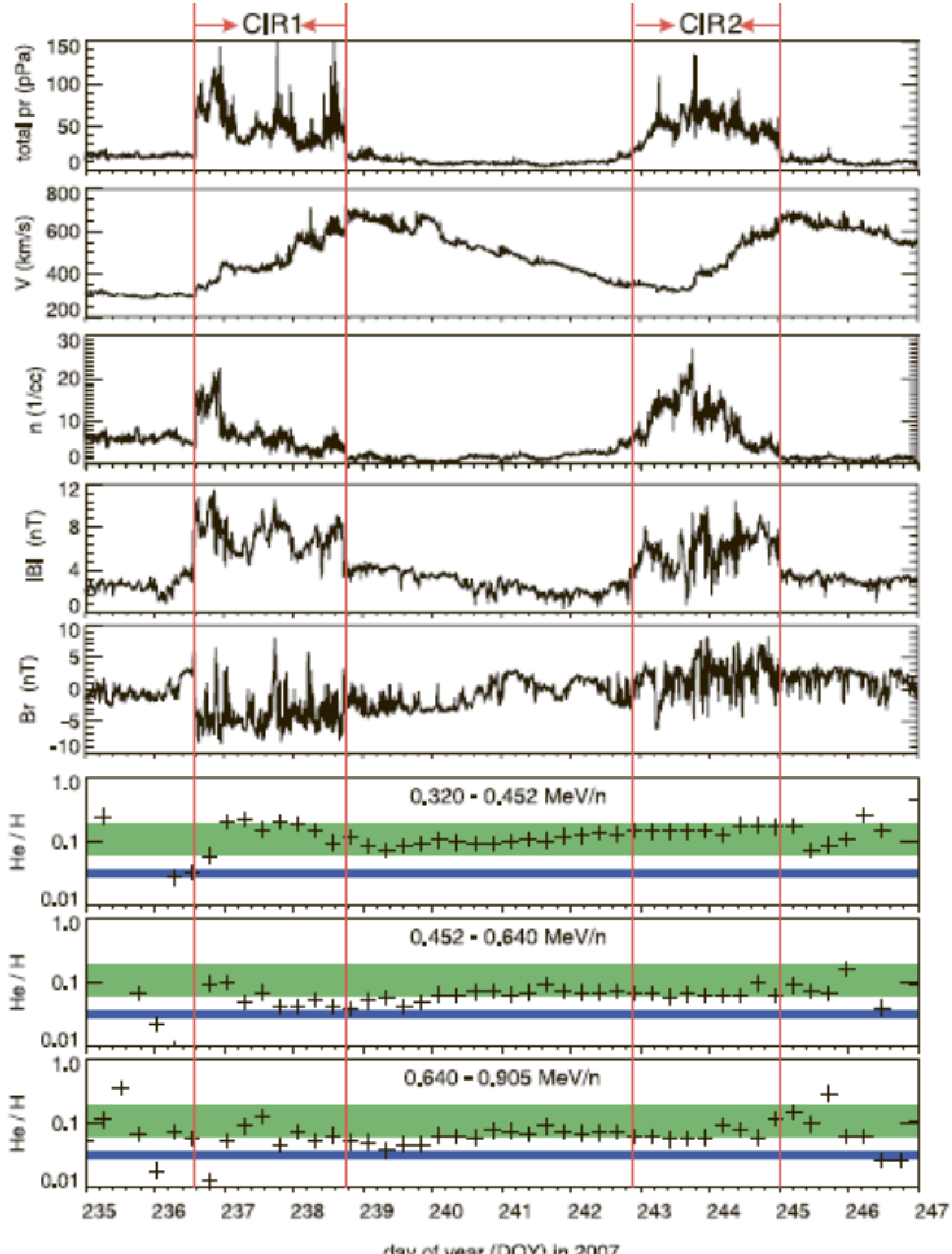


STEREO-B – WIND/ACE –

- STEREO A - Ulysses

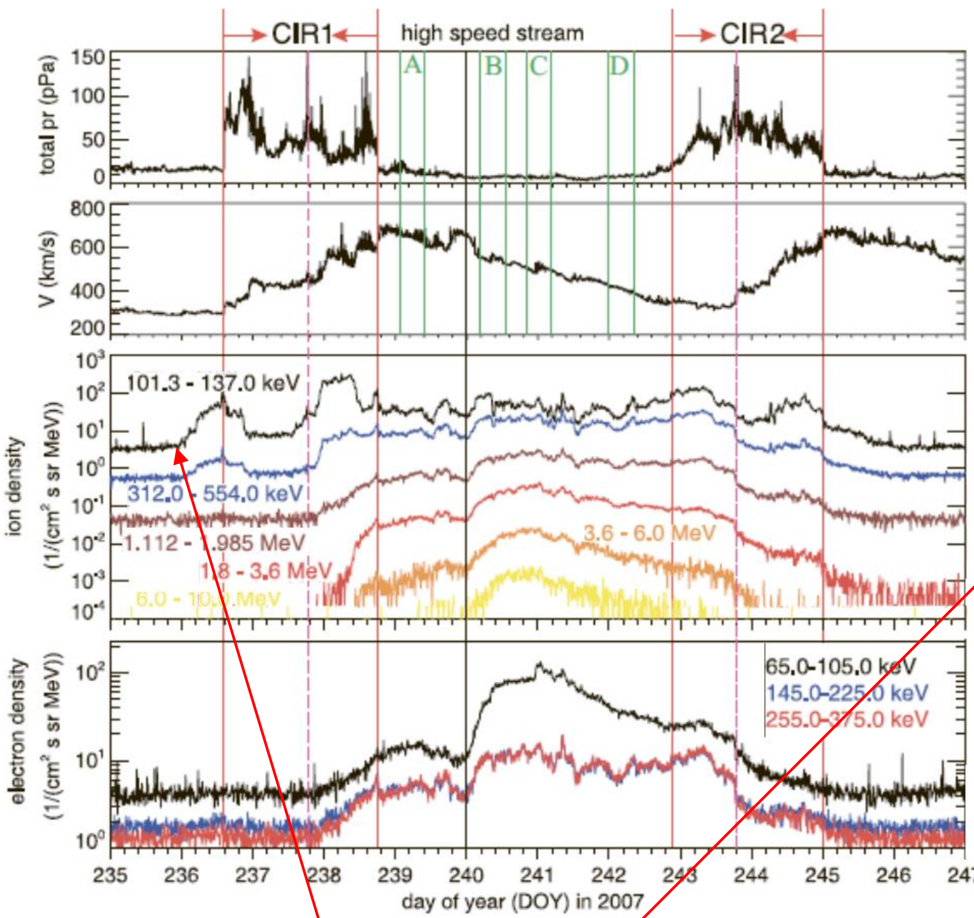
STEREO B observed two consecutive CIRs. Signatures of the HCS crossing are seen one day before CIR1, but the Wu et al. work ignored this earlier HCS observations.

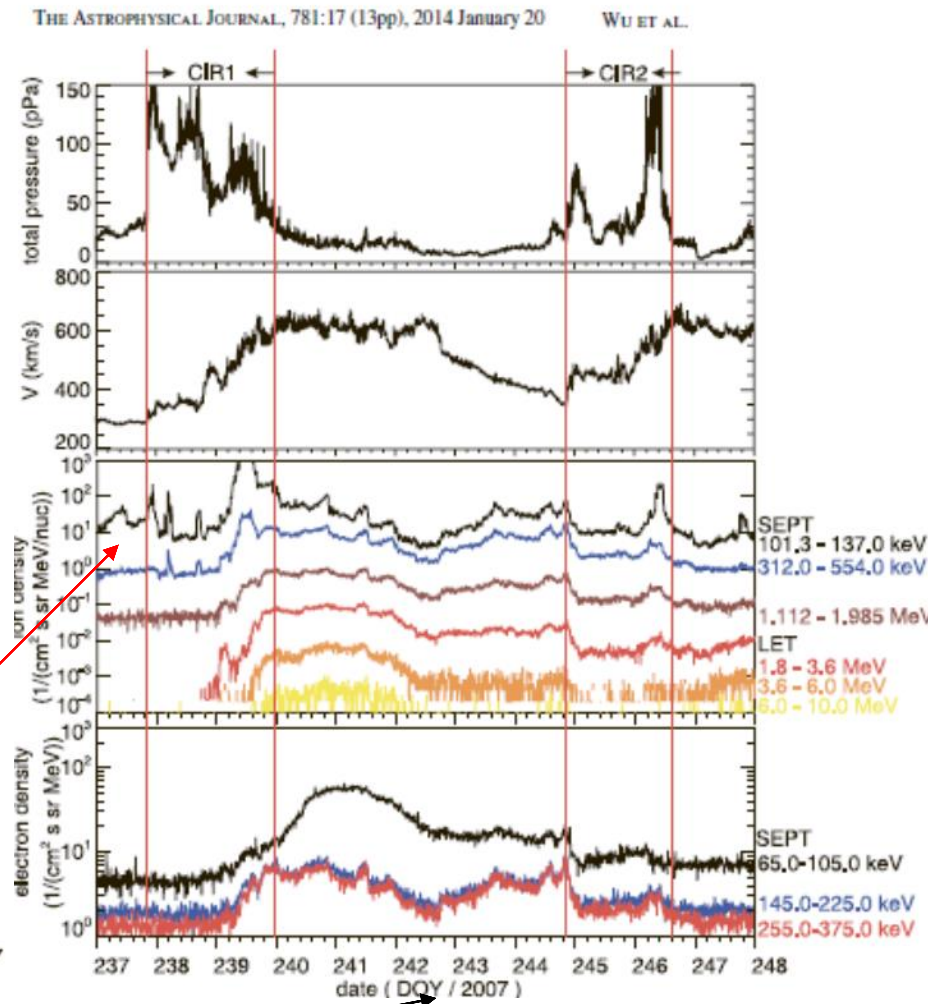
Z. Wu et al. Observations of energetic particles between a pair of corotating interaction regions. The Astrophysical Journal, 781:17 (13pp), 2014



STEREO B

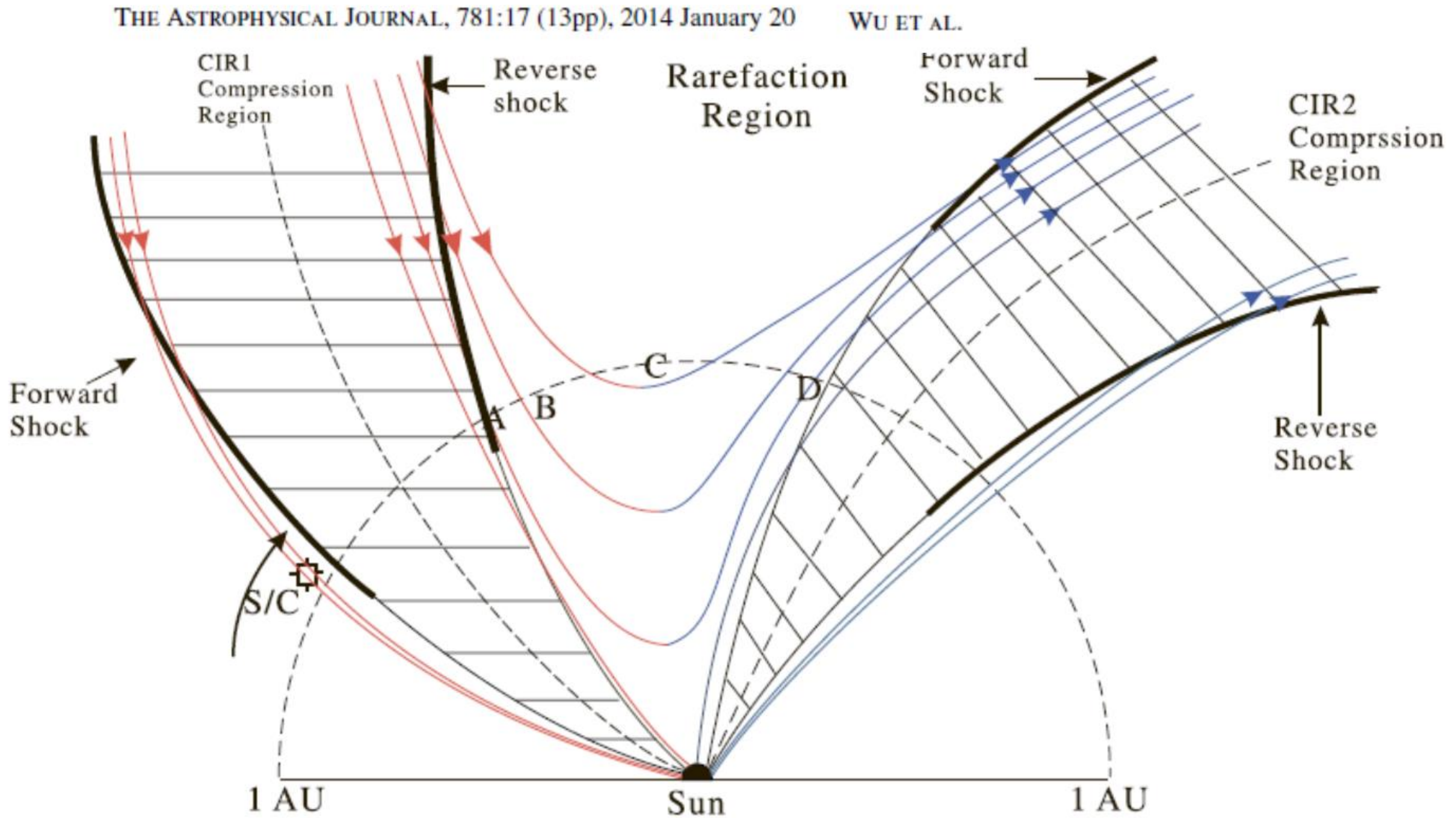
STEREO A





Wu et al.

Energetic particle flux increases observed between CIR1 and CIR2. Additionally, there were unexplained smaller-scale flux enhancements before CIR1.



Interpretation by Wu et al. is classic:

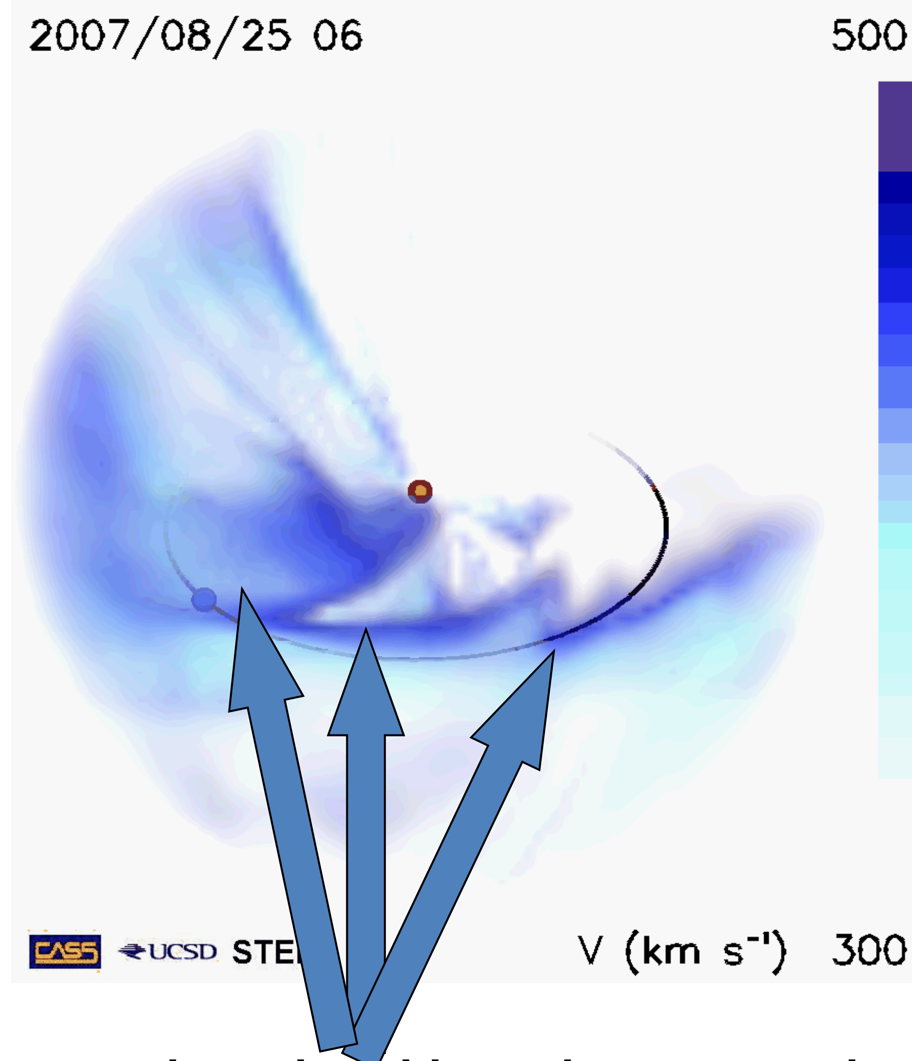
there were two couples of forward/reverse shocks in the U-shape system of CIRs with the curved-inward IMF lines. Particles are accelerated by reflection from the shocks.

Problem of the interpretation: the rarefaction region corresponds to the high-speed solar wind stream that does not allow such a configuration of the IMF lines. The high-speed streams make IMF lines more radial, and the quasi-local lines' bending would be swept out from such a U-shape configuration.

Our interpretation:

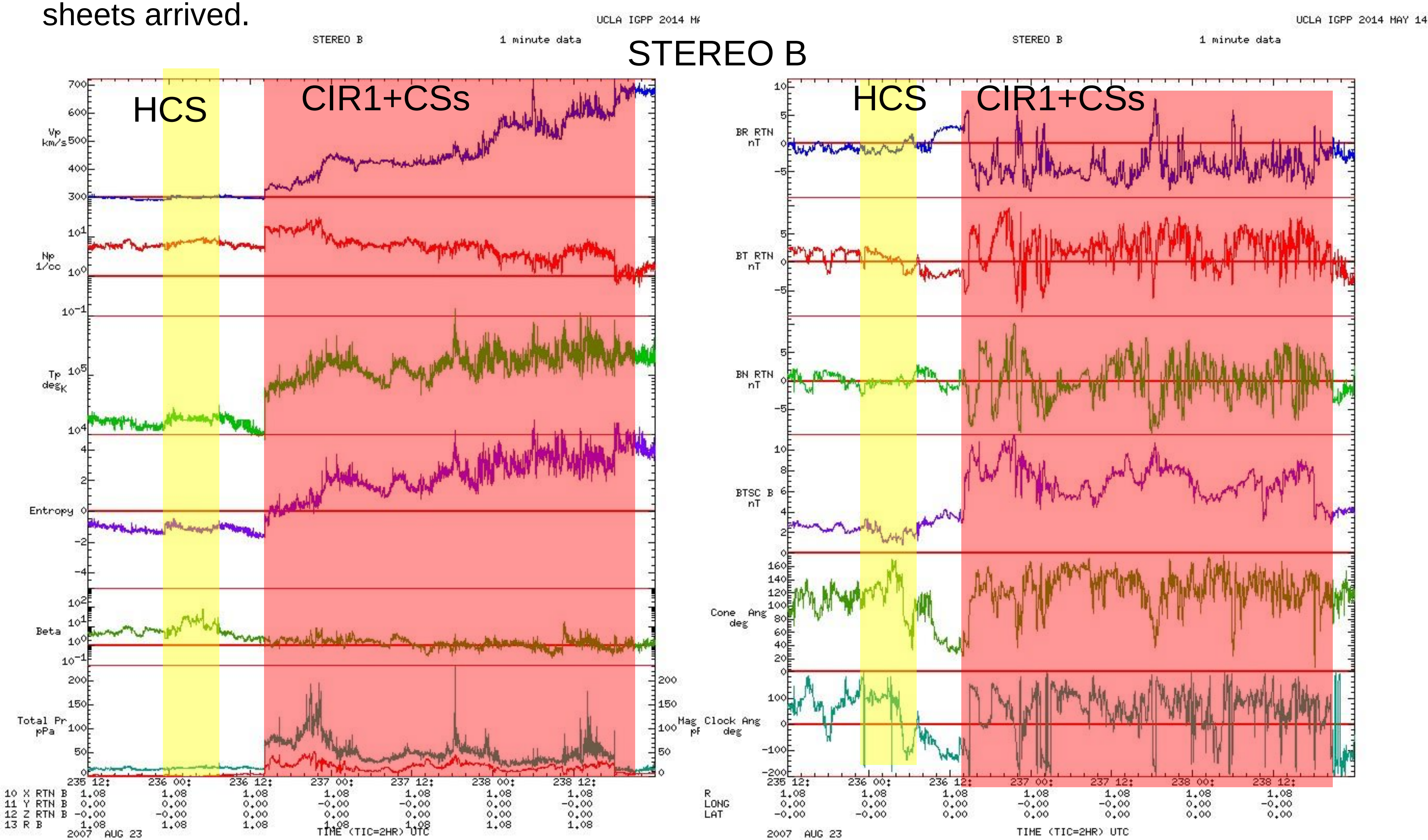
1) According to **STEL observations**, there were several **nabla-shaped** cavities formed by the sequence of streams from **coronal holes and CMEs. This led to plasma confinement between the heliospheric current sheet (HCS) and current sheets belonging to CIRs.** Details will be shown later.

2) The HCS and strong local current sheets together with magnetic islands localized inside the ∇ -shaped cavities played a significant role in particle acceleration, which was local.



∇-shaped cavities, where magnetic islands (observed in situ) are confined by walls of CIRs and the crumpled HCS

The HCS crossing occurred on 24 August 2007 (see the clock angle behaviour in the “Magnetic field” plot). Then, within several hours, a CIR1 filled with magnetic islands and small-scale current sheets arrived.



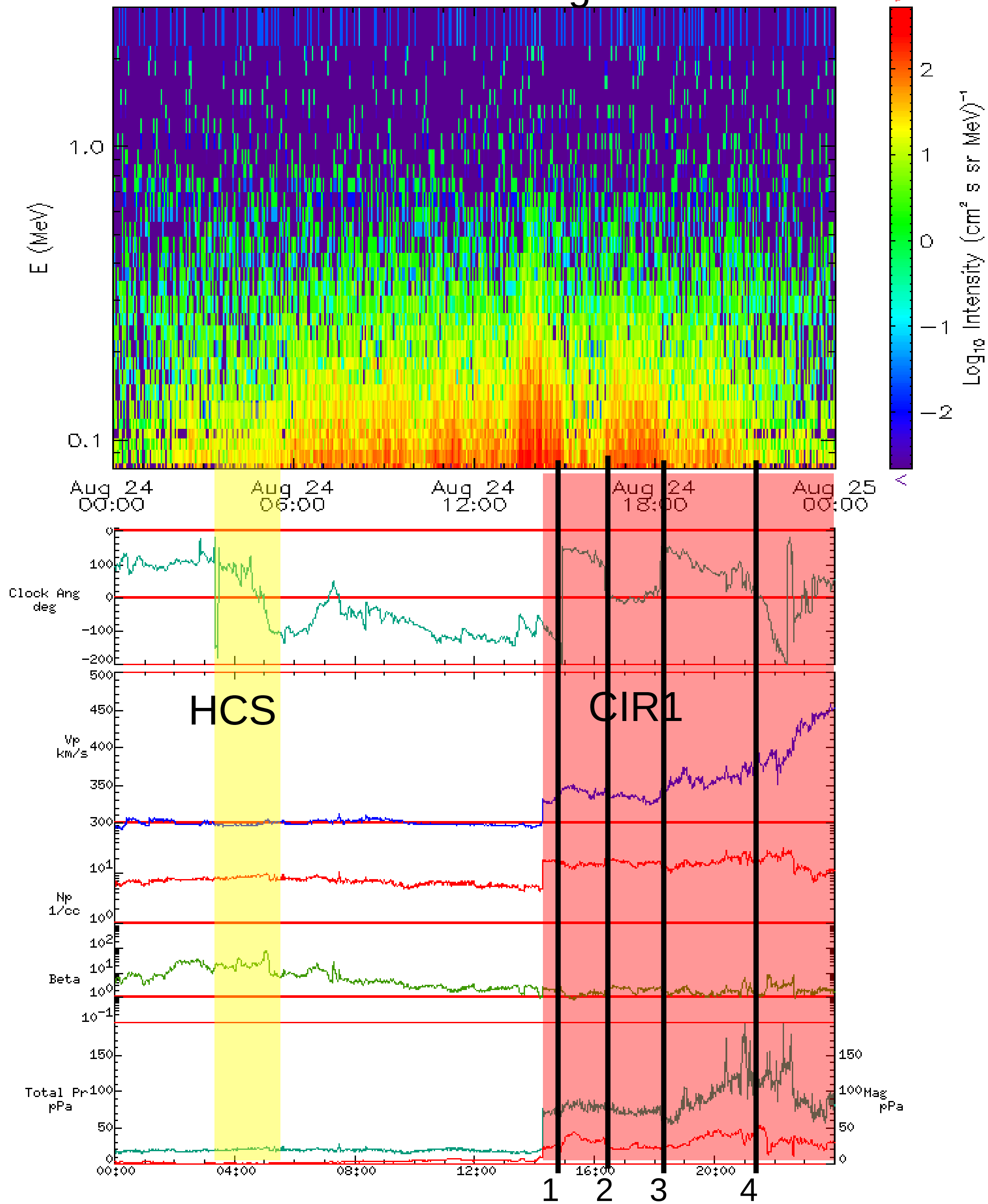
plasma

Magnetic field

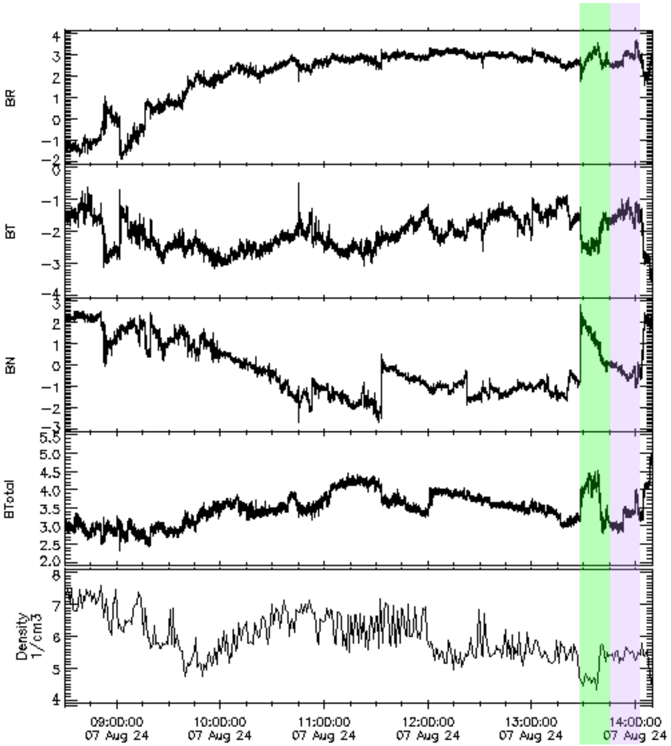
STEREO B – the HCS crossing before CIR1

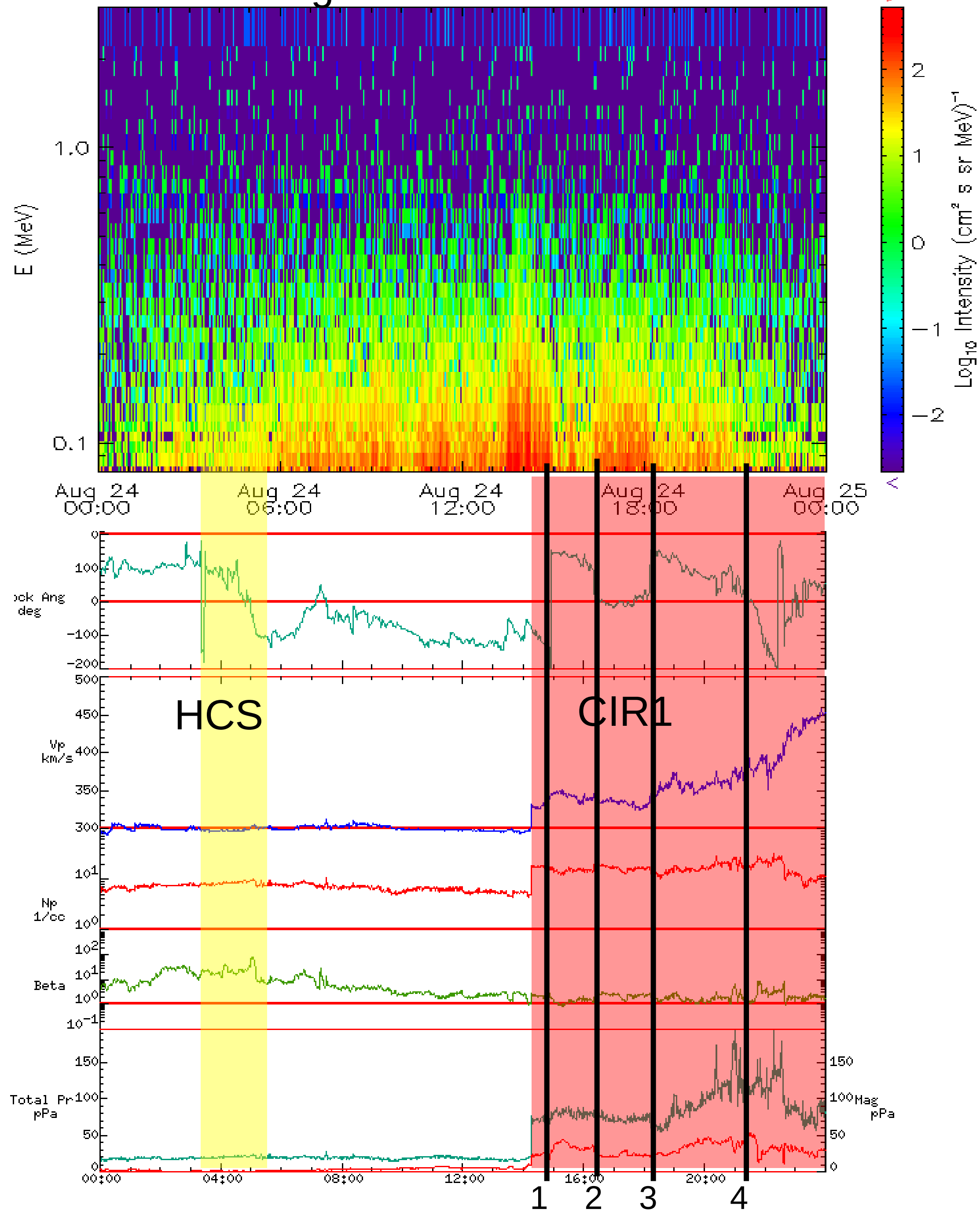
The HCS crossing occurred before the CIR1 leading front crossing. The detailed picture of the **ion energetic spectrum (the upper panel)** shows the energetic particle flux increase started from the moment of HCS crossing (the yellow stripe). The most expressed variations of flux occurred not between the HCS and the CIR's leading edge seen from plasma data (the left edge of the red stripe), but **between the CIR- associated current sheet (the vertical black line no.1) and the heliospheric current sheet.** Subsequent crossings of other current sheets (2-4) inside CIR1 are related to energetic particle flux increases as well, because current sheets at the leading edge of CIRs are as strong as the HCS due to compression and the IMF enhancement.

The difference between the way of particle acceleration at shocks and current sheets can easily explain observations. A shock accelerates particles predominantly in the direction of its propagation, but not backward. It works like a wall, pushing off particles in front of it. The reconnecting current sheet accelerates particles in both directions respective to its midplane. That is why the accelerated particles are observed in a wide area around the CIR's main current sheet at the leading edge and related to the location of other current sheets. **Magnetic islands locked in between CIR's current sheet and the HCS trap and additionally accelerate ions.** The same occurs between current sheets behind the CIR's leading edge if there are magnetic islands between two current sheets (see the next figure).



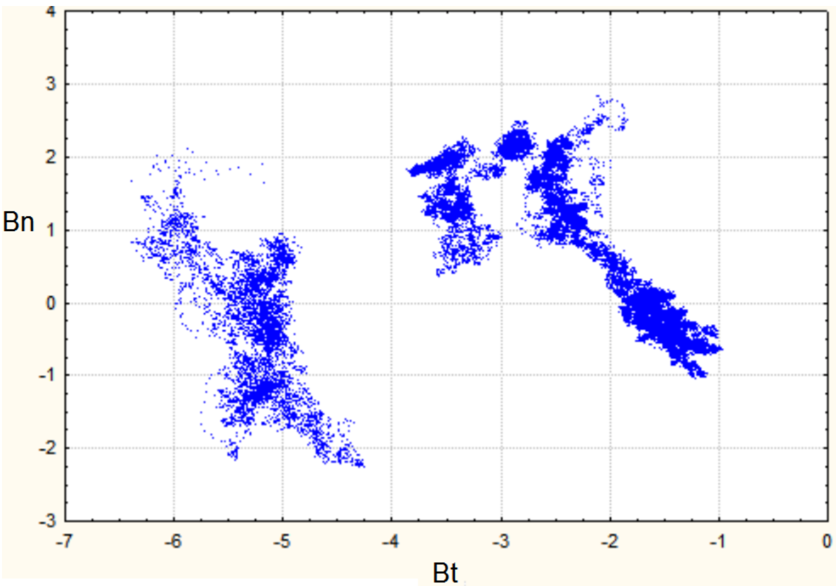
STEREO B – magnetic islands before CIR1

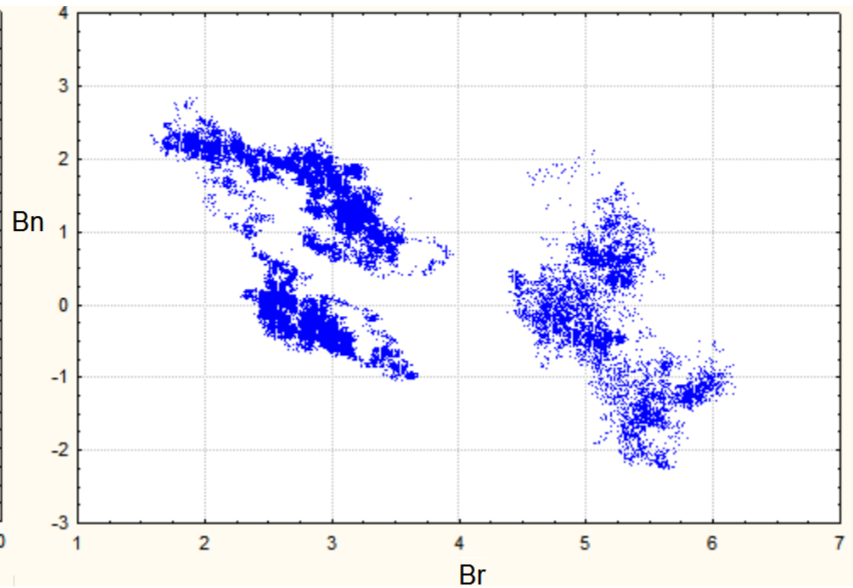


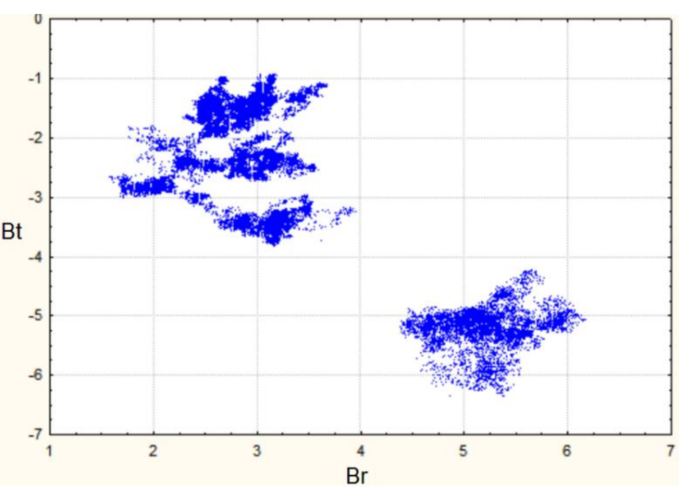


N and B **anticorrelate** in the area in between the HCS and CIR1**.** Most impressive magnetic islands (green and purple stripes) corresponding to the maximum of E (upper fig. on the right) are analyzed with 0.03 sec resolution in the next figure.

STEREO B – magnetic islands between the HCS and CIR1

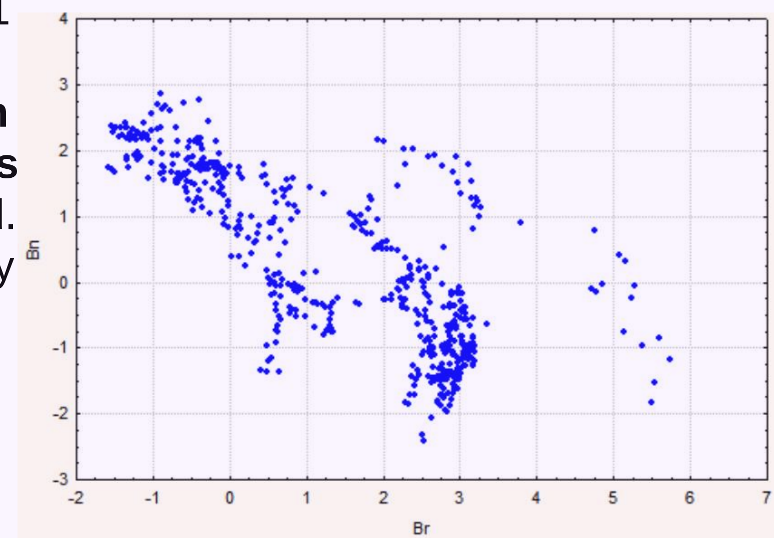






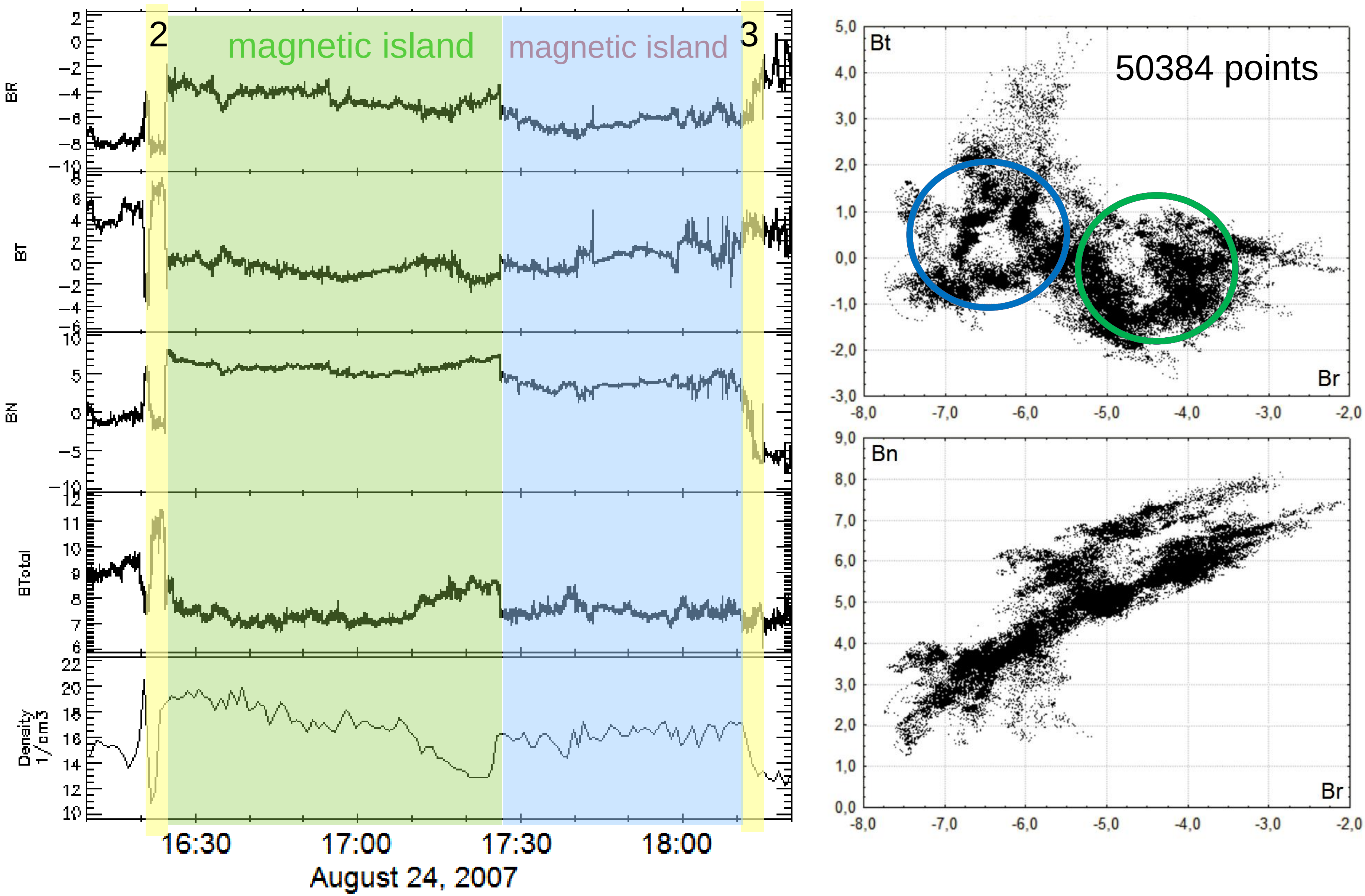
According to 0.03 sec resolution data (29641 points)**, 2 magnetic islands having width from 10 to 30 minutes are clearly separated**. Rotation occurs mainly in Bn-Br and Bt-Br planes, in Bn-Bt the polarization is predominately linear.

1-min resolution



B vector rotation in the Bn-Br plane during the whole period from the HCS to CIR1

STEREO B: IMF properties during the ion flux increase between current sheets no.2 and 3



Current sheets 2 and 3 are indicated as yellow stripes. **Strong anti-correlation between B and N together with the IMF vector rotation mainly in the ecliptic plane are signatures of magnetic islands**. **Two magnetic islands with L~10^6 km** between the current sheets 2&3 are revealed by the observations.

Preliminary conclusion

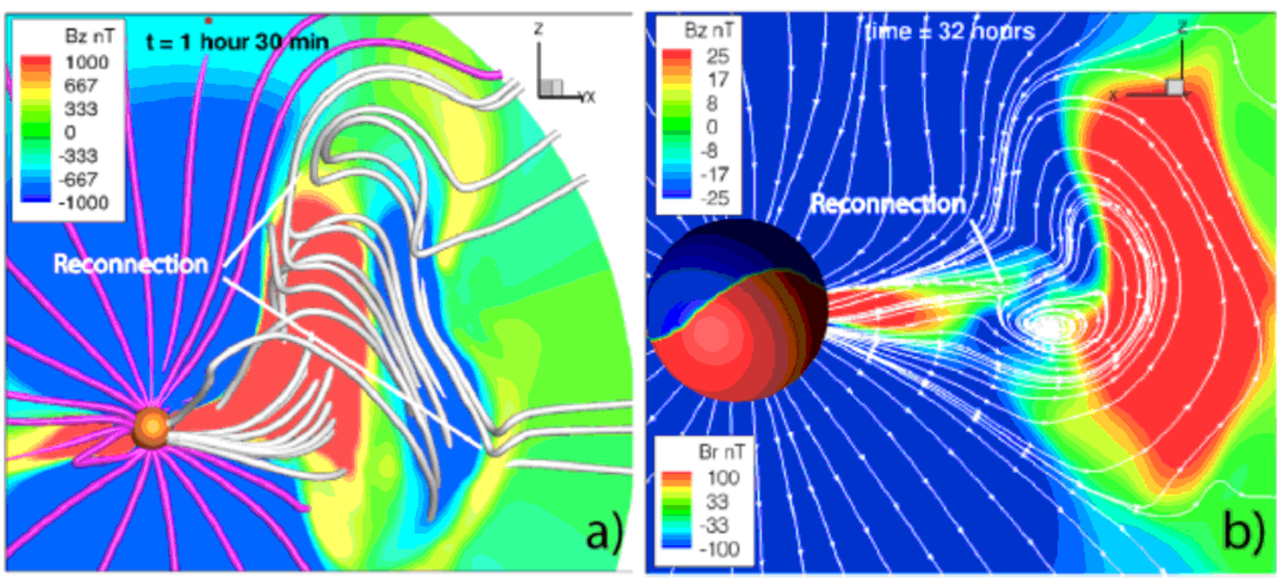
Particle acceleration may occur inside magnetically confined structures (closed areas between current sheets with strong surrounding magnetic field). This may be an **area between an ICME and the heliospheric current sheet**

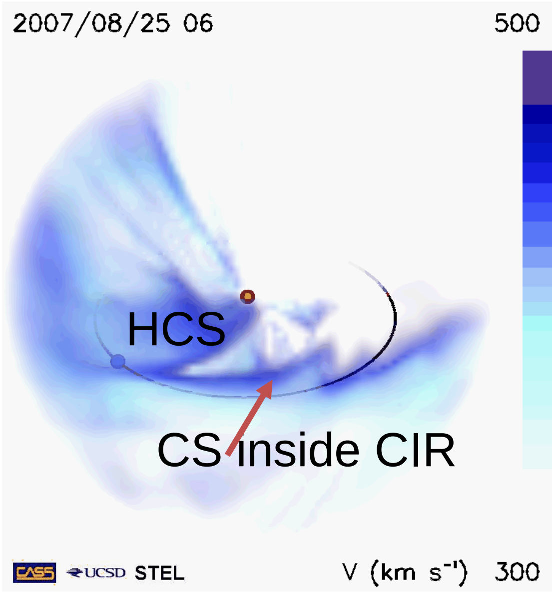
(Khabarova et al., 2015),

Preprint @ http://arxiv.org/abs/1504.06616

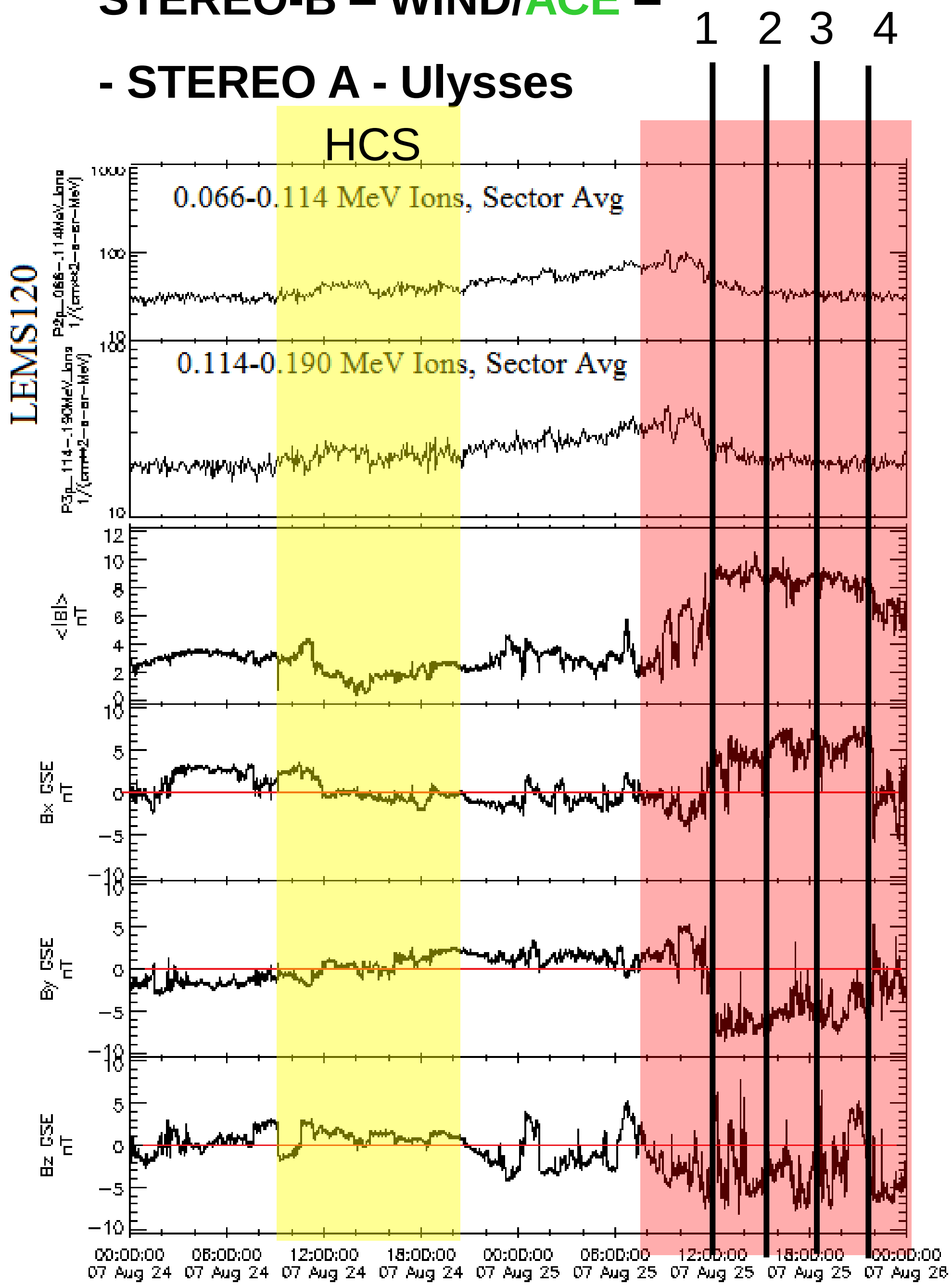
between **a CIR and the HCS, as well as between two strong current sheets of any origin**.

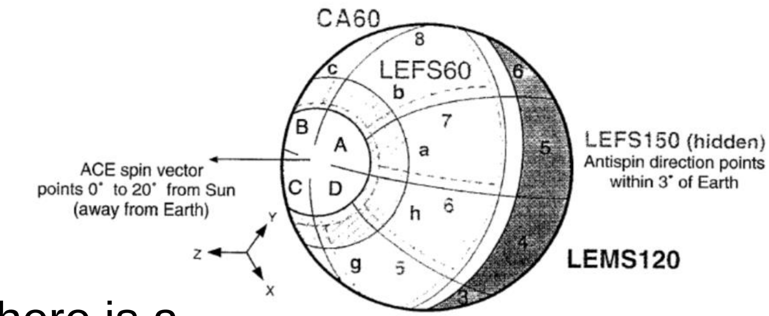
W B Manchester IV *et al* Plasma Phys. Control. Fusion **56** (2014)



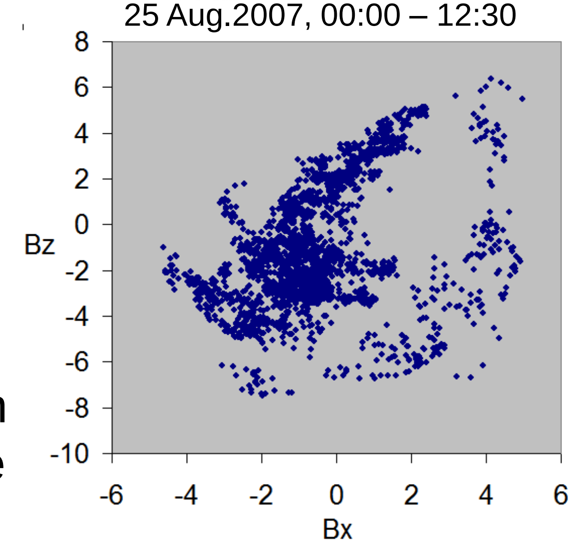


STEREO-B – WIND/ACE – - STEREO A - Ulysses

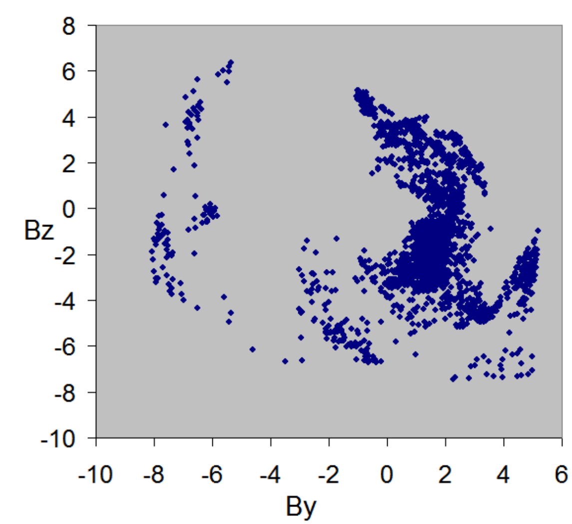




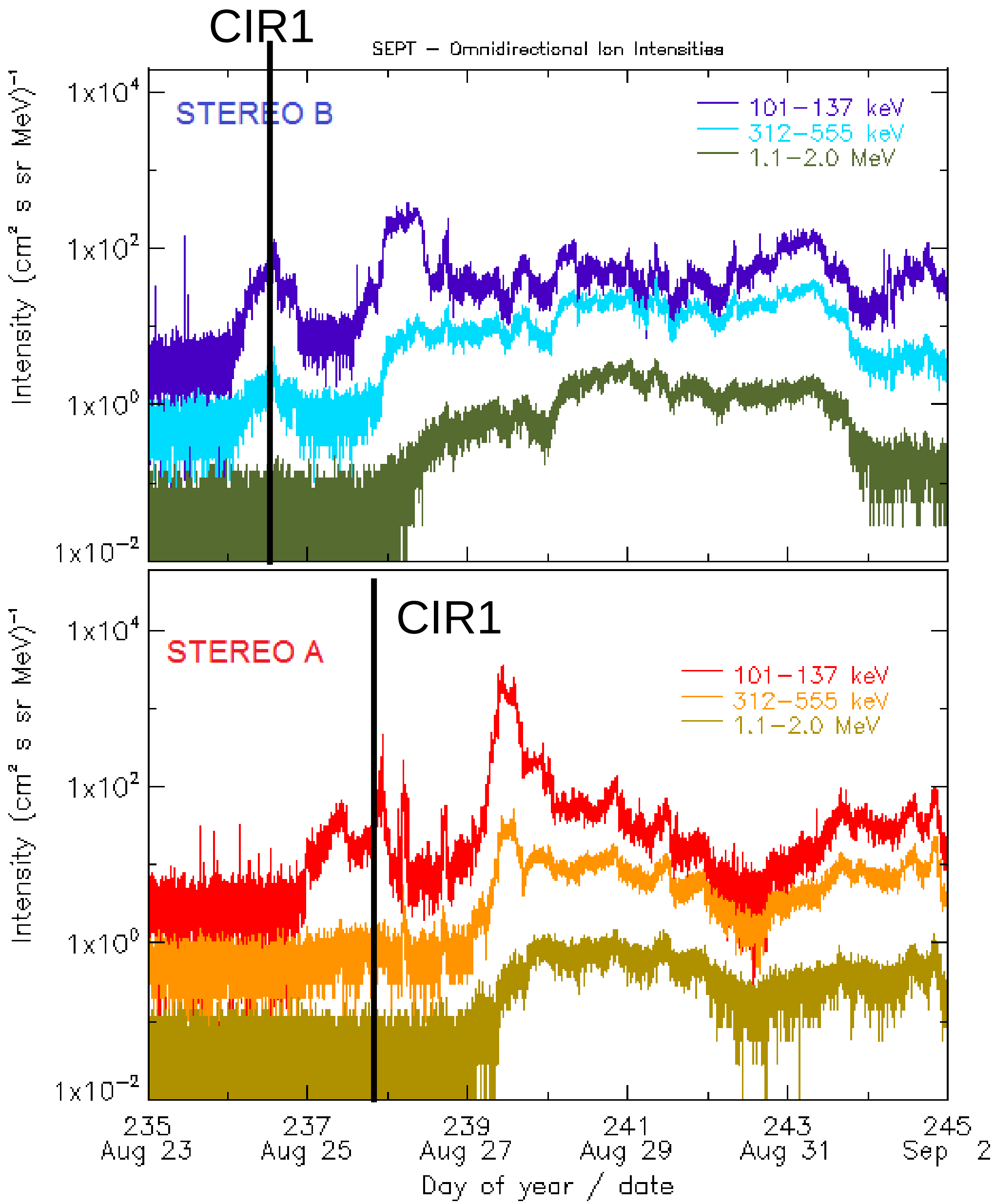
There is a vast area filled with **magnetic islands in between the HCS and the first CS** which belongs to the CIR1.



The ion flux increase is observed in this area. The maximum is related rather to the CS1 than to the CIR1 shock.



STEREO A observations of energetic particle flux enhancement before the CIR1 arrival



STA detected CIR1 later than STB, but the ion flux increase preceding CIR1 was seen even clearer and lasted longer.

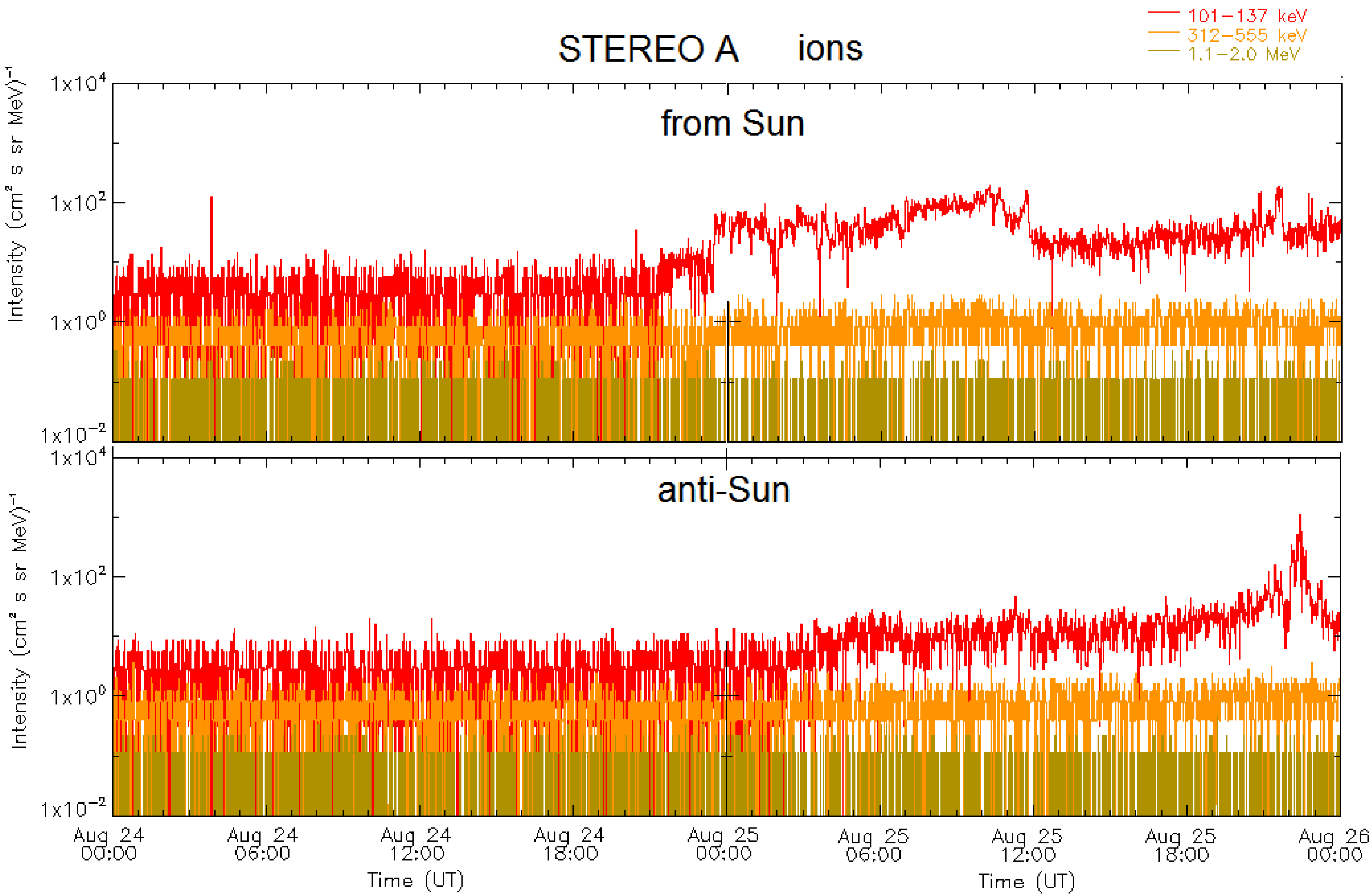
It was due **to anti-sunward ions**, which came first (see the next figure). That could not be if they were streaming sunward from the CIR1 forward shock.

Sunward accelerated ions were detected many hours later.

STEREO-B – WIND/ACE –

- STEREO A - Ulysses

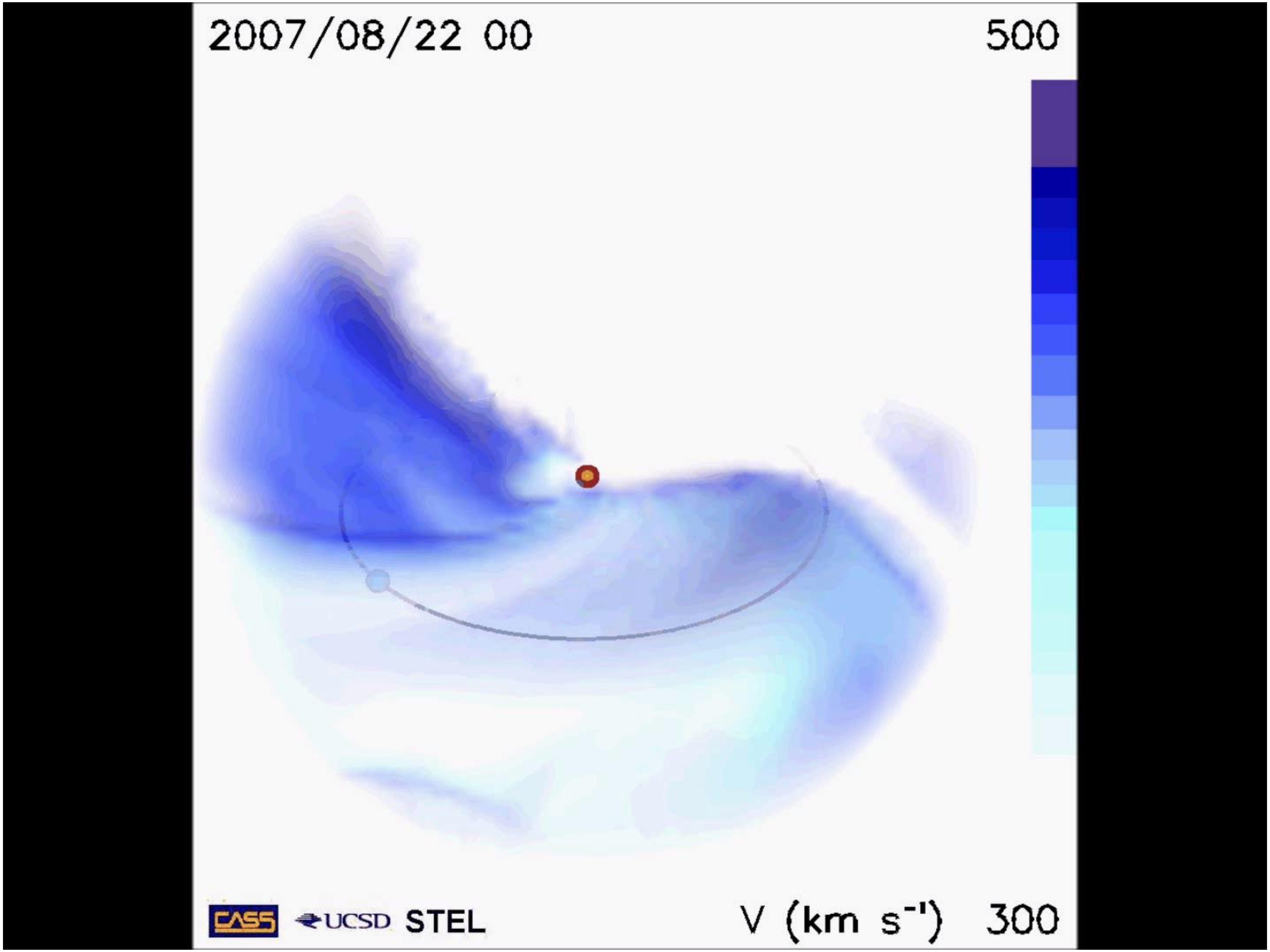
STEREO A observations of energetic particle flux enhancement before the CIR1 arrival

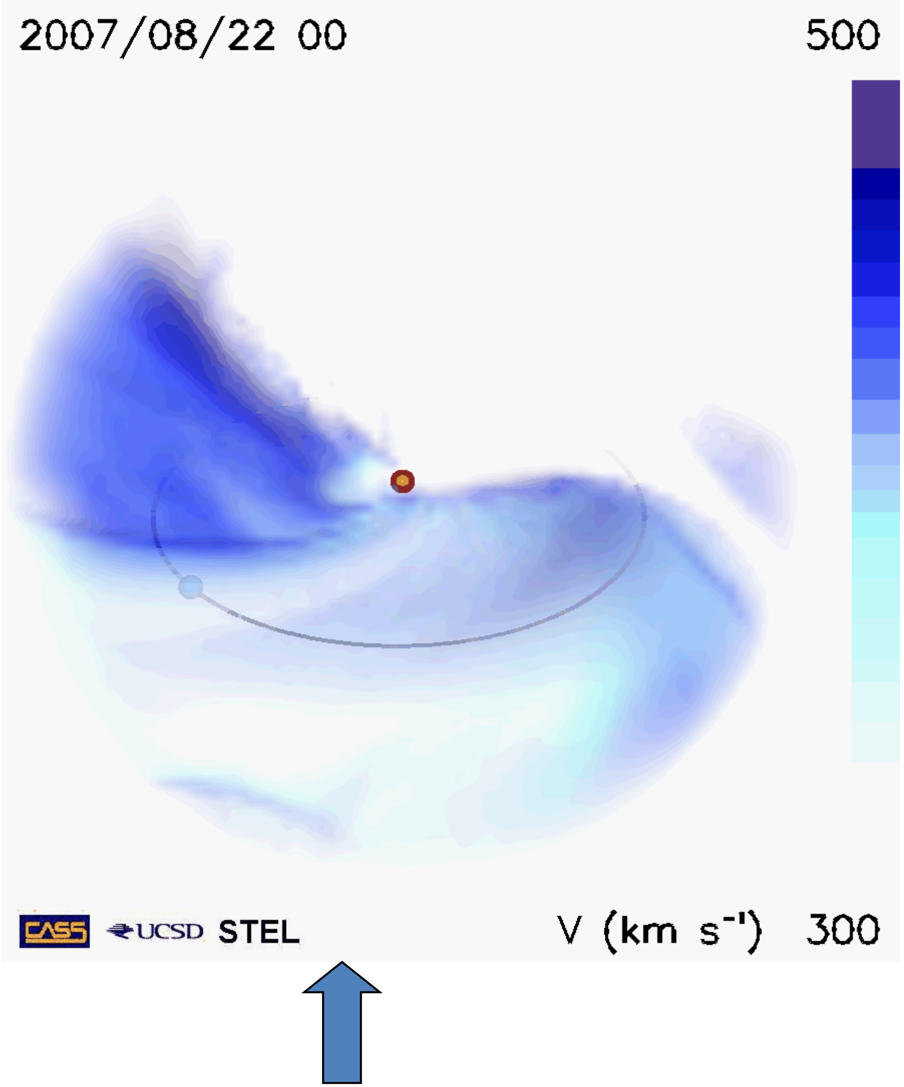


There was approx. **one day delay between detection of accelerated anti-sunward and sunward ions** .

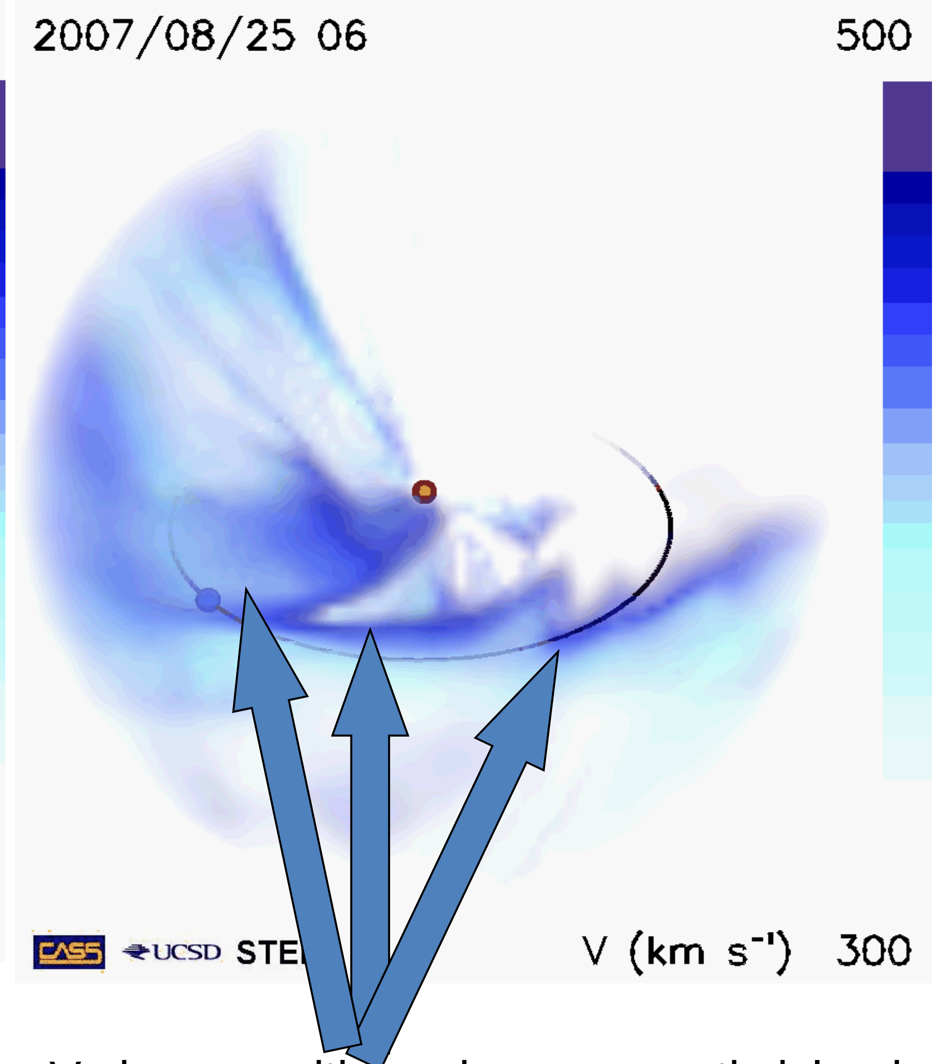
STEREO-B – WIND/ACE –

- STEREO A - Ulysses


2007/08/22 00
500
CASS
UCSD
STEL
V (km s^{-1})
300

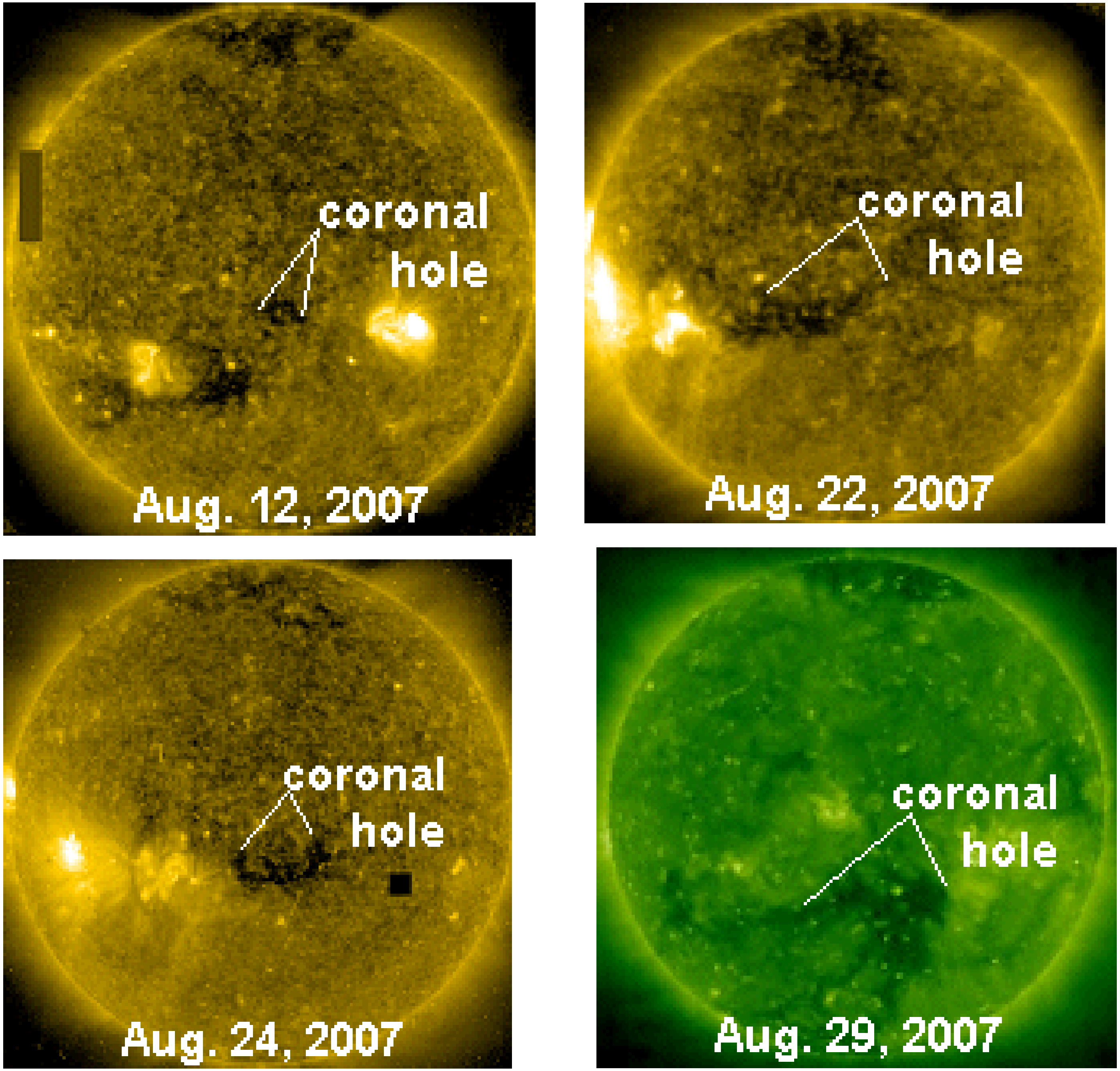


Classic view of the HCS



V-shape cavities, where magnetic islands (observed in situ) are confined by walls of CIRs and the crumpled HCS

Long-lived low latitude coronal holes

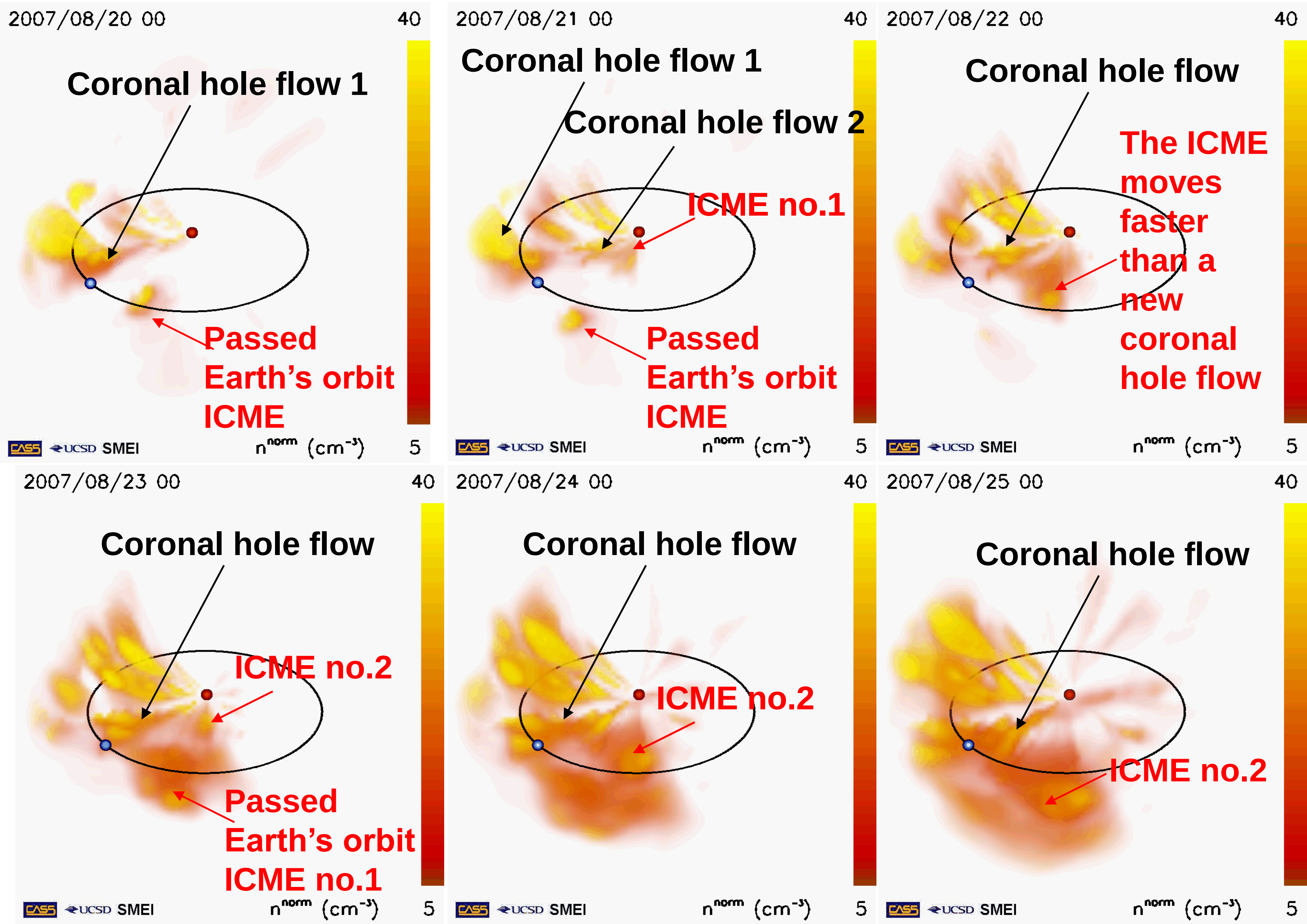


The V-shape cavities are consequences of stream interaction. Most streams flow from low-latitude coronal holes and sometimes face weak ICMEs. The streams of both kinds have different shapes, different speeds and different ways of propagation from the Sun to 1 AU. ICMEs propagate nearly radially and look like expanding balls, but the streams from coronal holes look like expanding corotating tubes. As a result, V-shape structures can be formed.

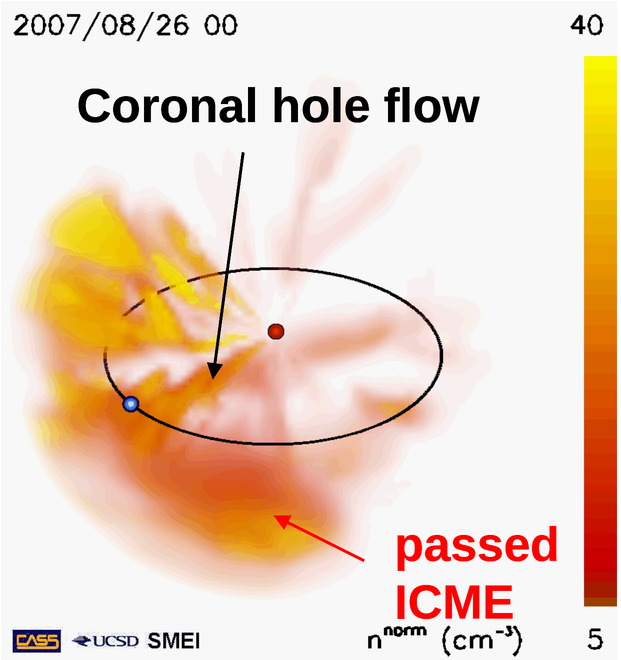
Next two slides shows SMEI measurements of the solar wind density in the visible light. SMEI was designed to observe ICMEs, but, in fact, it can show merely borders of ICMEs or flows from coronal holes (which are SIRs/CIRs), no more. It cannot ‘look inside’ ICMEs until they have crossed Earth’s orbit.

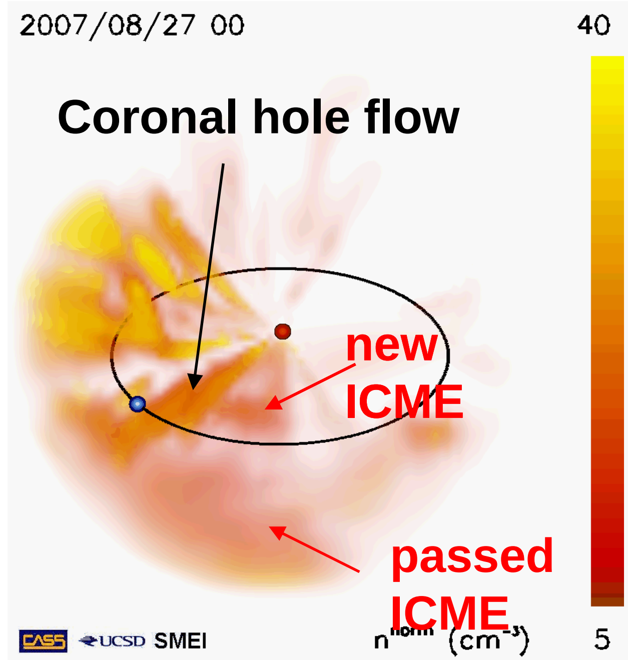
Anyway, it is not bad for us, because we want to know where CIRs were. CIRs from coronal holes are stable and conic-like, but ICMEs, even after weak CMEs, move faster, and they produce ball-like “CIR-shells”. Actually, an ICME can move slower than a coronal hole flow, but since the latter has a permanent source at the Sun, the entire picture looks like the ICME moving on the background of a stable slowly rotating stream.
Density structure is partially responsible for what we see in blue velocity pictures. On the other hand, velocity determines the IMF shape, so the whole picture of the event is in our hands.

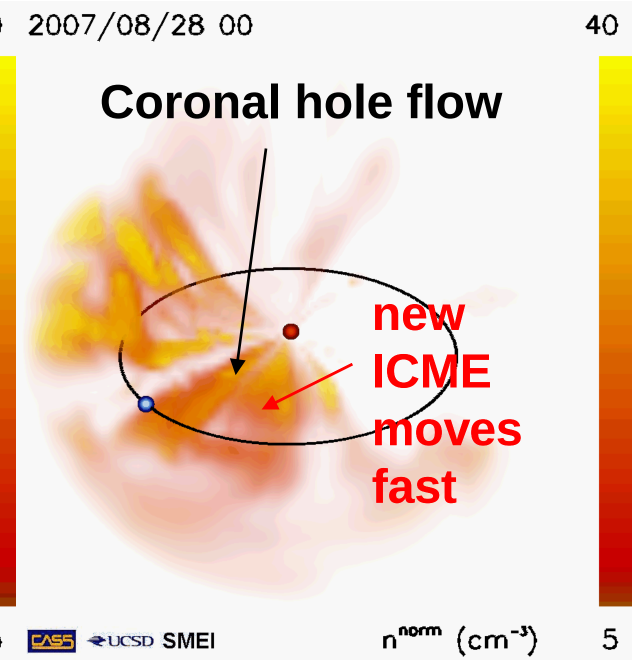
Density daily pictures

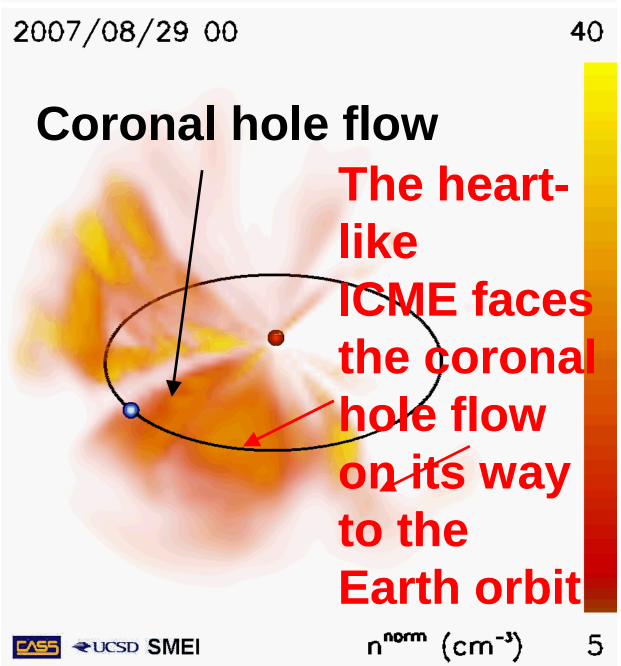


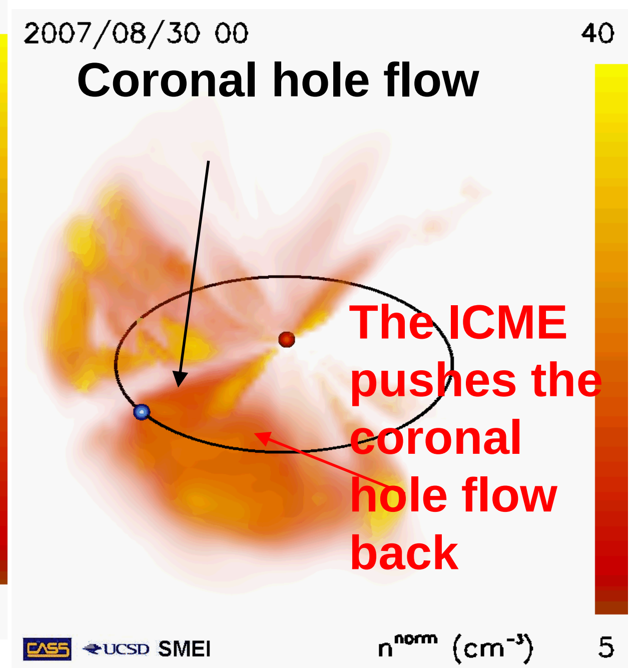
Density daily pictures

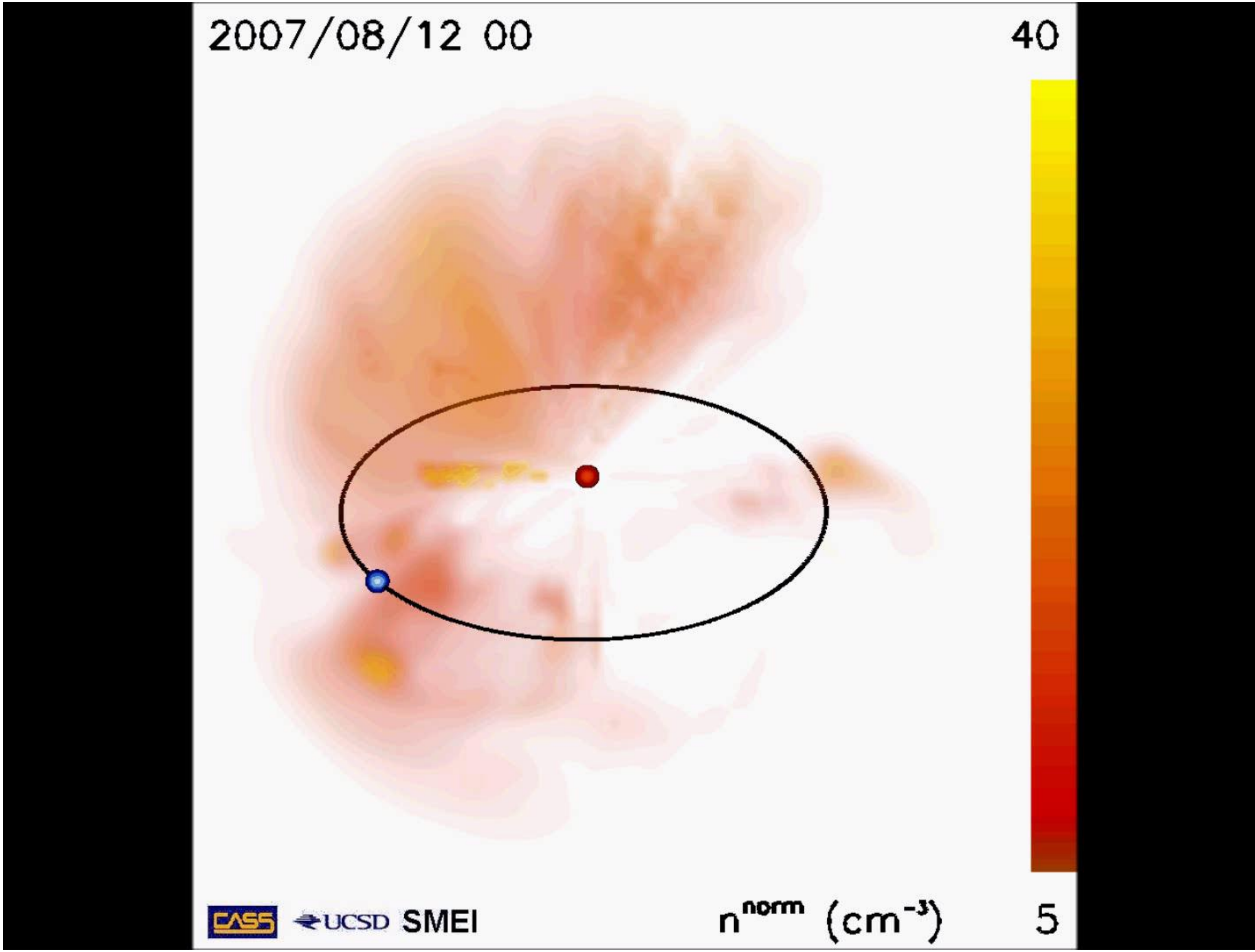


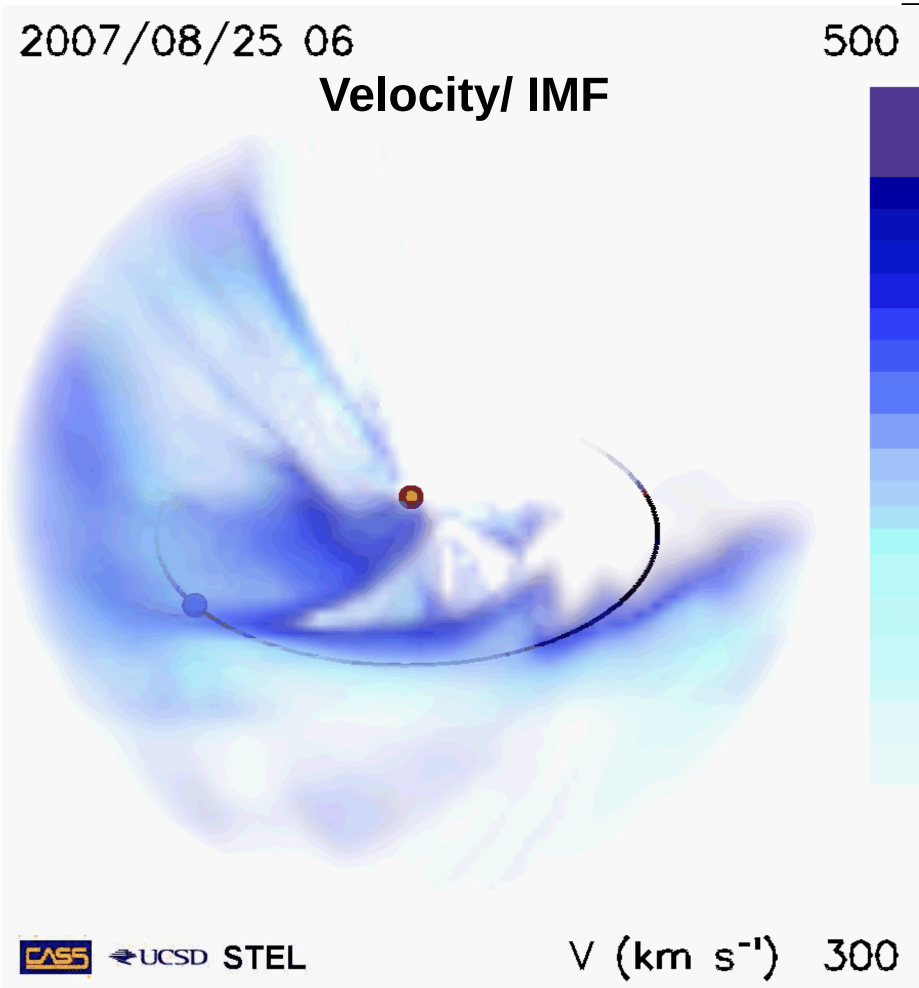


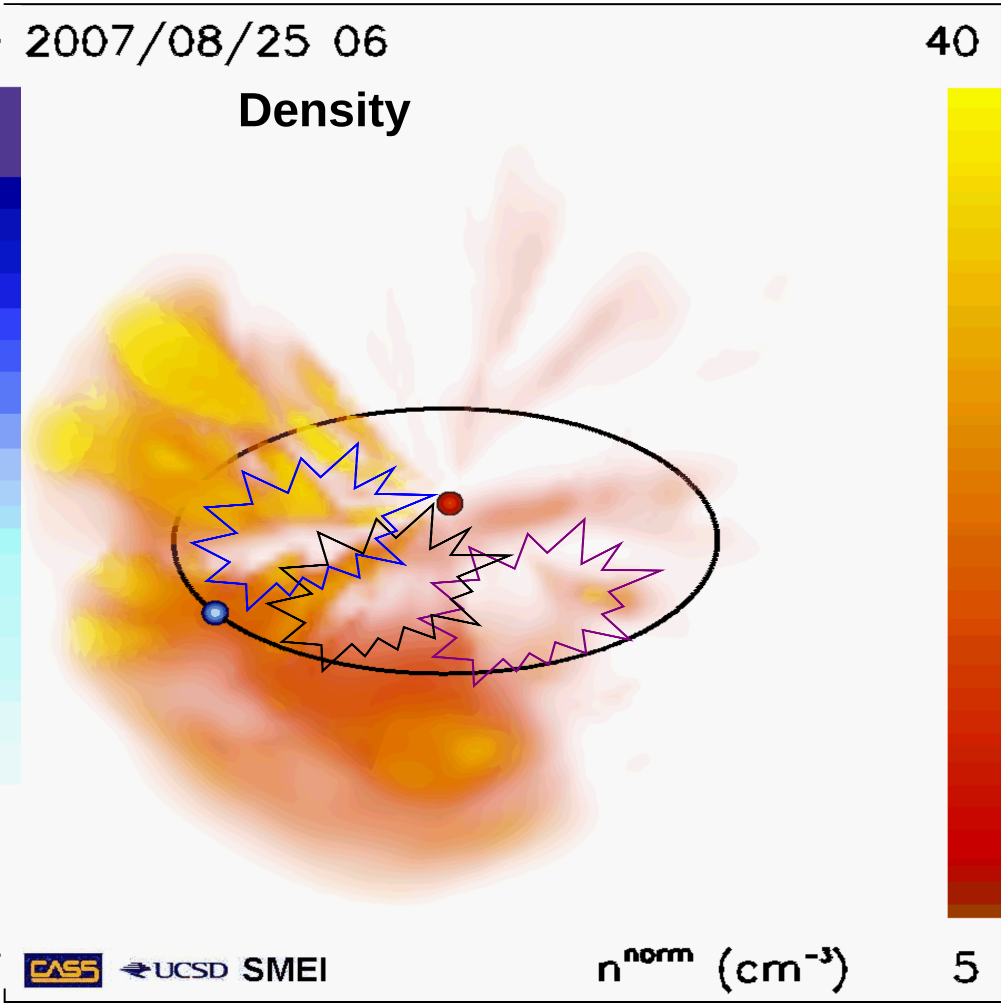







2007/08/12 00
40
5
CASS UCSD SMEI
n^{norm} (cm^{-3})





An illustration how interacting streams form V-shape cavities

DISCUSSION - CONCLUSIONS

✓ Using multi-s/c observations, we have presented evidence for **significant LOCAL particle acceleration associated with CIRs** in August 2007

✓**Our new paradigm**: Particle acceleration occurs inside magnetically confined structures (closed areas between current sheets with strong surrounding magnetic field) i.e. **in numerous small-scale magnetic islands observed between the HCS and the CIR, also containing local Current Sheets.**

✓ The new paradigm can well account for local low energy particle enhancements **up to 1 MeV associated with CIRs**.

✓ In recent theoretical work (Zank et al. 2014, ApJ): **Particle Energization by reconnection related processes of Magnetic Island Merging and Contraction**