Numerical Heliospheric Code ENLIL and Space Weather

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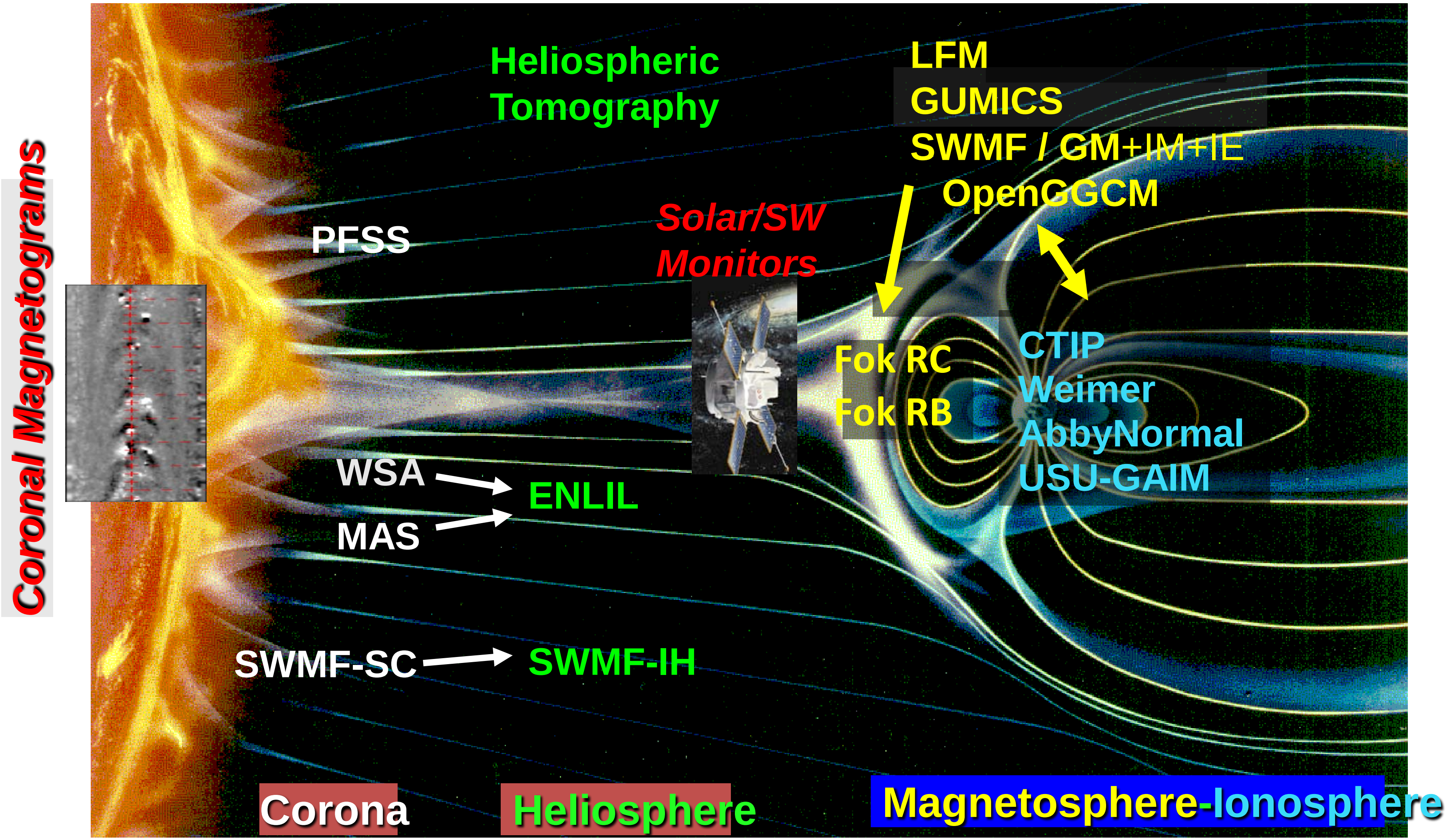
OUTLINE

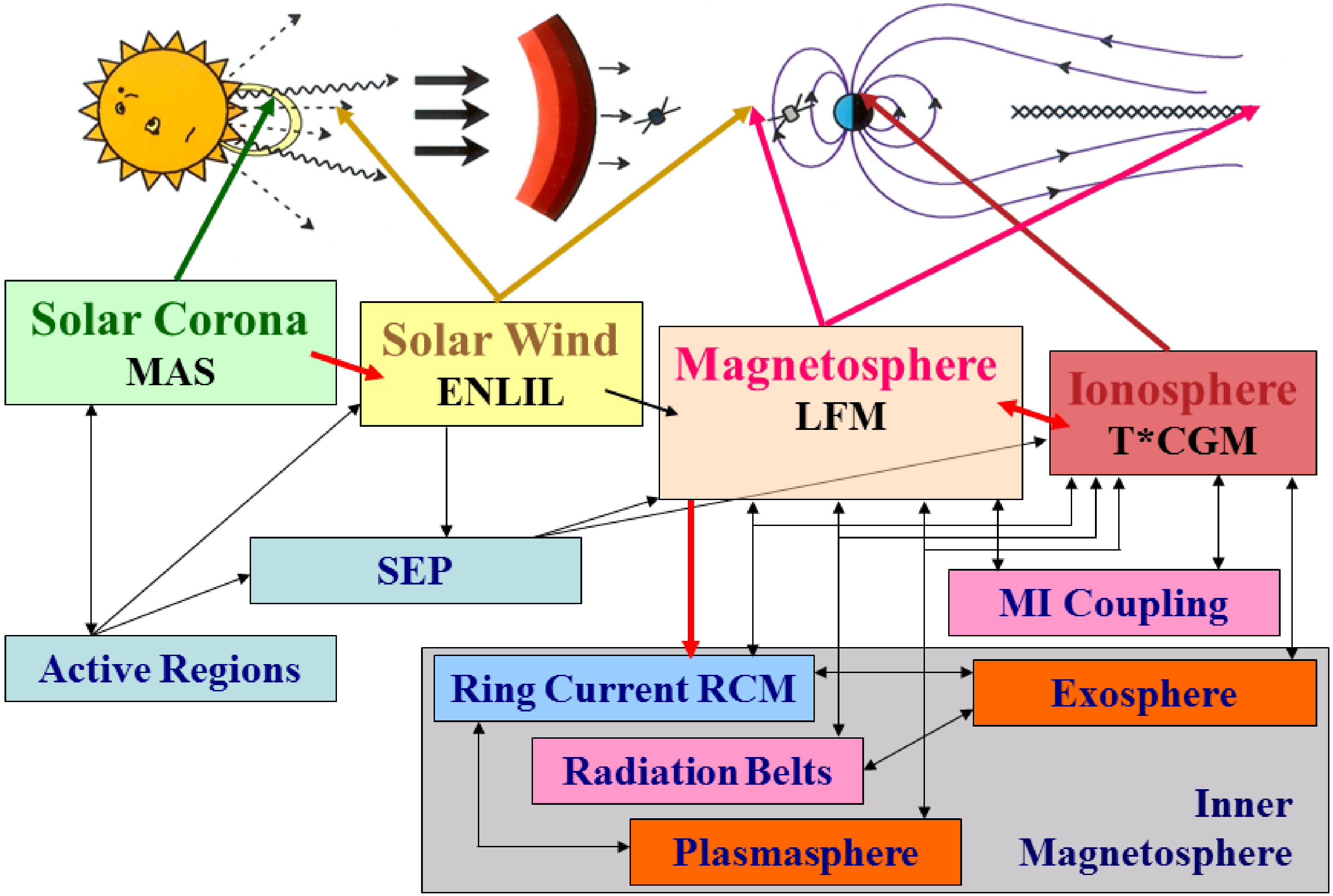
- Space Weather Models
- Heliospheric Simulations and ENLIL
- Simulation of Background Solar Wind
- Application of Cone Models
- Interpretation of White-Light Observations
- Need for Ensemble Modeling
- Output for Solar Energetic Particles
- Run-on-Request Service at CCMC

Space Weather Models

Space Weather Models
hosted by NASA/CCMC



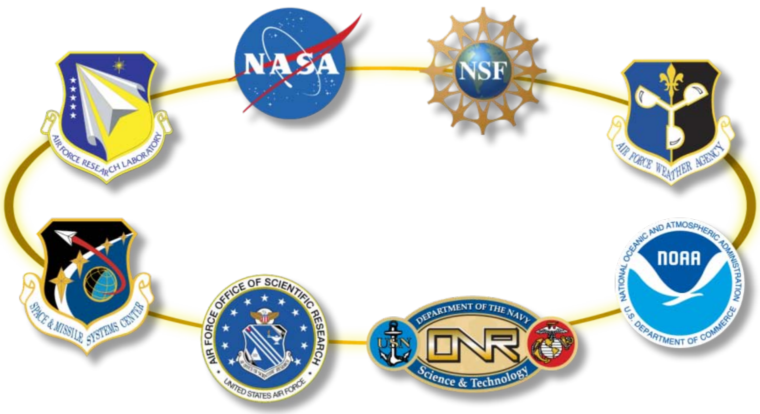
Coupled Physics-Based Model



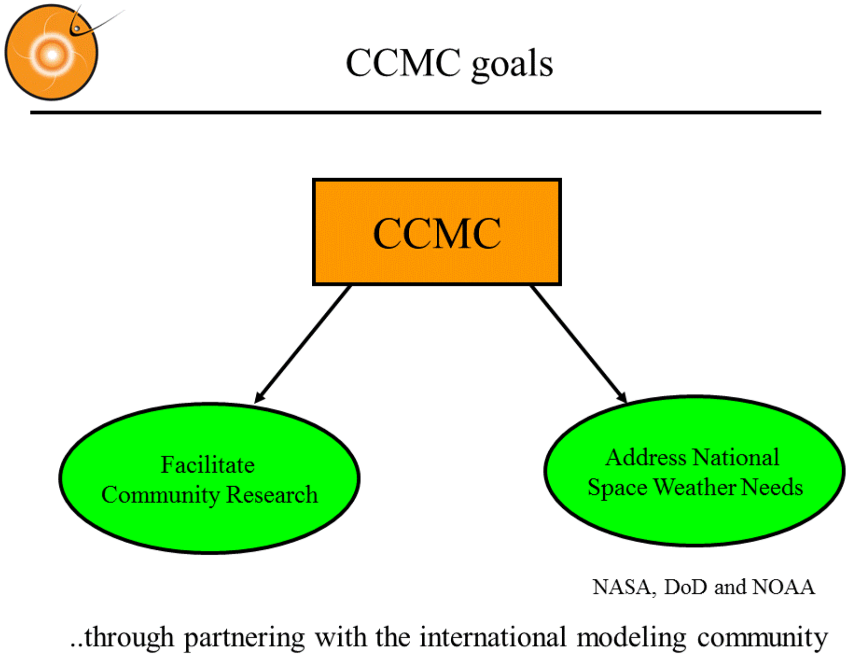
[flowchart from the Center for Integrated Space Weather Modeling (CISM BU); Similar project is the Space Weather Modeling Framework (SWMF Umich)]

Community Coordinated Modeling Center (CCMC)

Multi-Agency Facility at NASA/GSFC

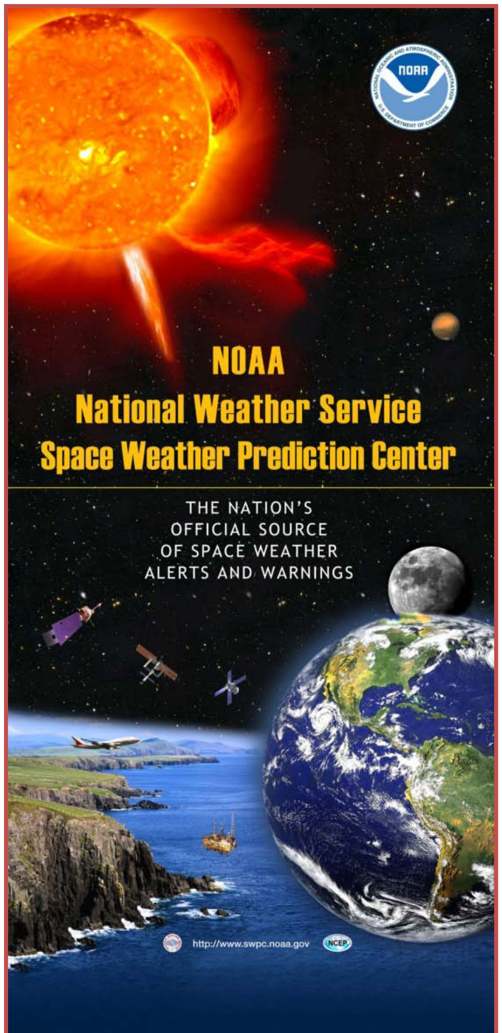


>700 CPU Beowulf system, sponsored by **NASA, NSF,** started by **AF/XOW** investment



Space Weather Analysis Facility

NOAA Space Weather Prediction Center (SPWC) and National Center for Environmental Predictions (NCEP)



NOAA/SWPC

Operational forecasting

24/7 service

WSA, CME fitting, visualization, forecasting products, archiving

(Boulder, CO)

NOAA/NCEP

Operational supercomputing

IBM 156 Power6 32-way nodes, 4,992 processors @ 4.7GHz

Stratus – primary (Gaithersburg, MD)

Cirrus – backup (Fairmont, WV)

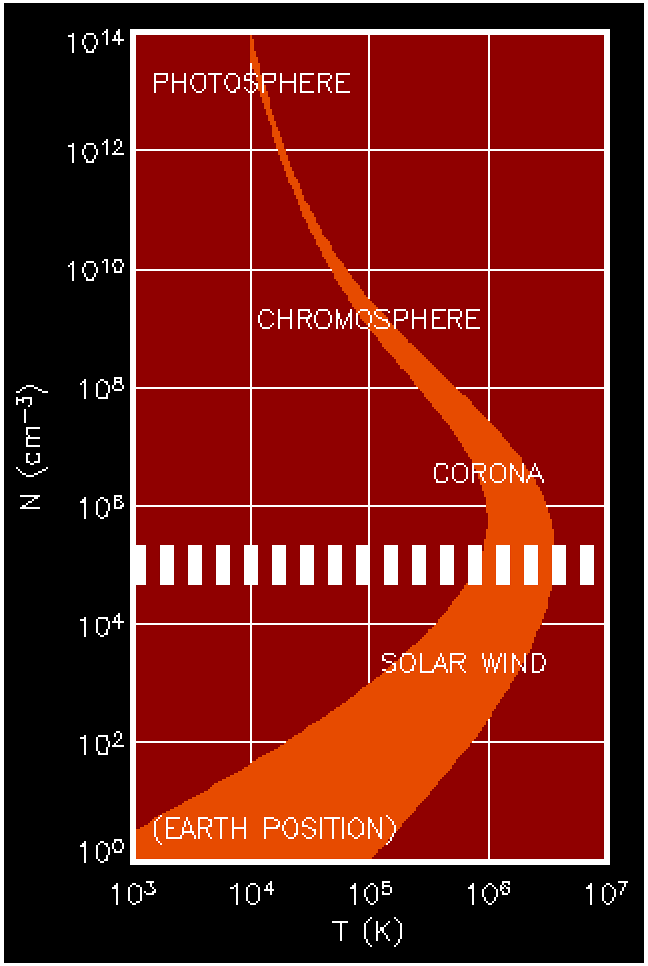
Heliospheric Simulations and ENLIL

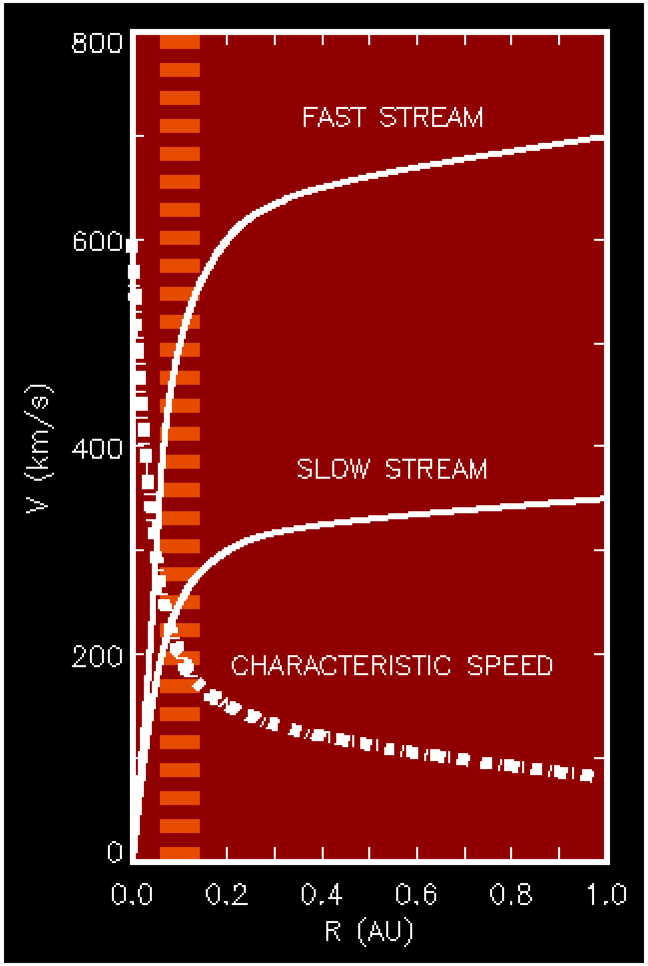
ENLIL – 3-D Solar Wind Model

- <u>Mathematical Description:</u>
  - ideal magnetohydrodynamic (MHD) approximation
  - volumetric heating
  - additional equations for injected mass and polarity tracking

- <u>Method of Solution:</u>
  - explicit finite-volume scheme
  - TVD Lax-Friedrichs (Rusanov) MUSCL Hancock algorithm
  - Dedner's magnetic field diffusion – div(B) treatment
  - parallelization by domain-decomposition

Solar Wind Plasma Parameters

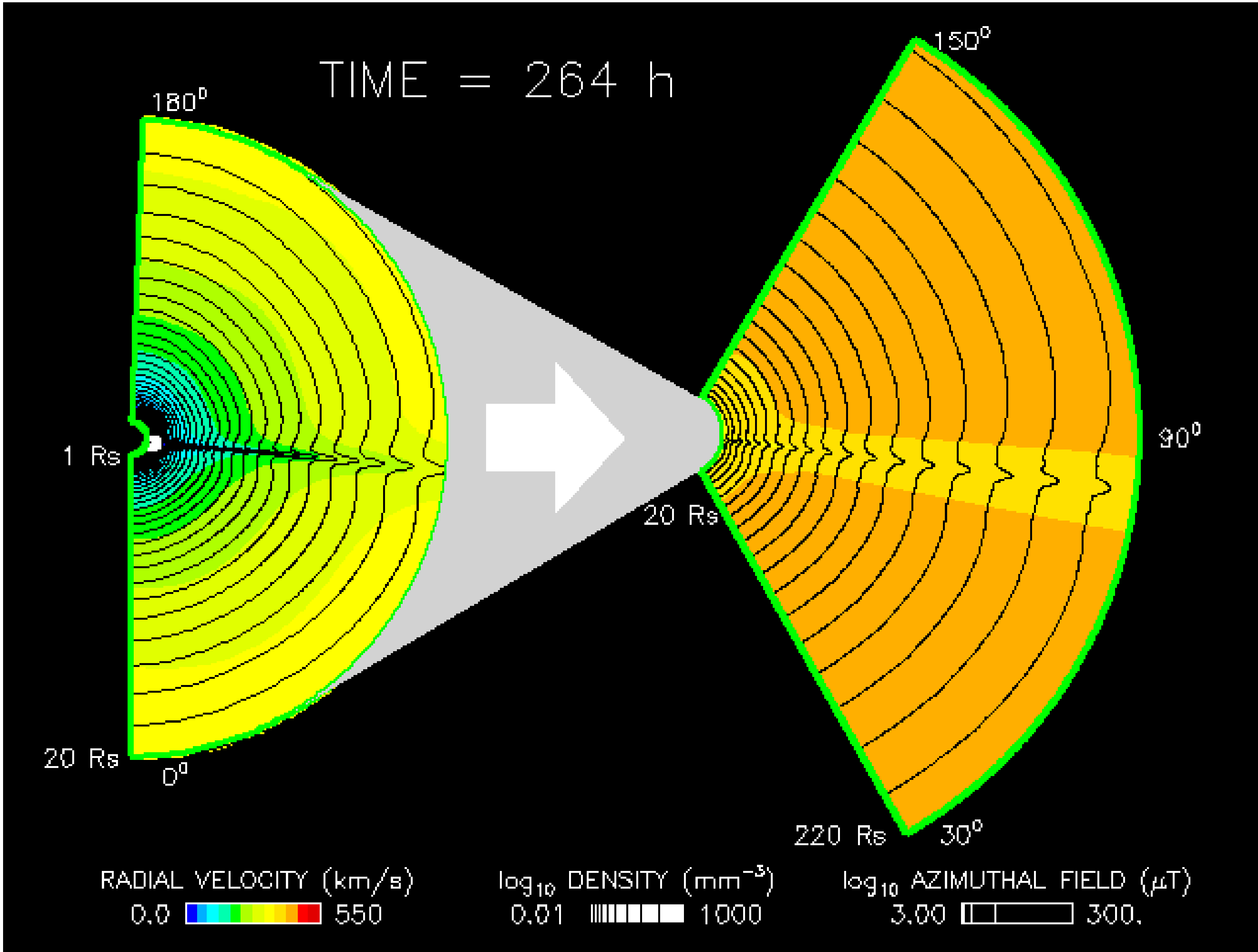




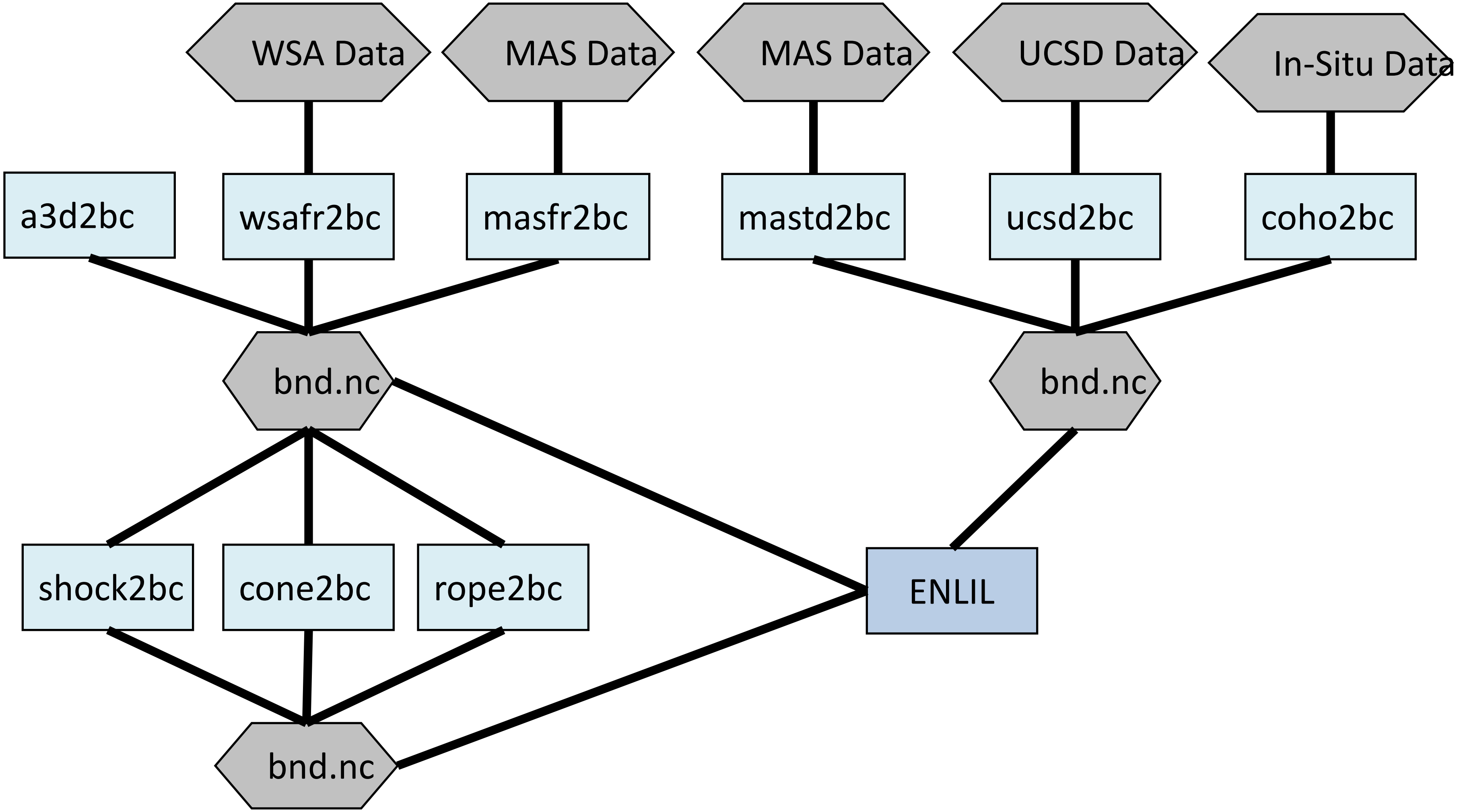
Large variations in plasma parameters between the Sun and Earth; different regions involve different processes and phenomena

We distinguish between the coronal and heliospheric regions with an interface located in the super-critical flow region (usually 18-30 Rs)

Merging of Coronal & Heliospheric Models

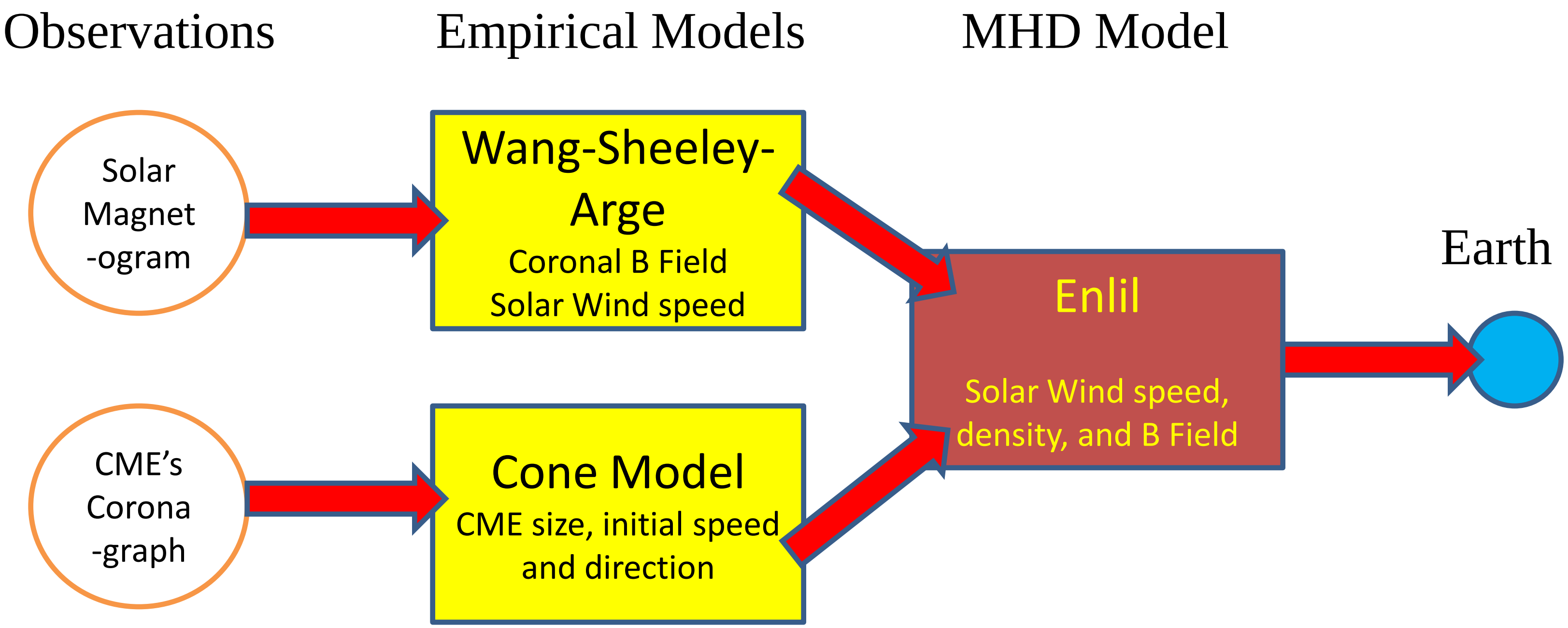


Driving Heliospheric Computations



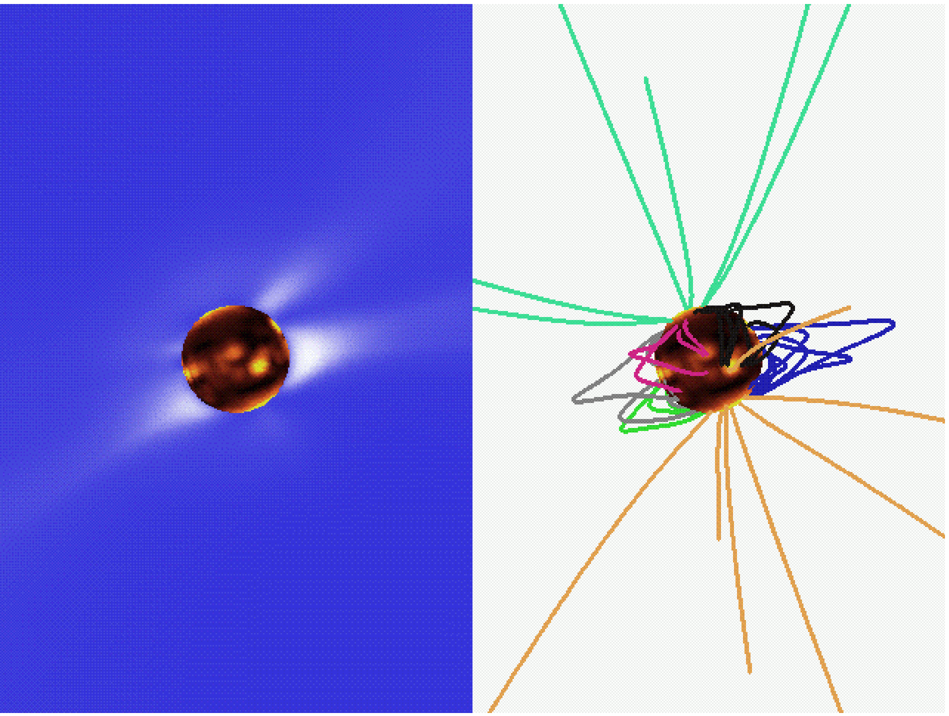
- Analytic, empirical, and numerical models and observational data can be used to drive ENLIL (green) by sharing data sets (light blue) and using couplers (blue).

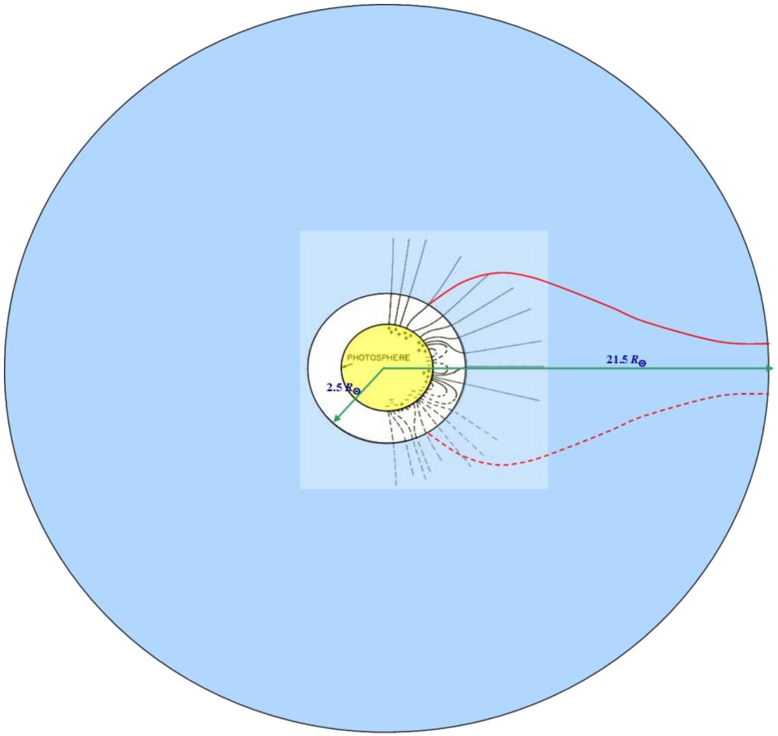
“Event-by-Event” Application



Background Solar Wind

Ambient Solar Wind Models





SAIC 3-D MHD steady state coronal model based on photospheric field maps

CU/CIRES-NOAA/SEC 3-D solar wind model based on potential and current-sheet source surface empirical models

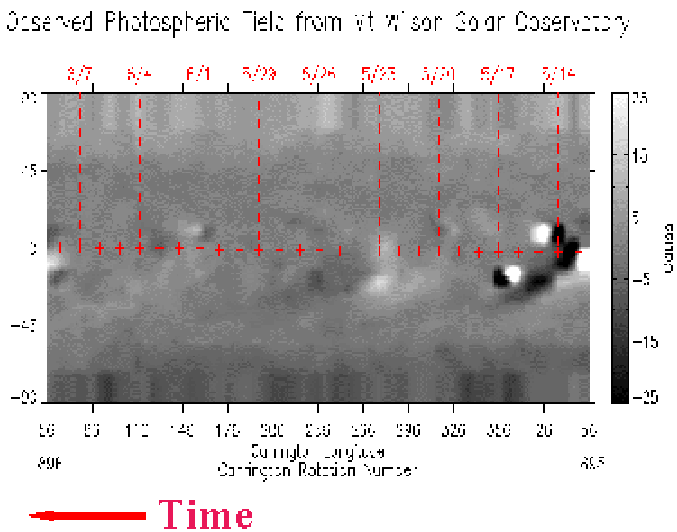
[*SAIC maps – Pete Riley*]

[*WSA maps – Nick Arge*]

Wang-Sheeley-Arge (WSA) Maps

CU/CIRES-AFRL model based on potential and current-sheet source surface empirical models and empirical relationship between CH open flux and SW speed

Model Input



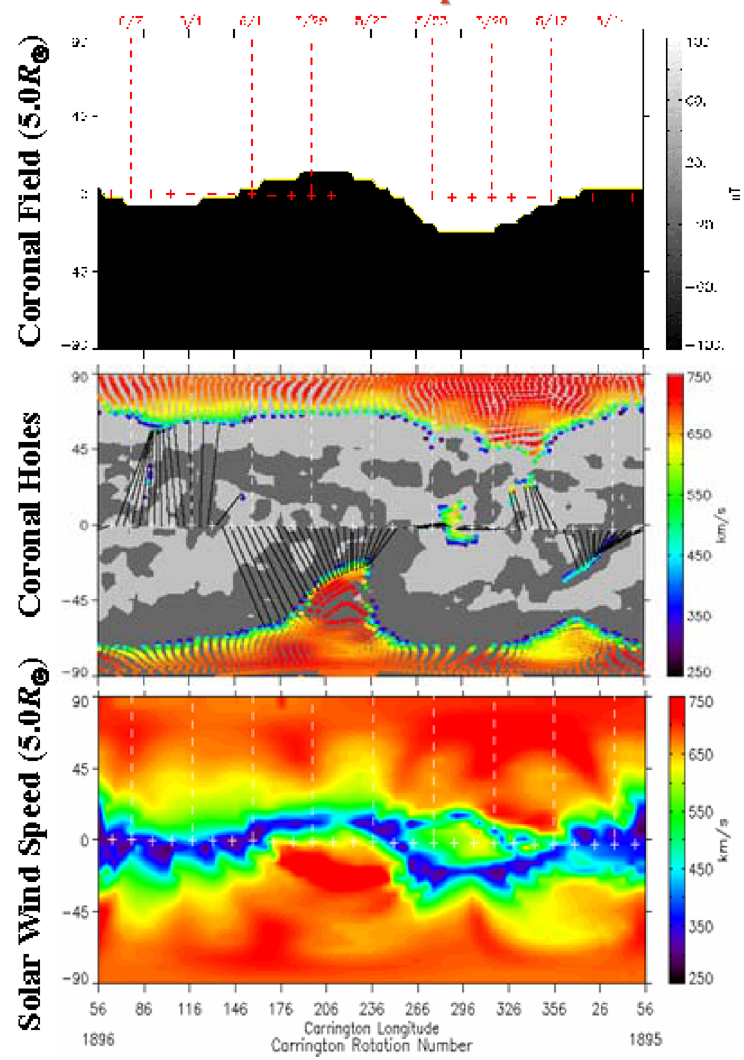
$$V(f_s,\theta_b) = 250 + \frac{650}{(1+f_s)^{2/7}}\left\{1.0 - 0.8e^{-\left(\theta_b/3\right)^{7/4}}\right\}^3 \text{ km s}^{-1}$$

Where:

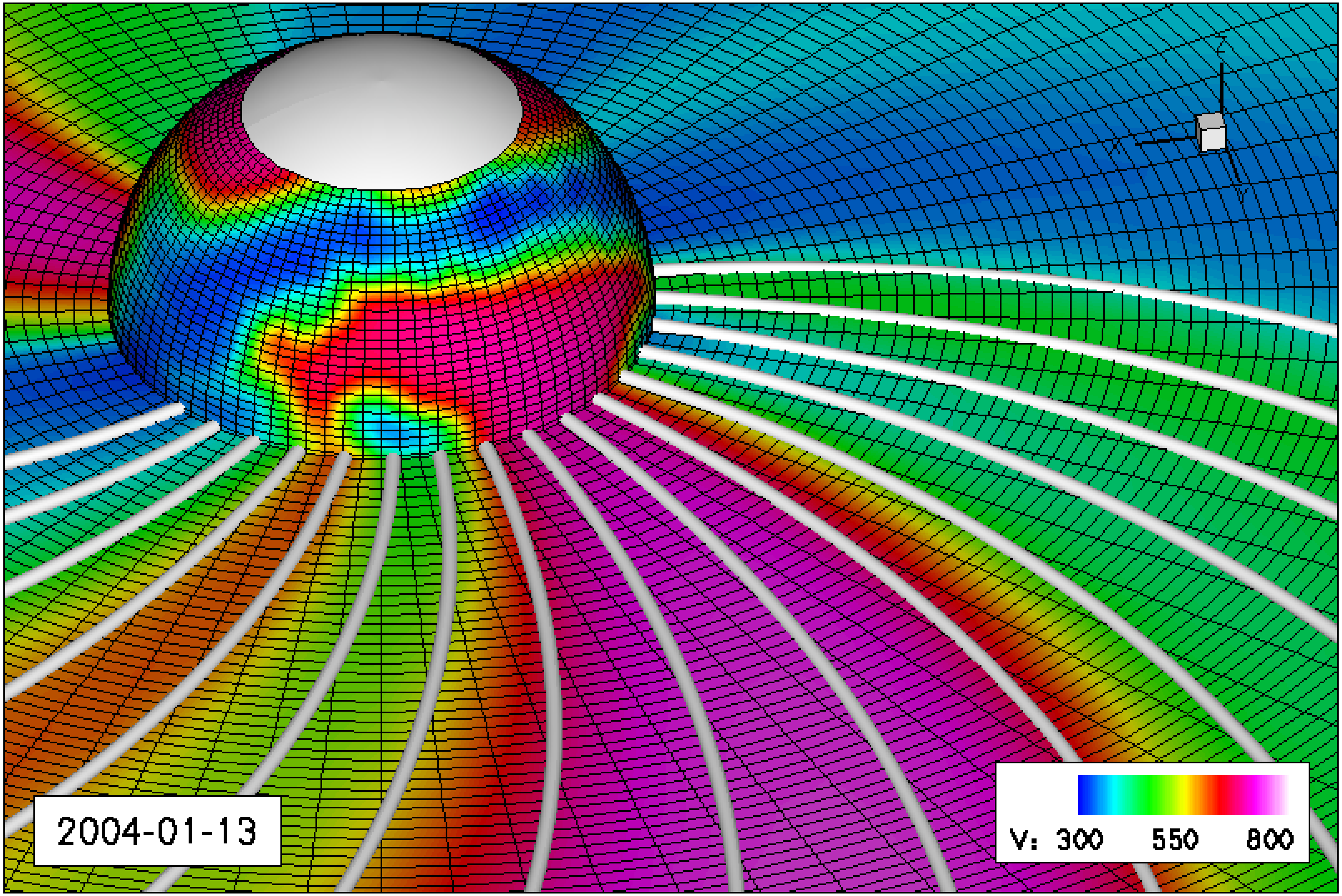
f_s = Magnetic field expansion factor

θ_b = Minimum angular distance that an open field footpoint lies from nearest coronal hole boundary (i.e., Angular depth inside a coronal hole)

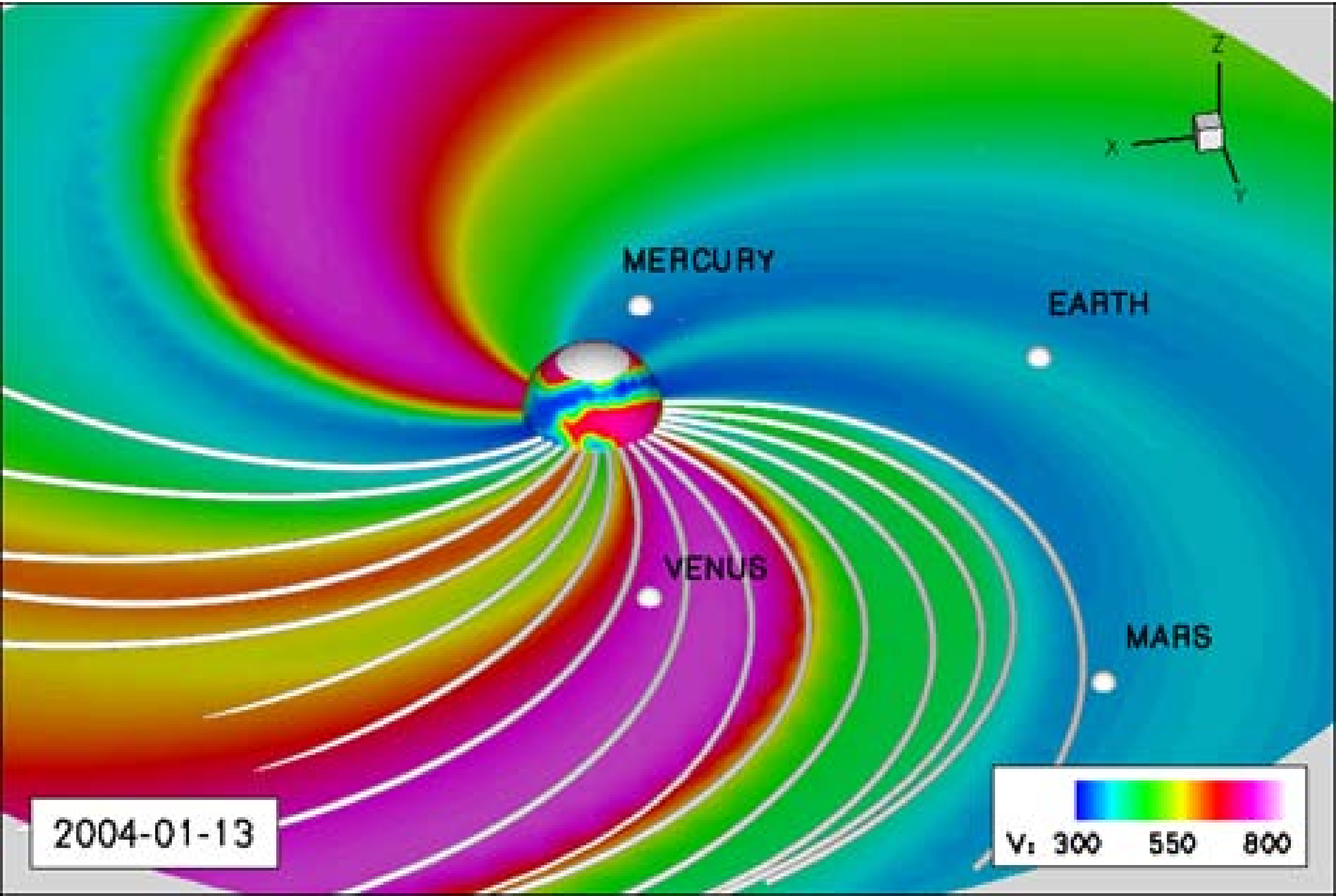
Model Output



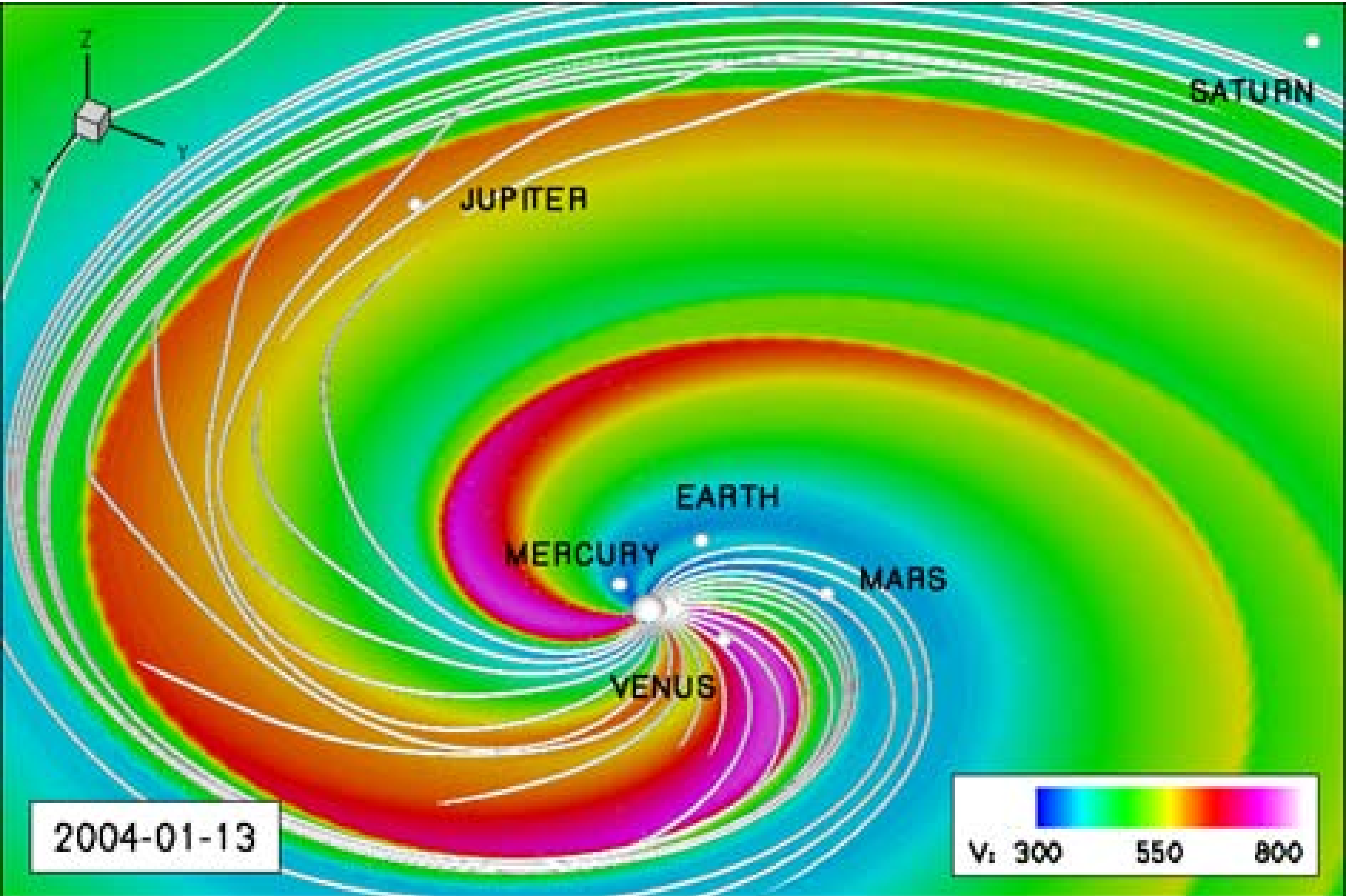
Boundary Conditions



Solar Wind at Inner Heliosphere

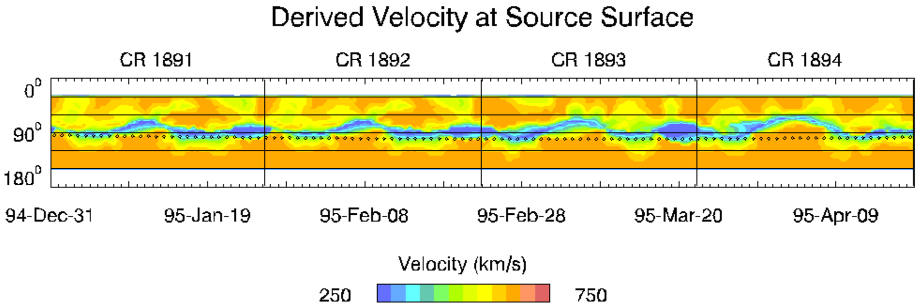


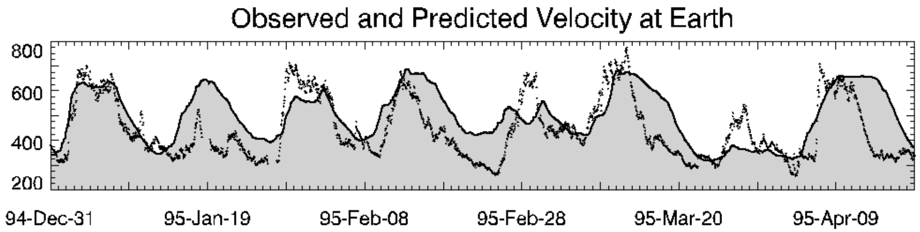
Solar Wind at Mid Heliosphere



Calibration of Ambient Solar Wind

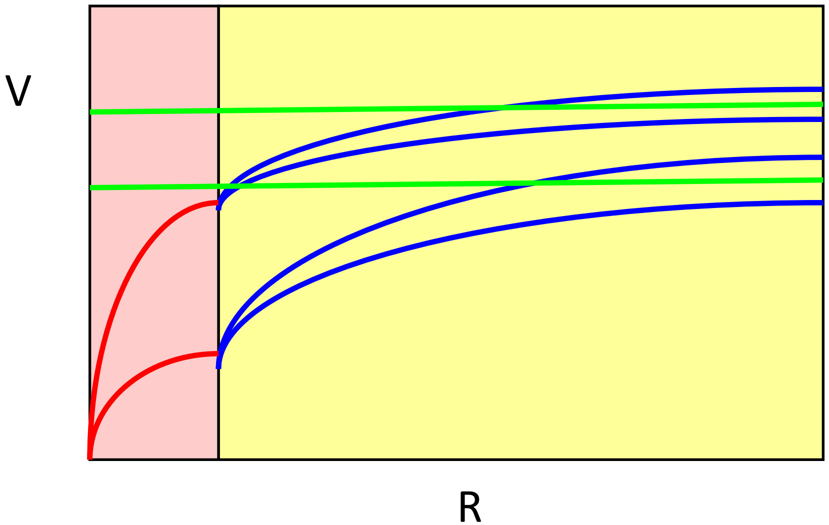
- Latitudinal distribution of the outflow velocity at model interface (top panel)
- Predicted evolution at Earth (solid line) together with actually observed values (dots) by Wind s/c (bottom panel)





Match with observations has to be improved

Radial profiles of the solar wind flow velocity for MAS, WSA, and ENLIL models

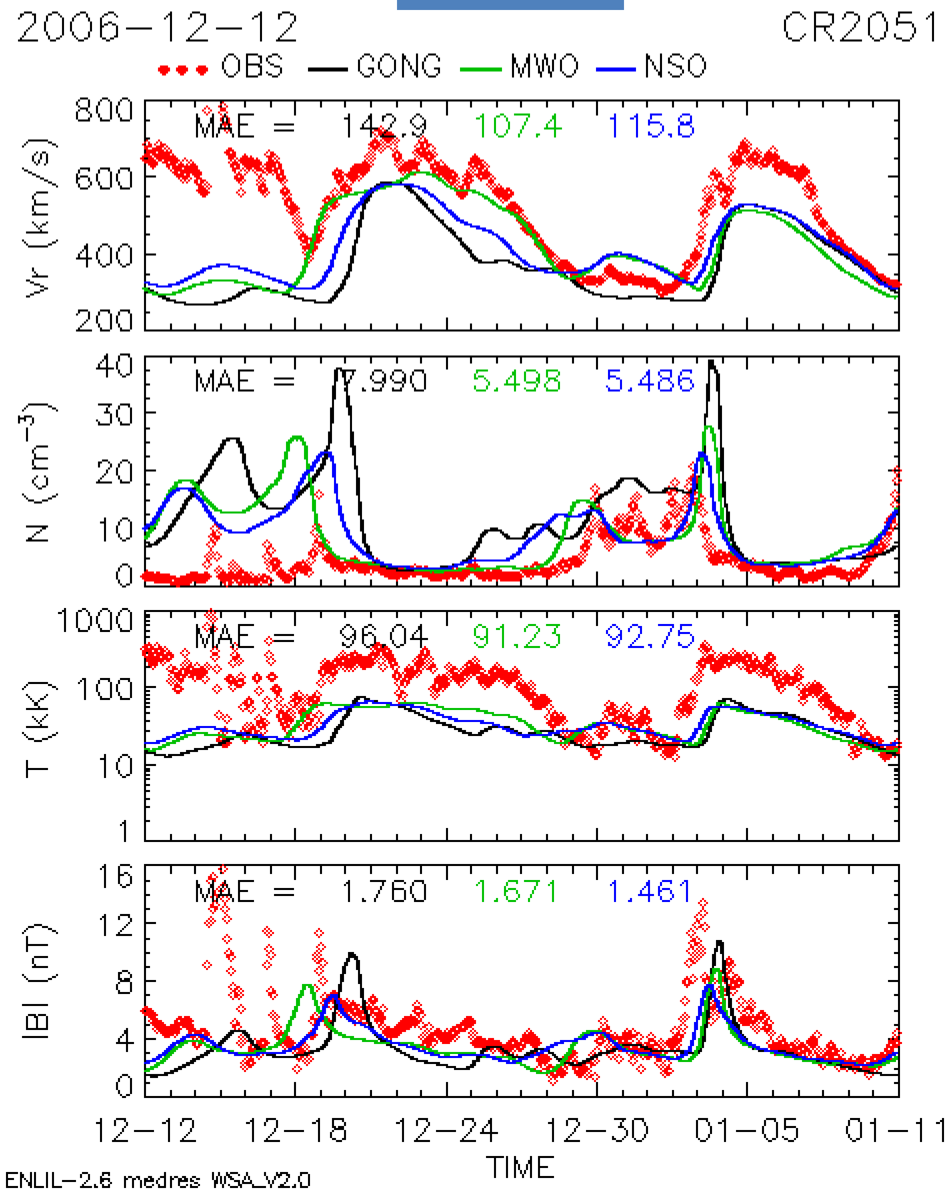


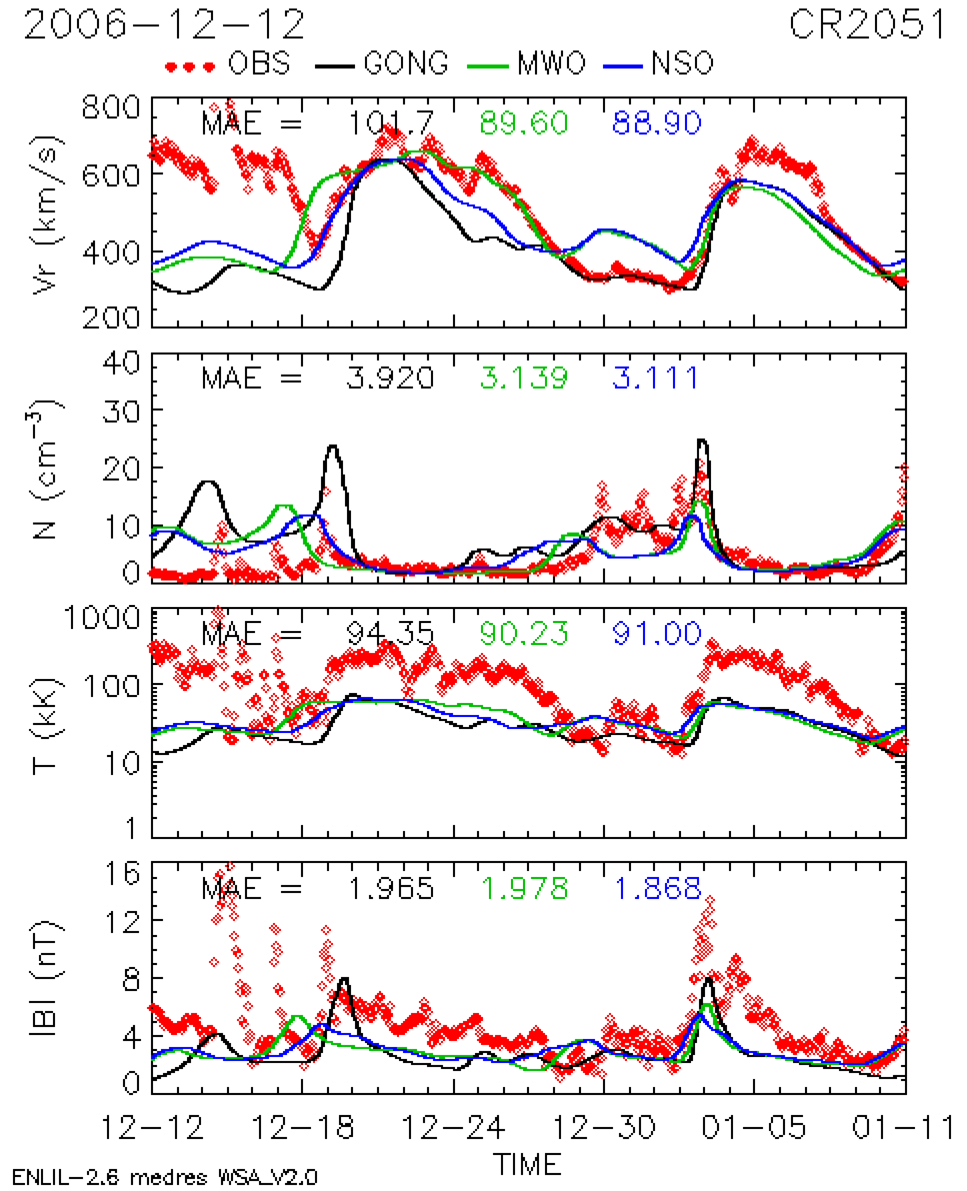
ENLIL needs to use re-calibrated MAS or WSA solar wind flow speeds at the models interface boundary.

Solar Wind – 2007 – CR2051

a2b2

a3b2

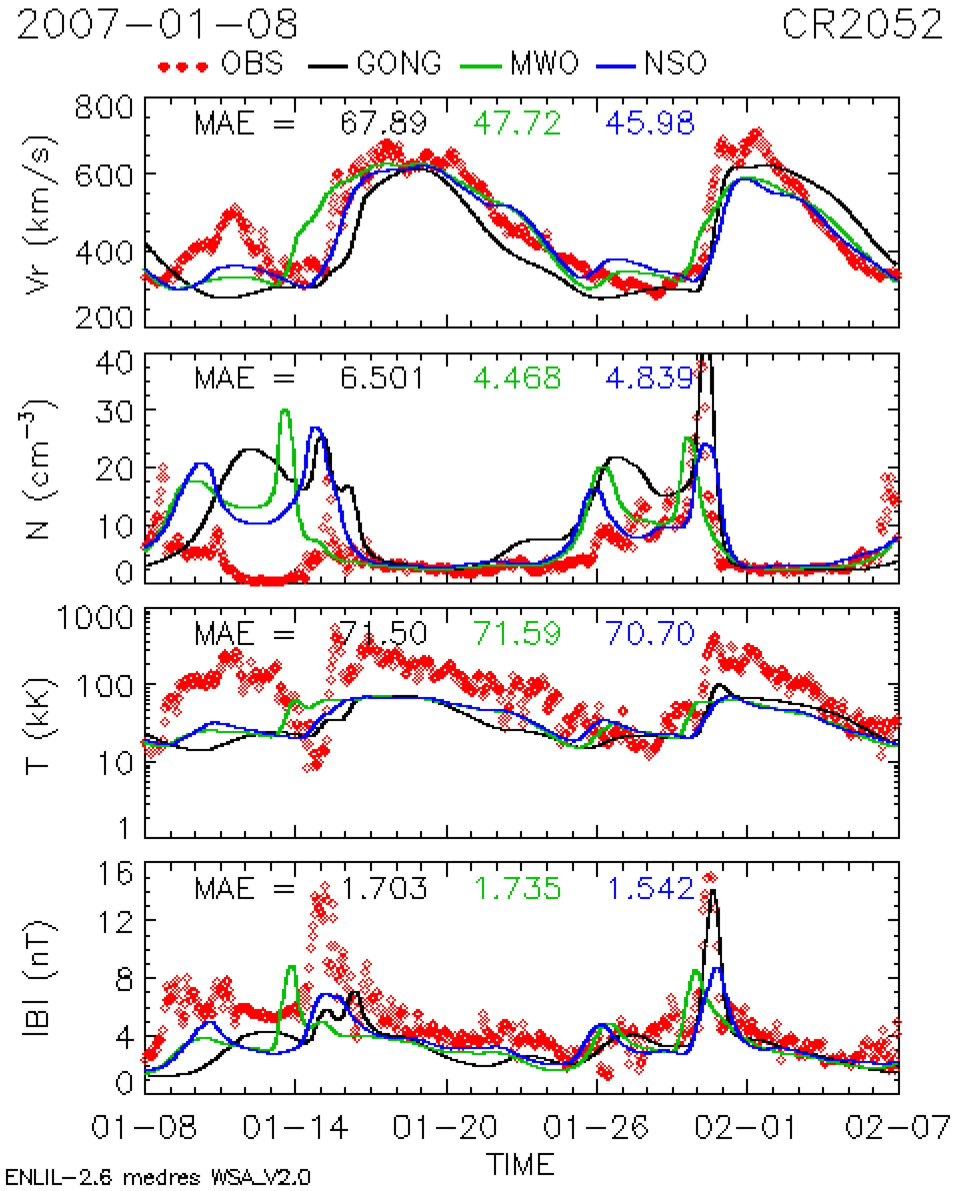


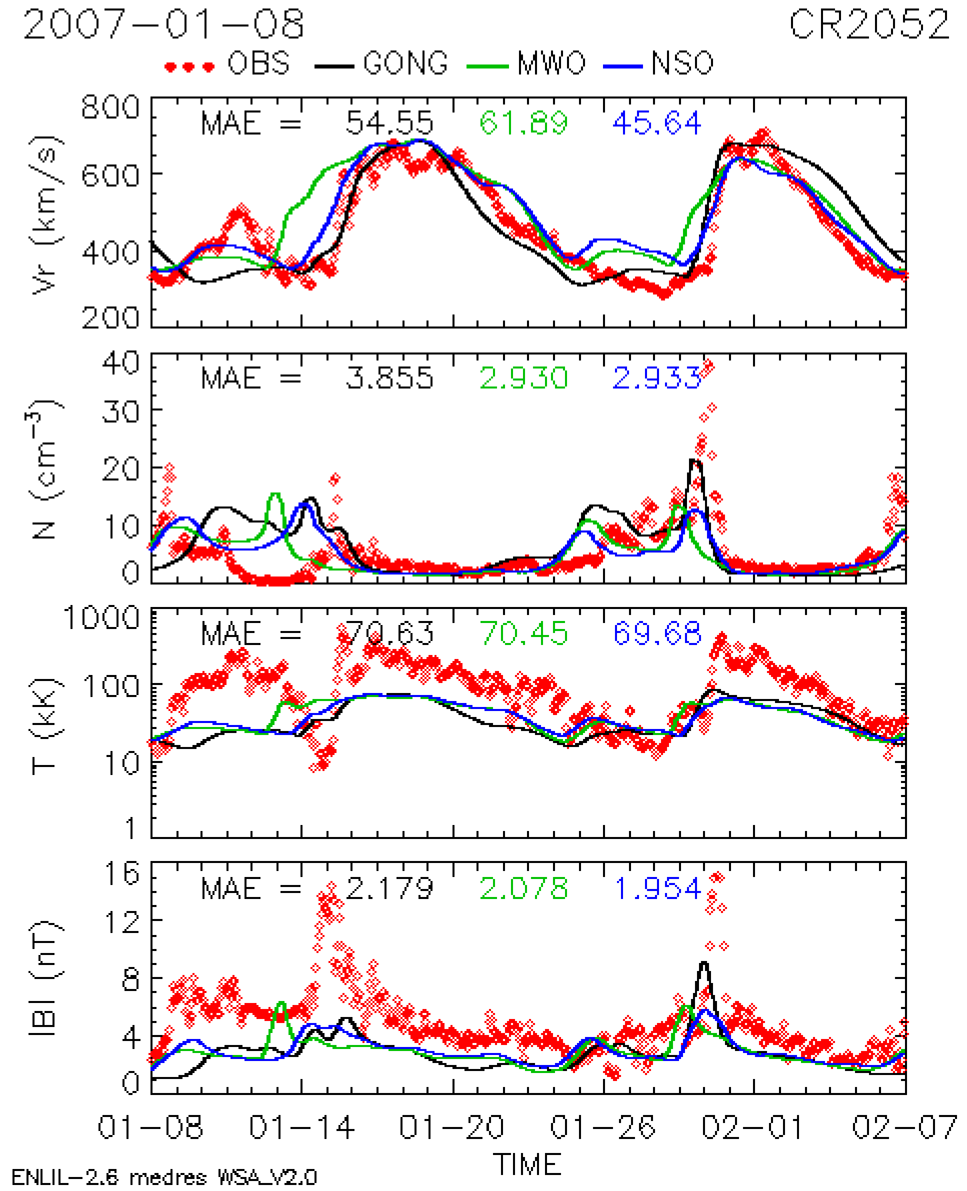


Solar Wind – 2007 – CR2052

a2b2

a3b2

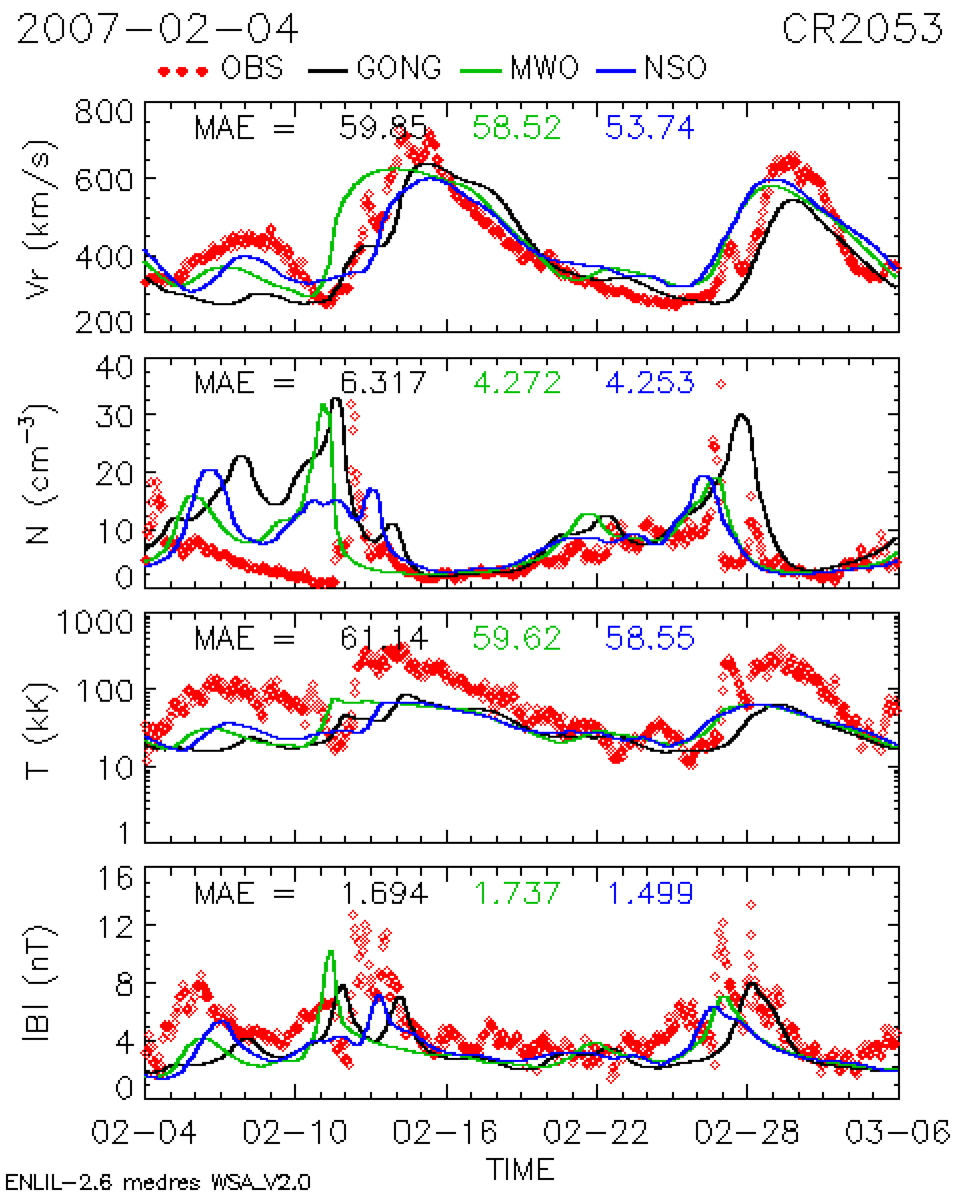


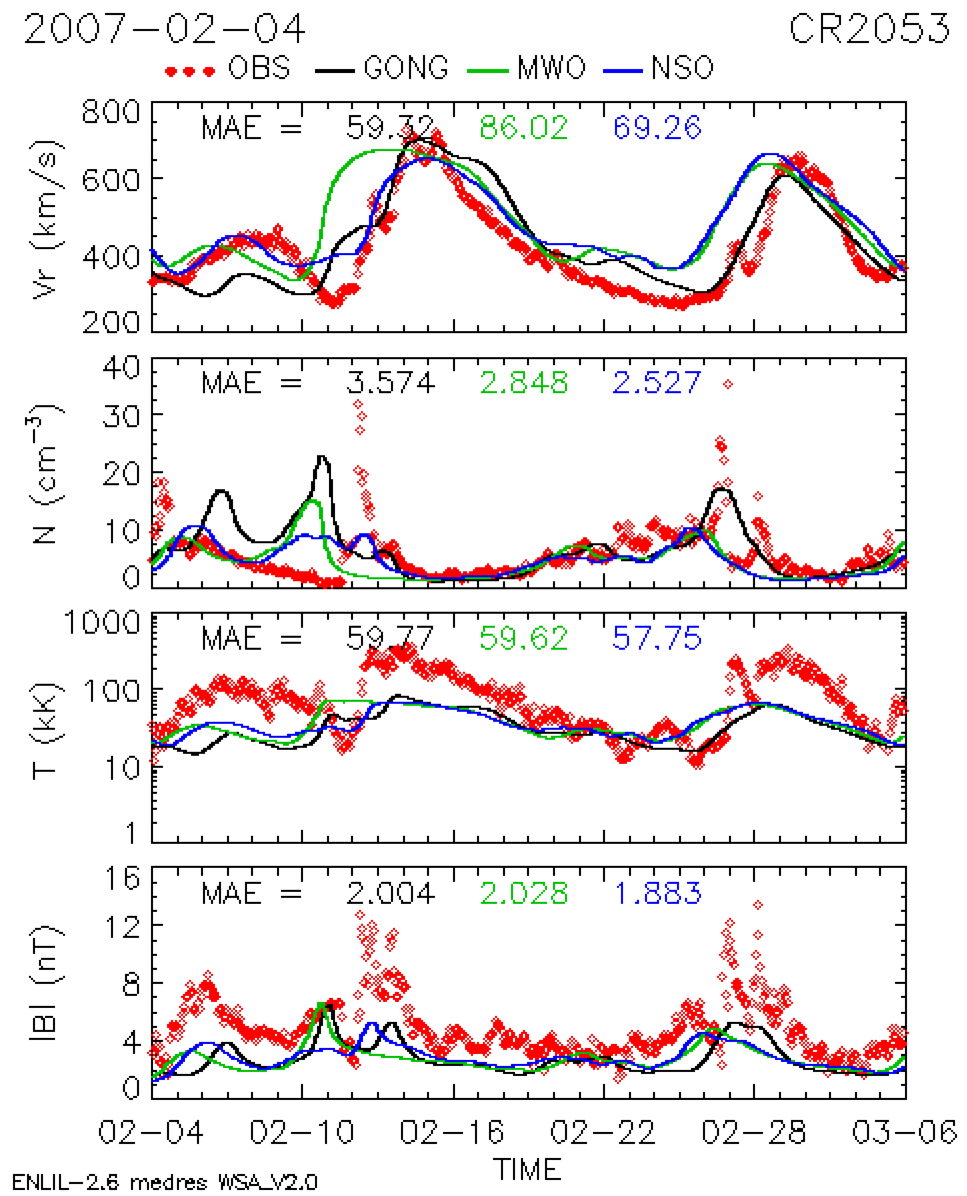


Solar Wind – 2007 – CR2053

a2b2

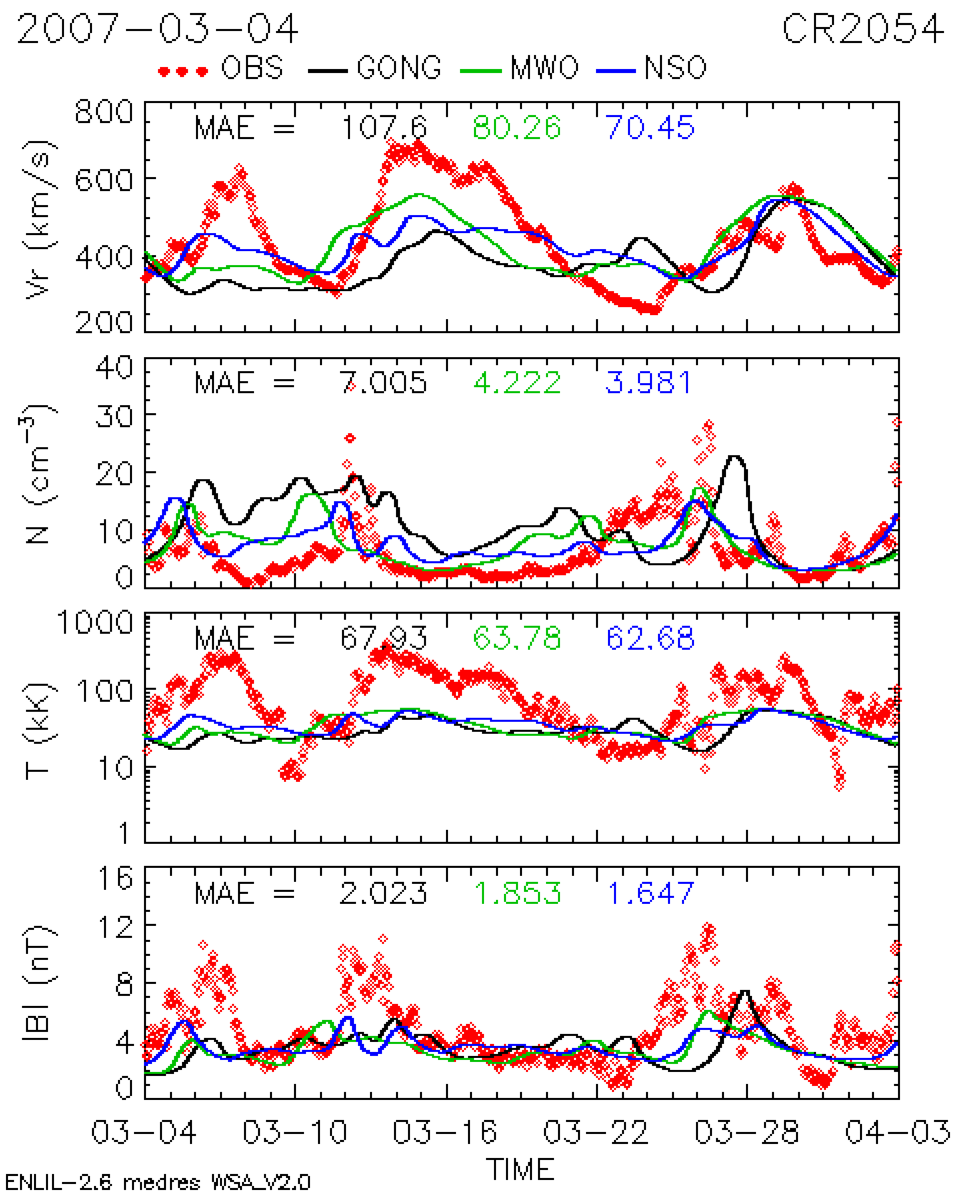
a3b2



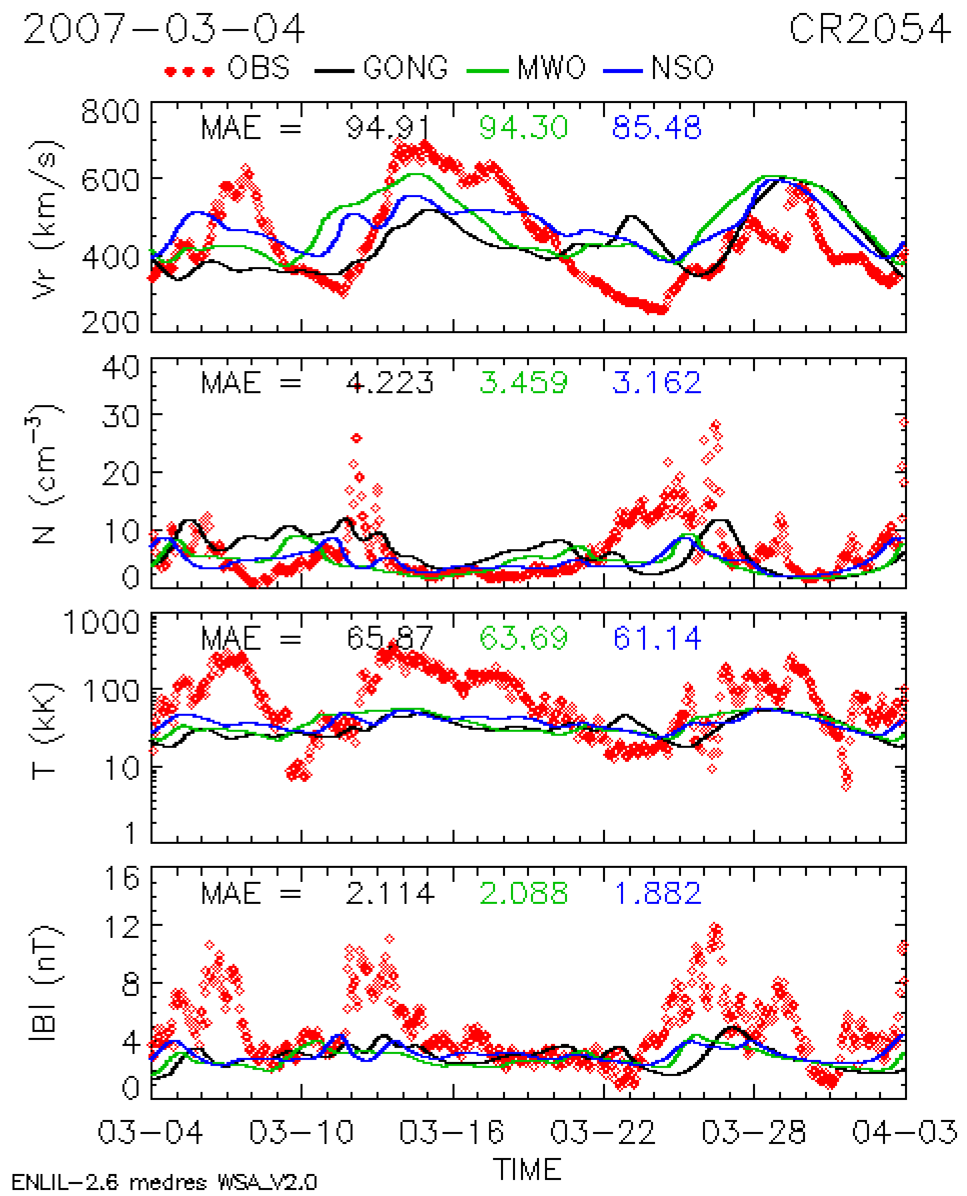


Solar Wind – 2007 – CR2054

a2b2



a3b2



Solar Wind – Model Calibration – V_{MAE}

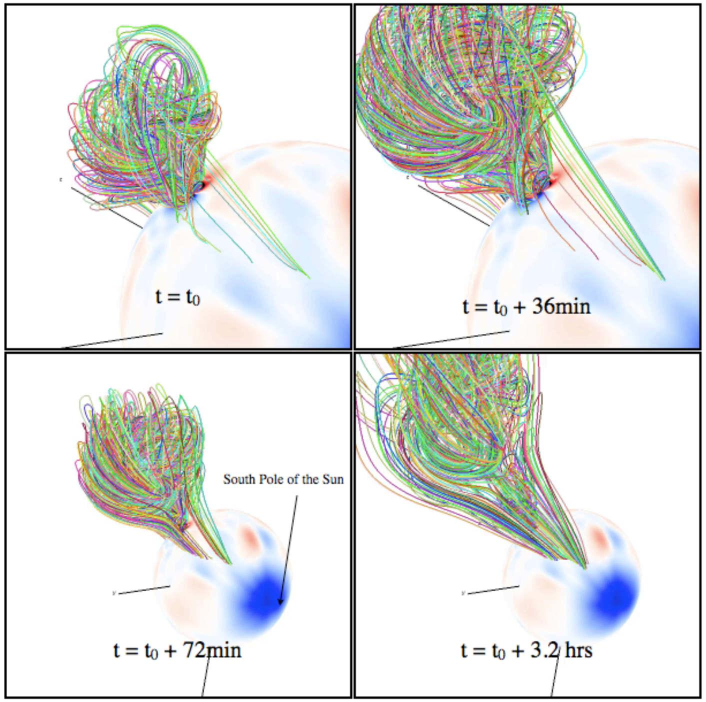
	a2b2	a3b2
CR2051	GONG = 142.9 **MWO = 107.4** NSO = 115.8	GONG = 101.7 MWO = 89.60 **NSO = 88.90**
CR2052	GONG = 67.89 MWO = 47.72 **NSO = 45.98**	GONG = 54.55 MWO = 61.89 **NSO = 45.64**
CR2053	GONG = 59.85 MWO = 58.52 **NSO = 53.74**	**GONG = 59.32** MWO = 86.02 NSO = 69.26
CR2054	GONG = 107.6 MWO = 80.26 **NSO = 70.45**	GONG = 94.91 MWO = 94.30 **NSO = 85.48**

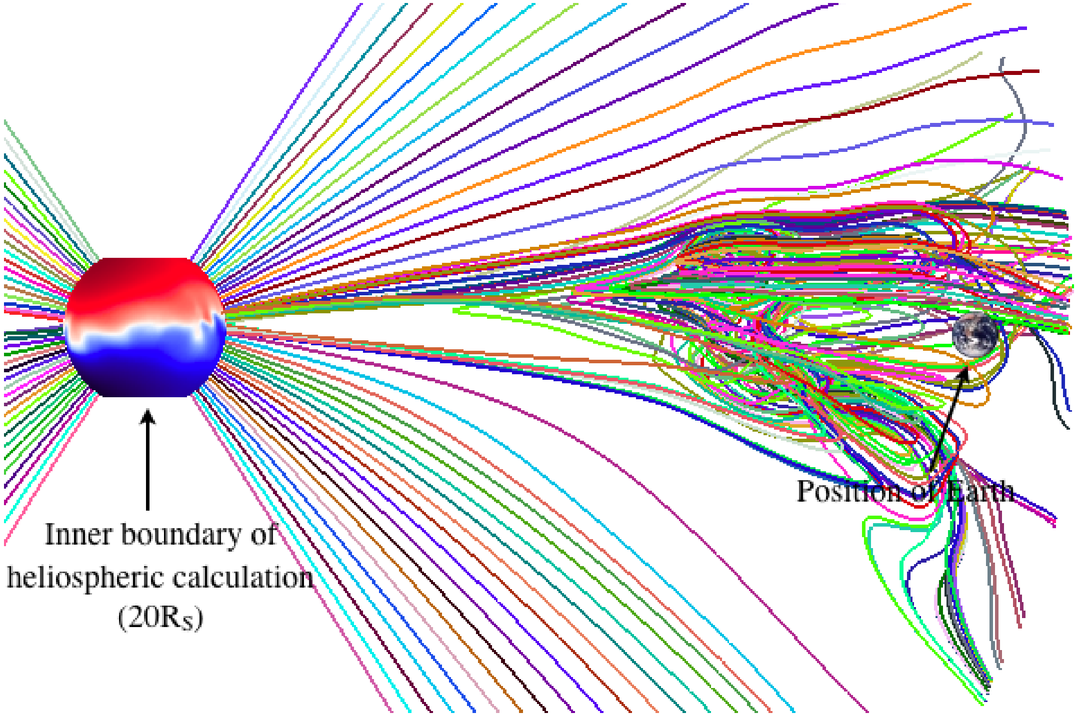
Transient Disturbances

May 12, 1997 – Interplanetary CME

MAS coronal model (PSI)

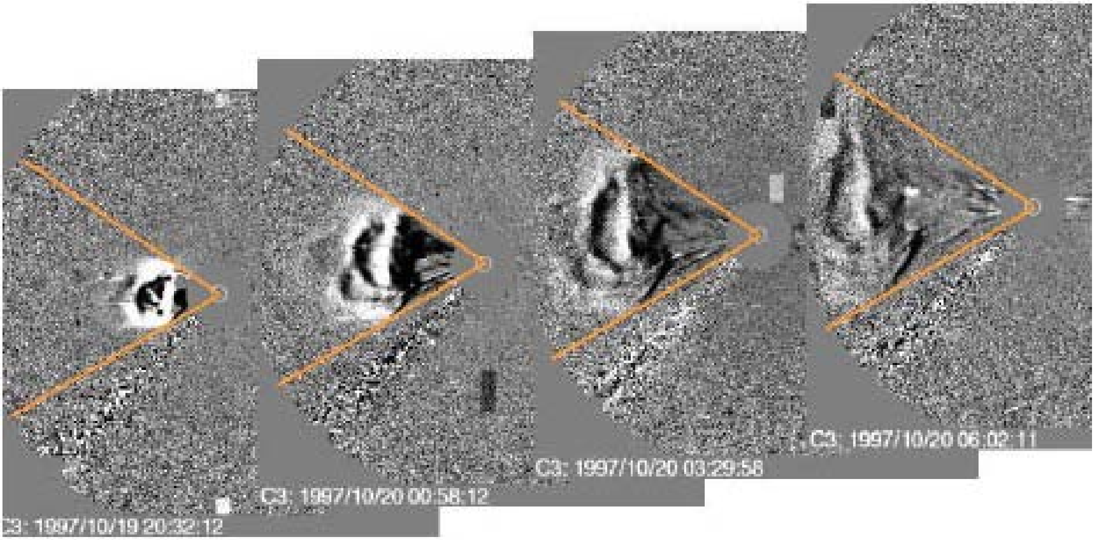
ENLIL heliospheric model (*GMU-NASA /GSFC*)

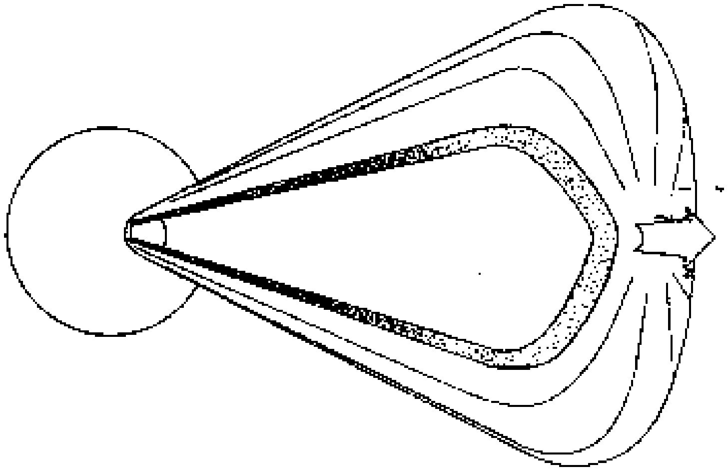




Self-consistent end-to-end numerical simulation of space weather event
(NSF/CISM effort in progress)

CME Cone Model





Observational evidence:

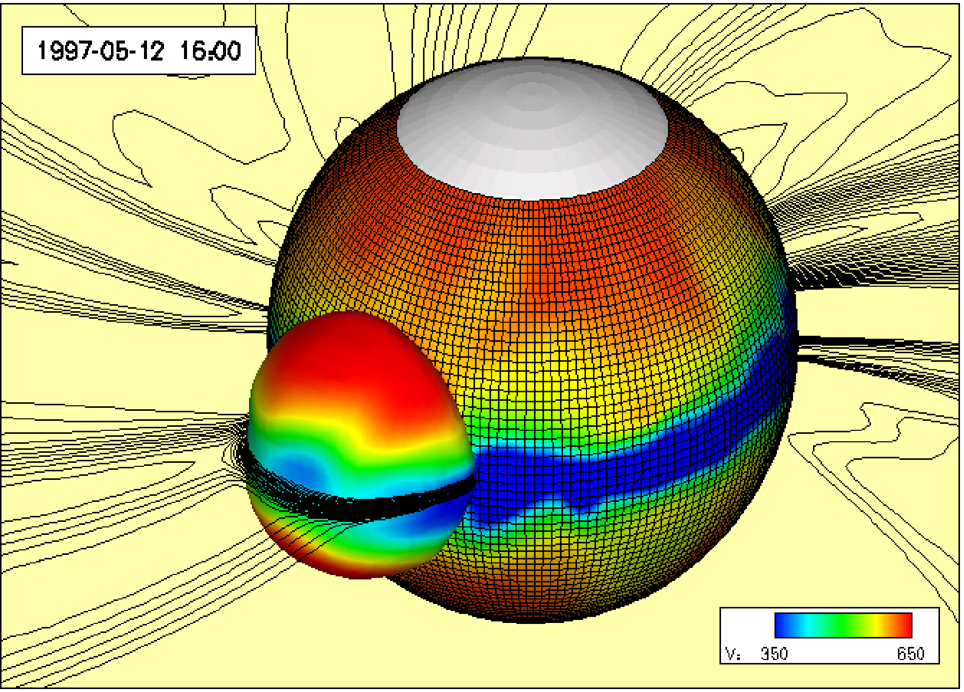
- CME expands self-similarly
- Angular extent is constant

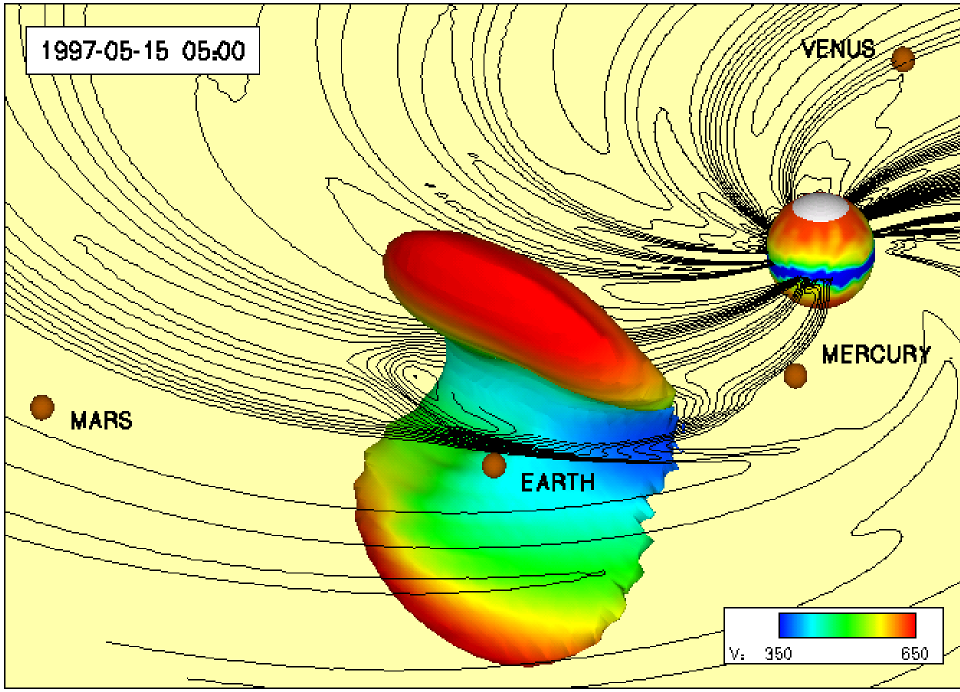
Conceptual model:

- CME as a shell-like region of enhanced density

[*Howard et al,* 1982; *Fisher & Munro,* 1984]

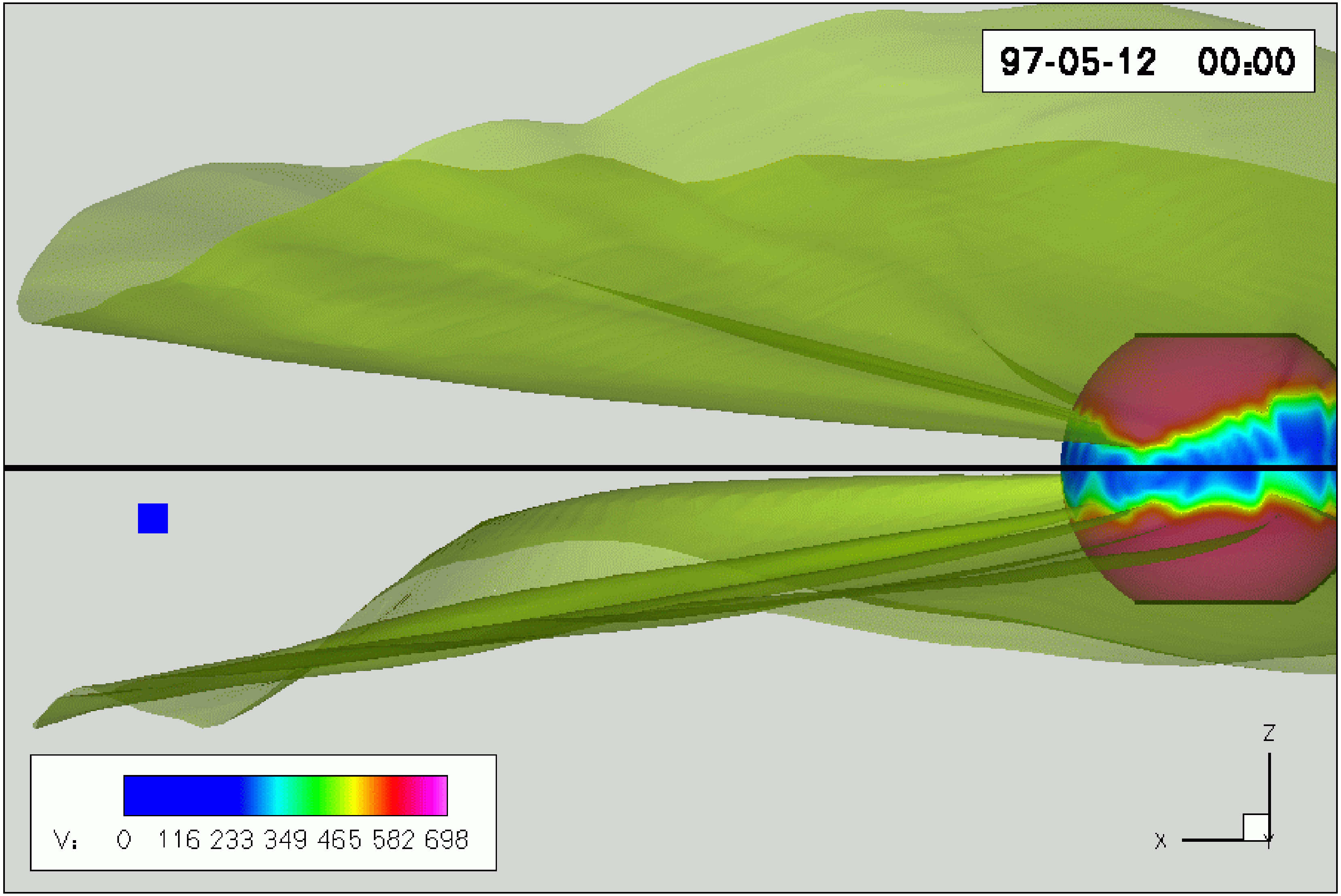
Transient Disturbances





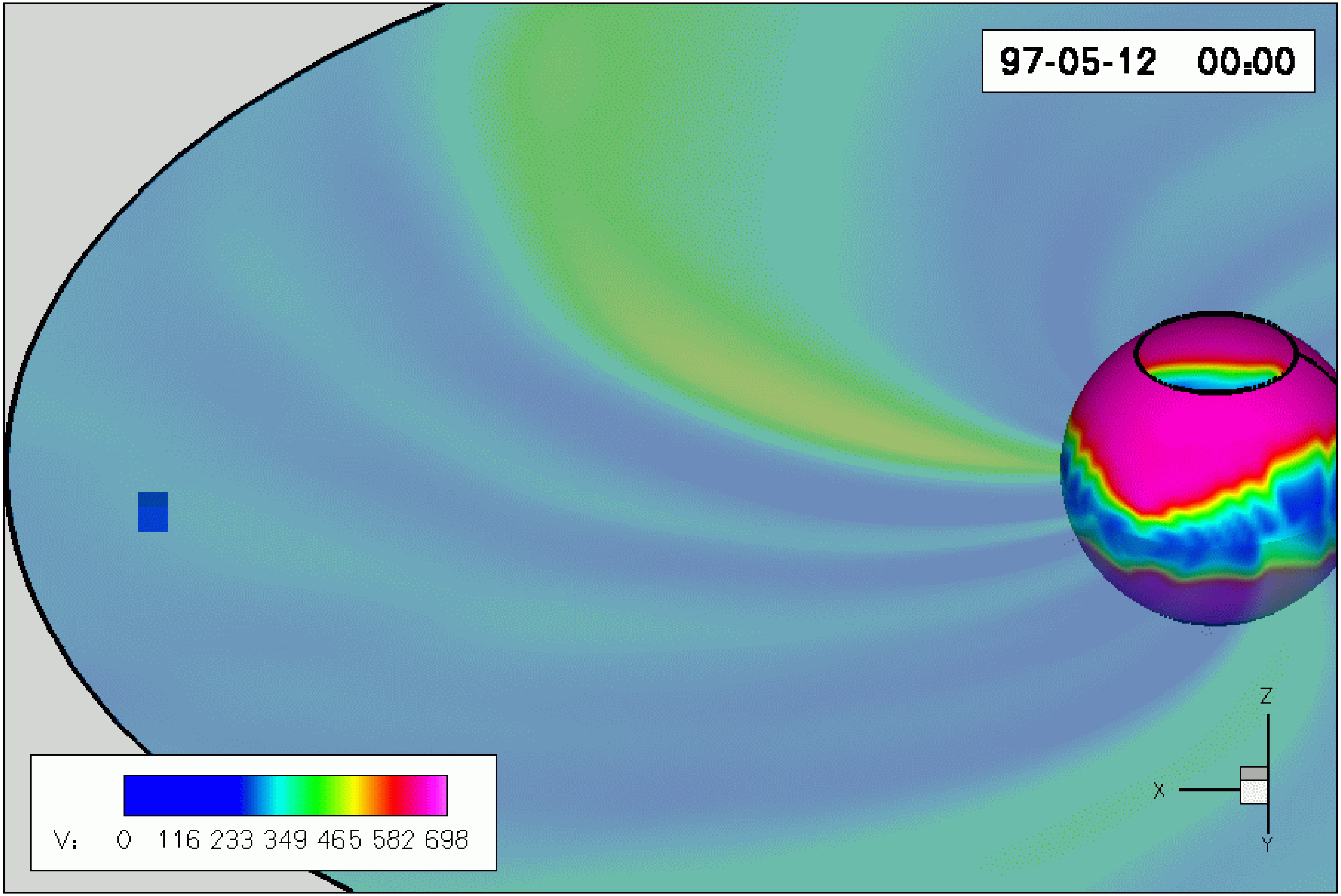
Modeling of the origin of CMEs is still in the research phases and it is not expected that real events can be routinely simulated in near future. Therefore, we have developed an intermediate modeling system which uses the WSA coronal maps, fitted coronagraph observations, specifies 3D ejecta, and drives 3D numerical code ENLIL.

Latitudinal Distortion of ICME Shape



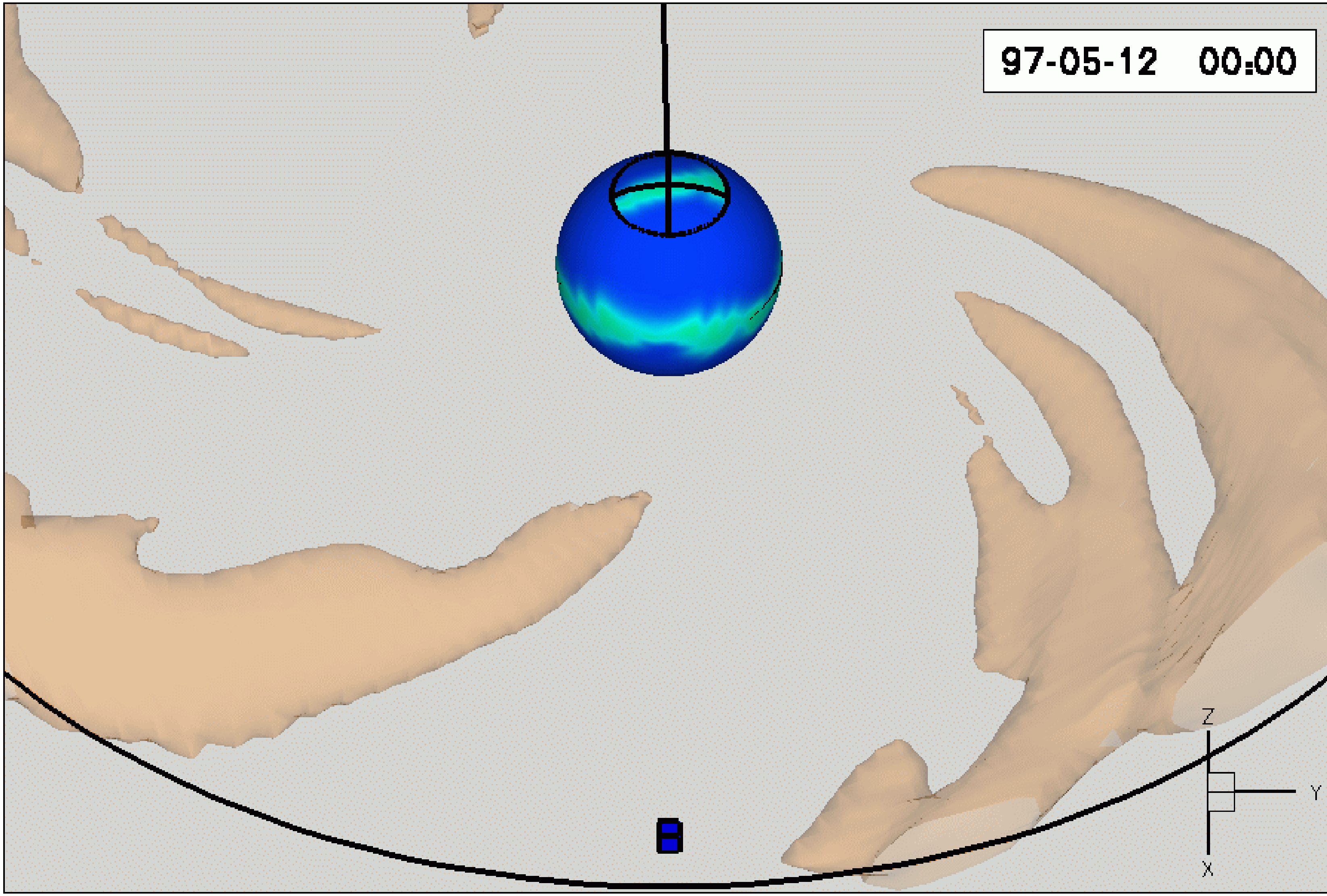
ICME propagates into bi-modal solar wind

Radial Compression of ICME Structure



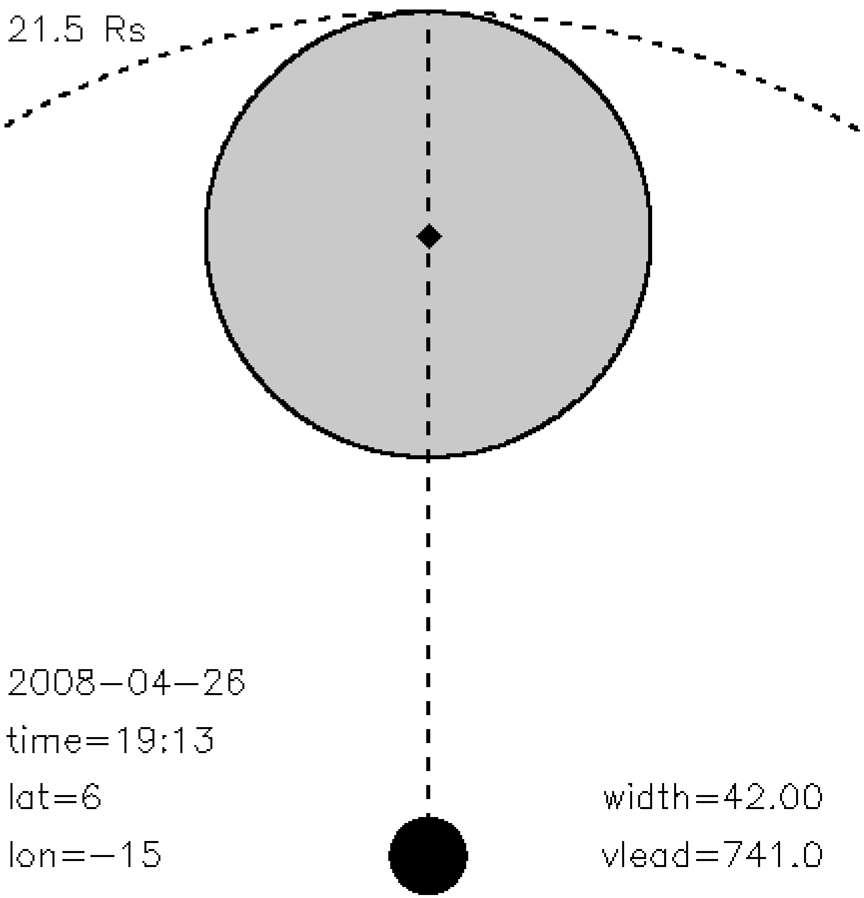
Fast stream follows the ICME

Evolution of Density Structure

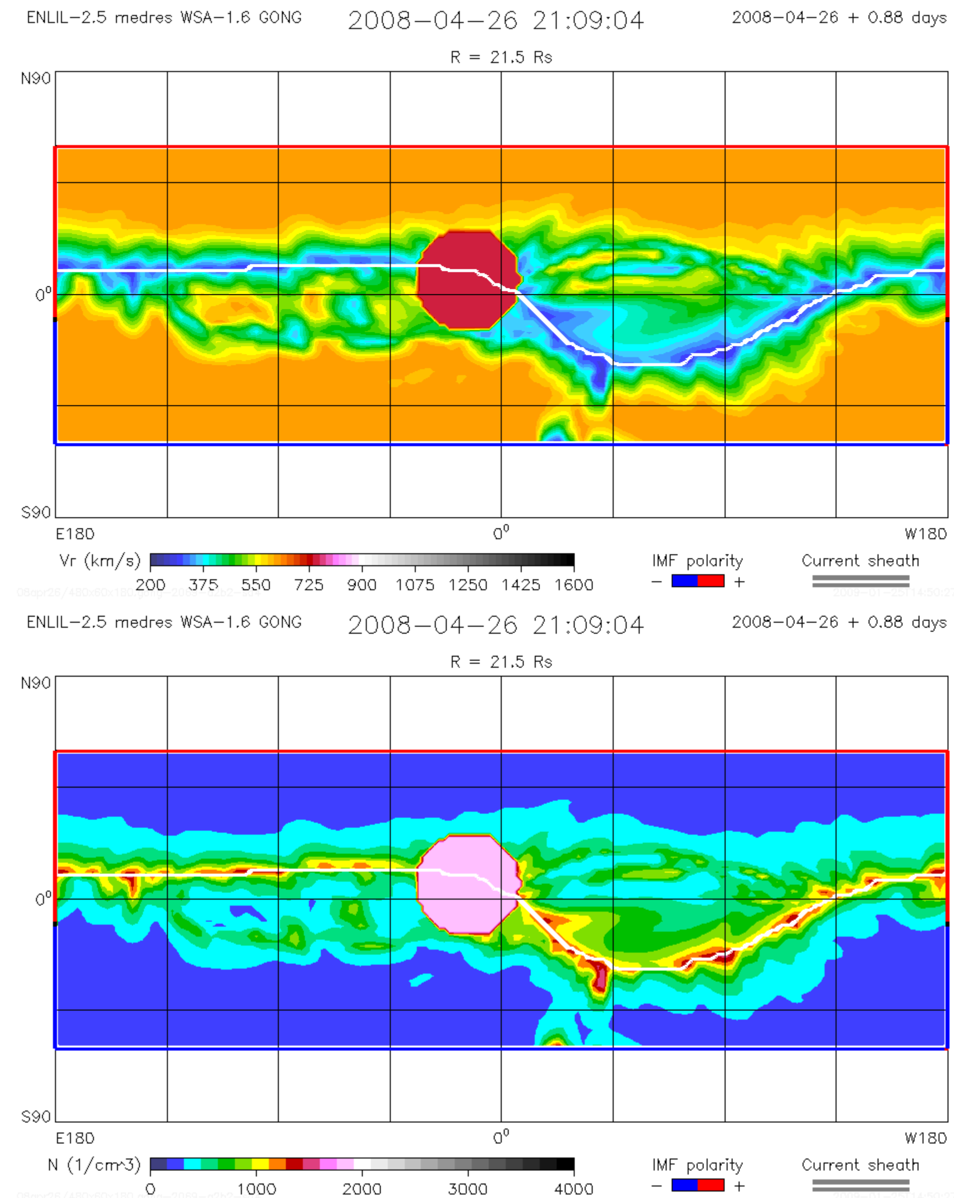


ICME propagates into the enhanced density of a streamer belt flow

2008 April 26 CME with Cone Model

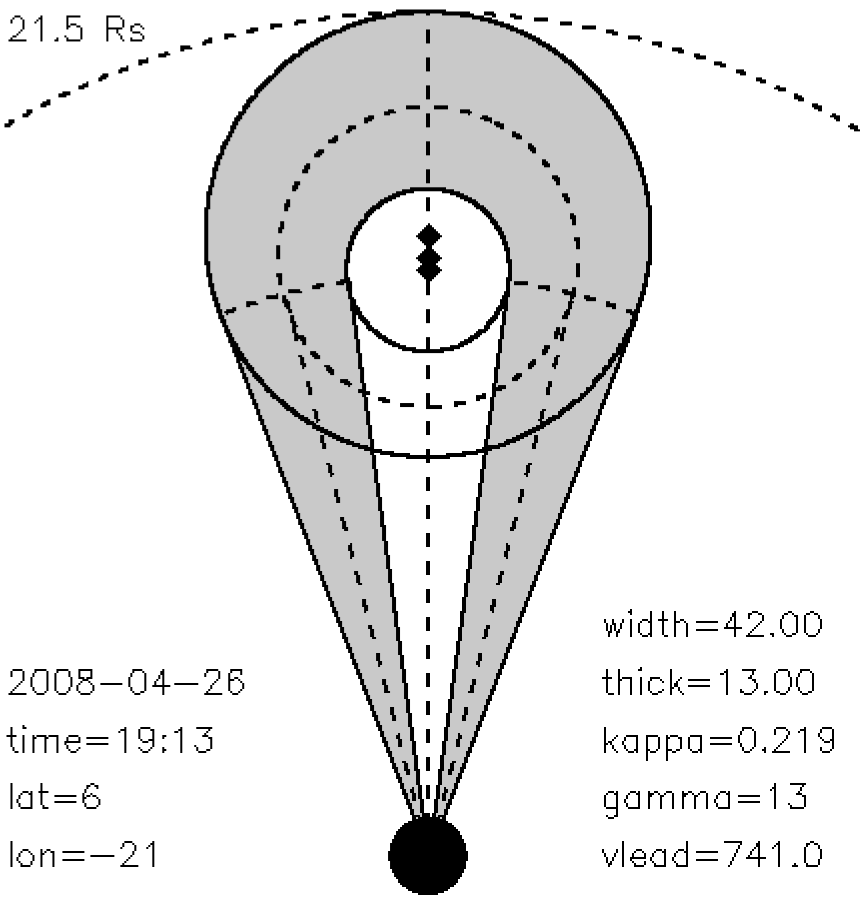


(Thernisien et al., 2009)

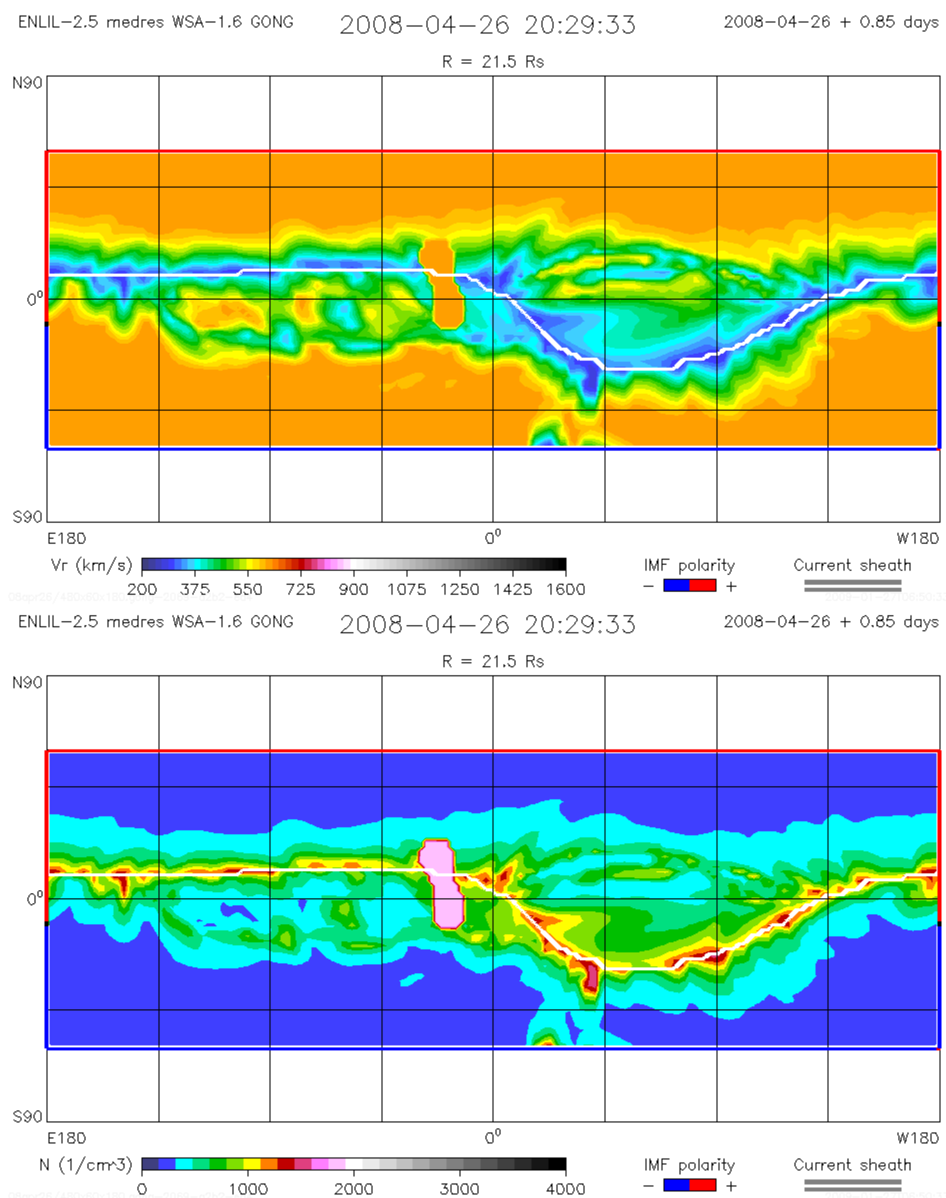


(WSA-1.6-GONG-CR2069)

2008 April 26 CME with Rope Model



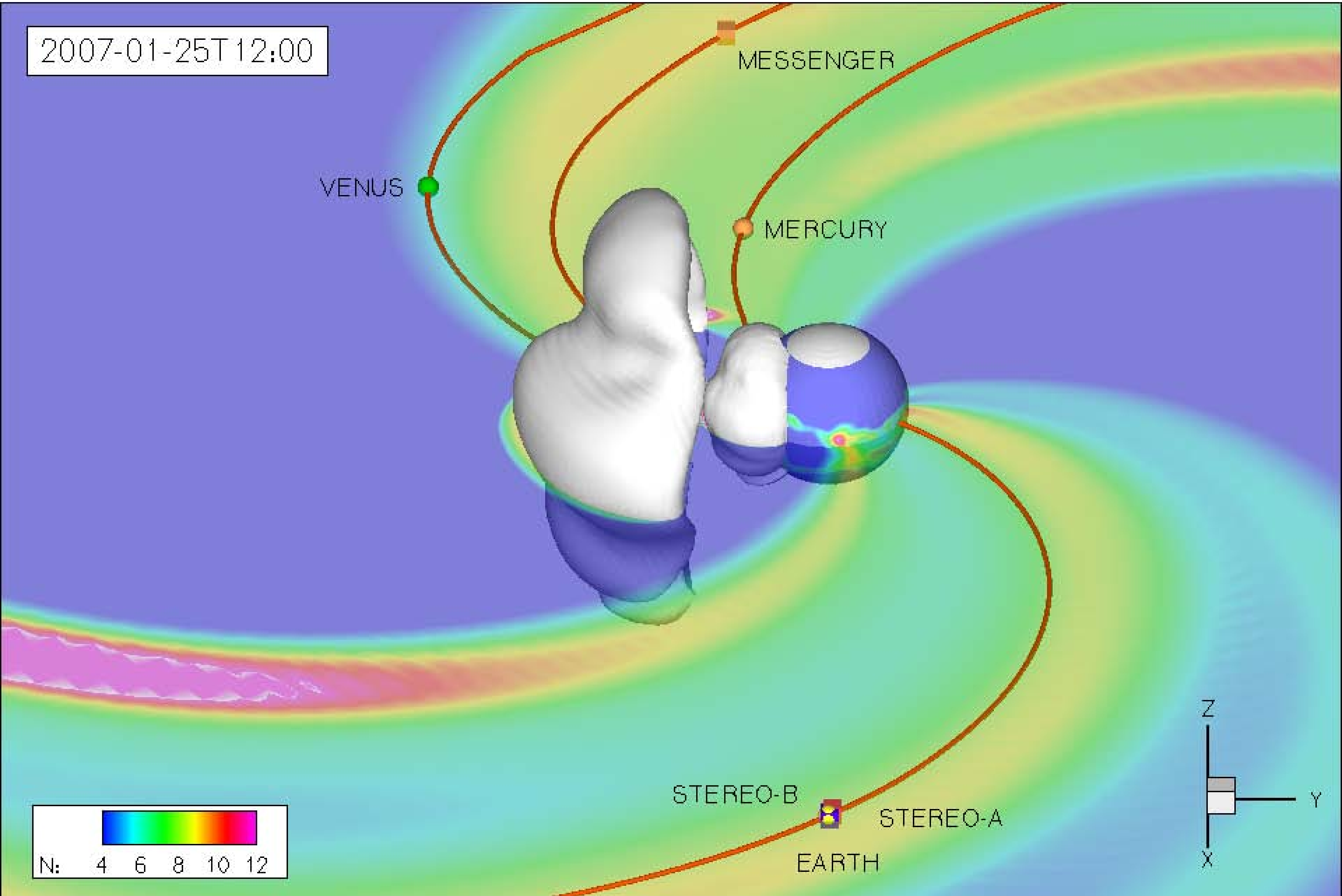
(Thernisien et al., 2009)



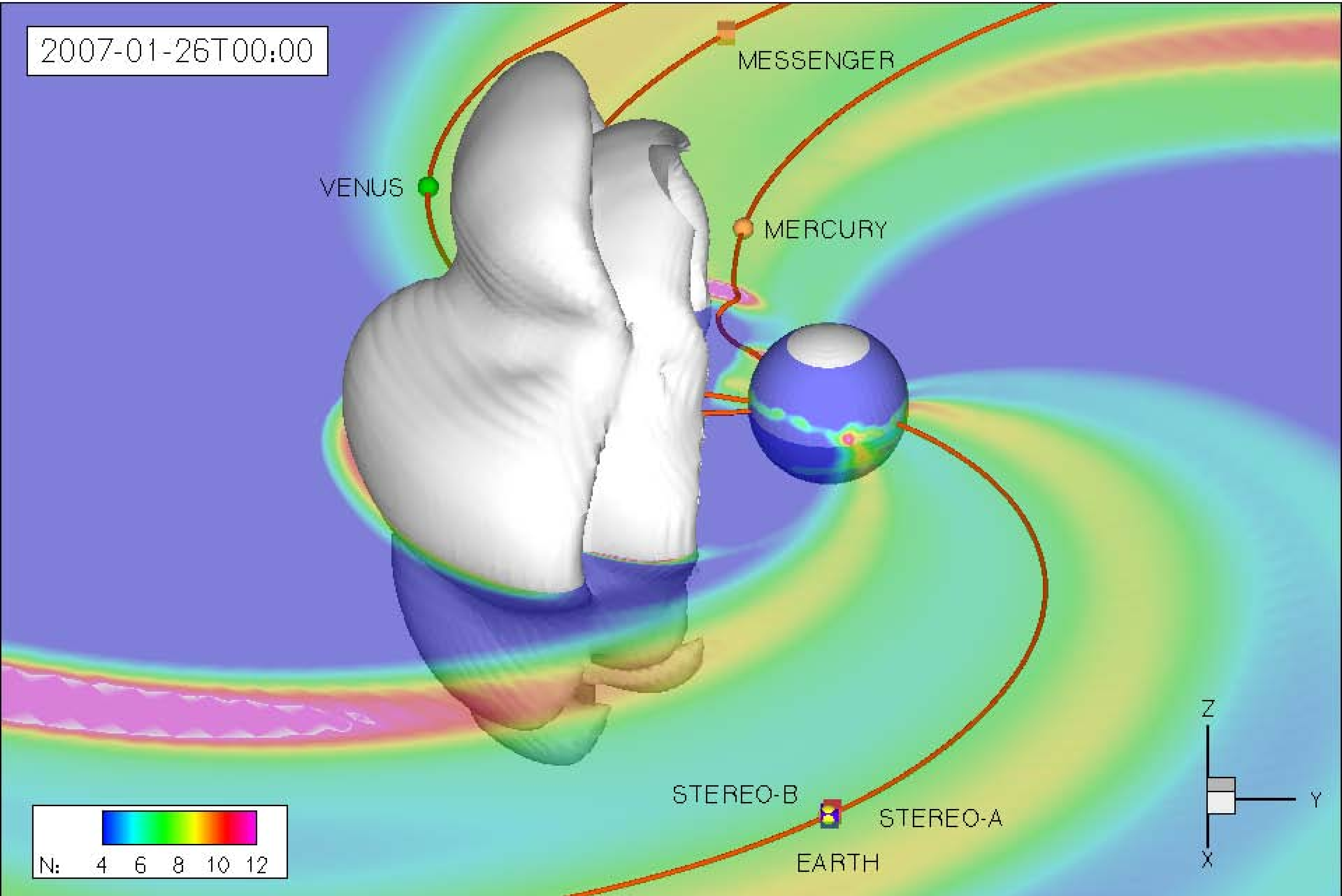
(WSA-1.6-GONG-CR2069)

Interpretation of White-Light Observations

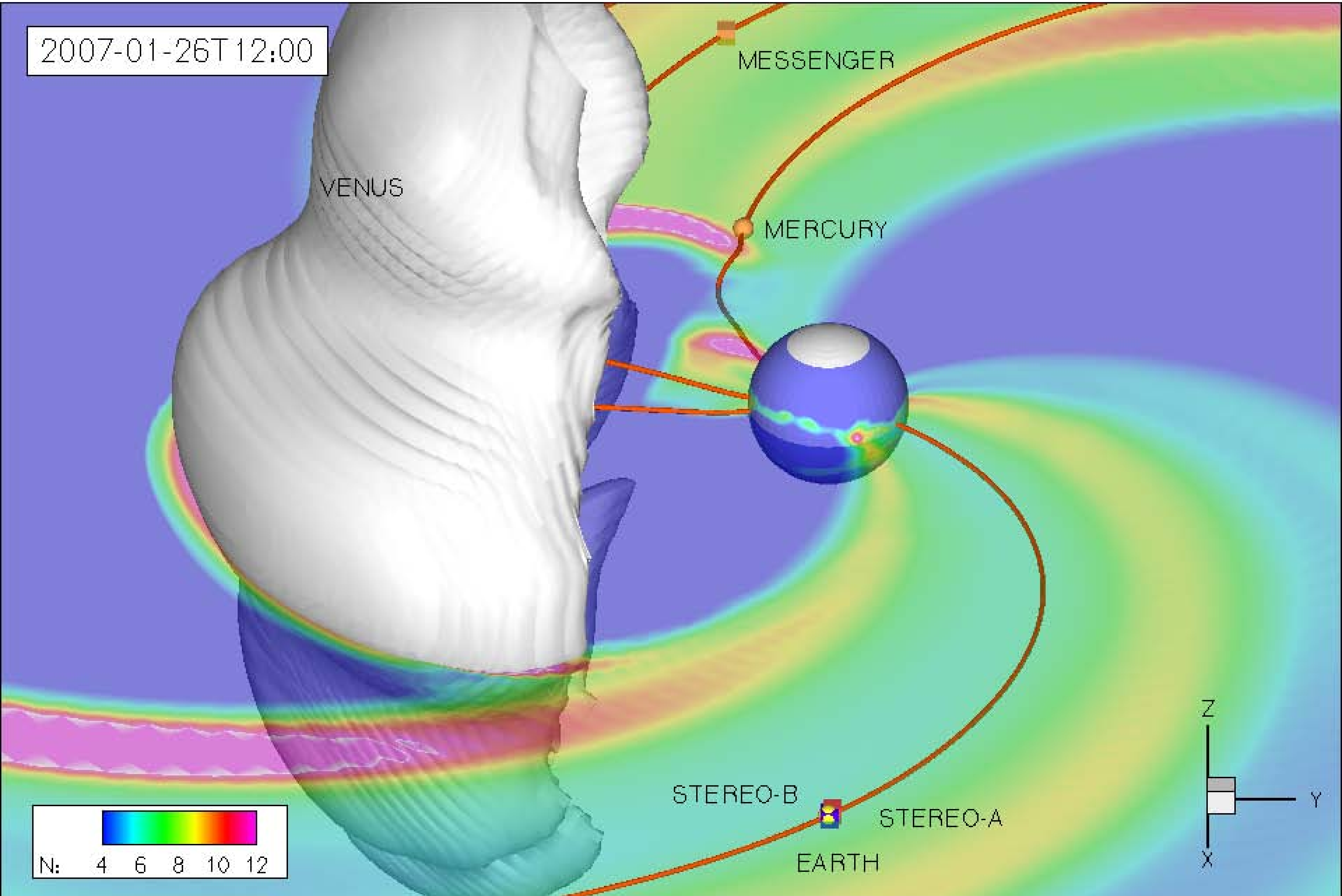
2007 January 24-25 CMEs – Time 1



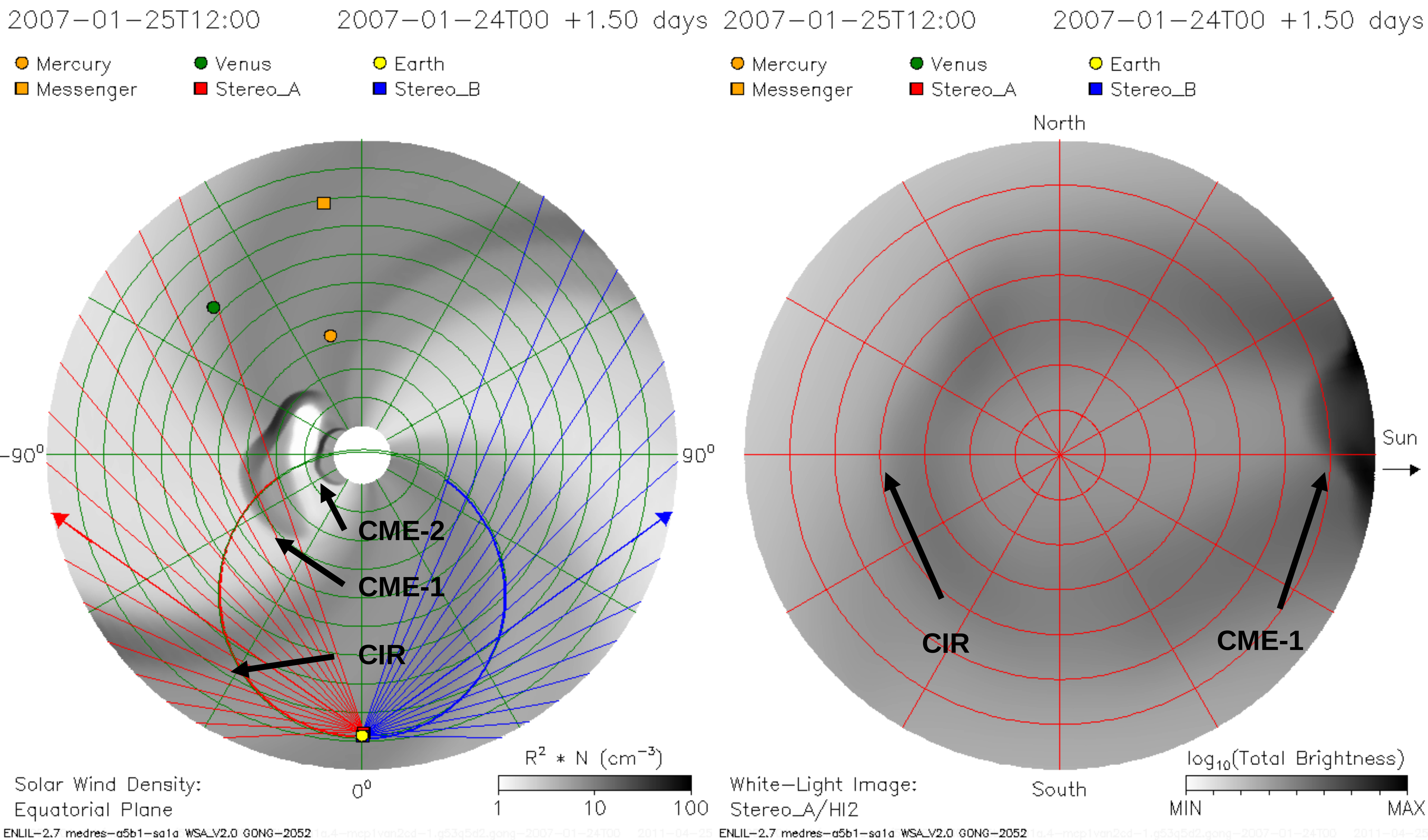
2007 January 24-25 CMEs – Time 2



2007 January 24-25 CMEs – Time 3

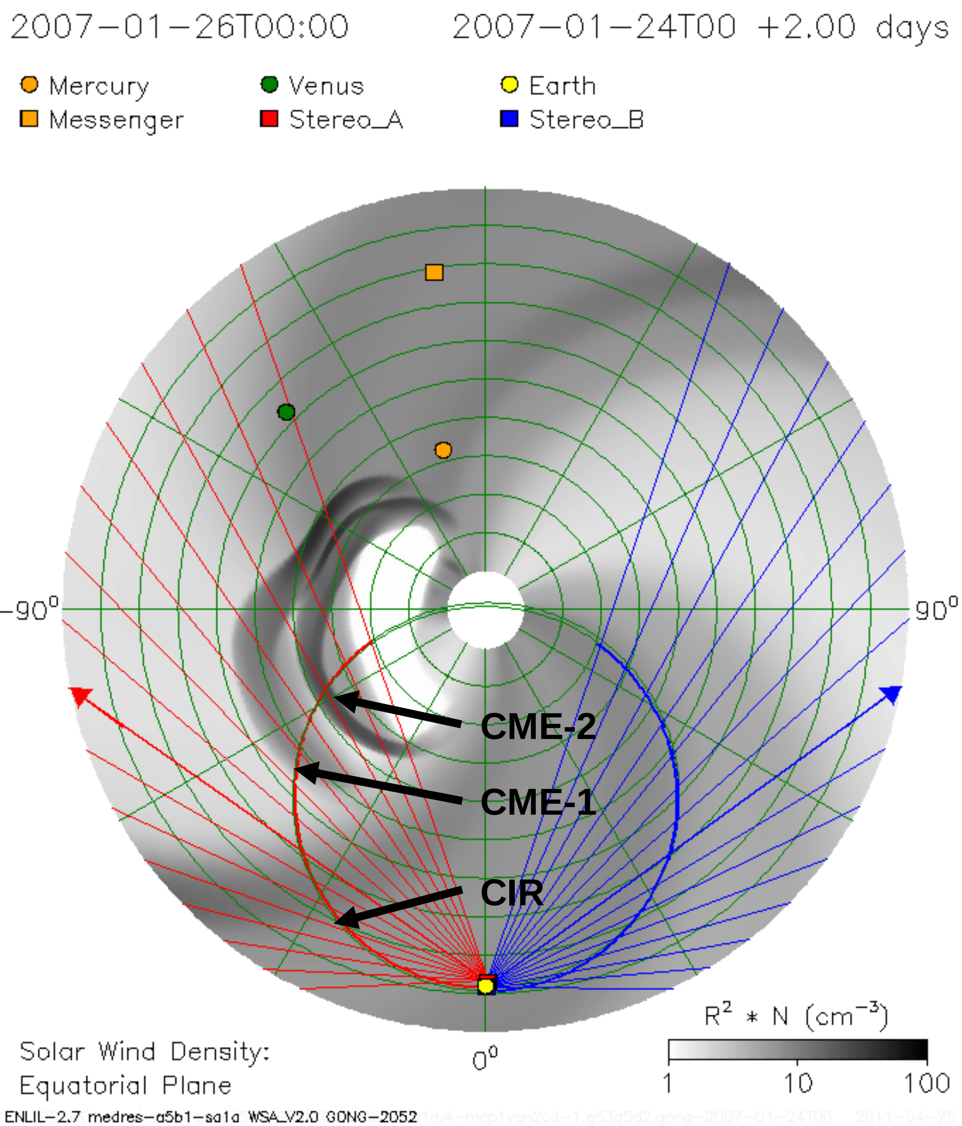


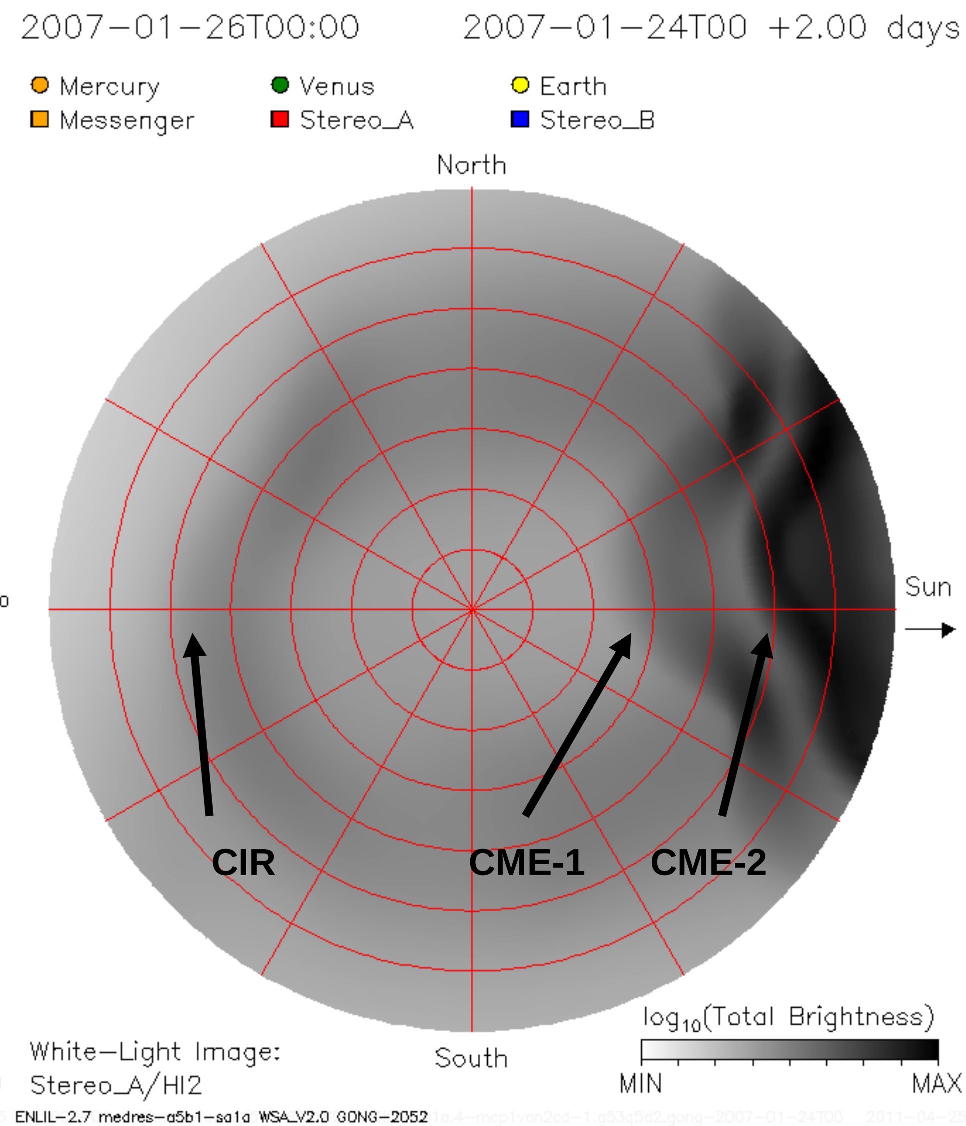
2007 January 24-25 CMEs – Time 1



- Modeling + imaging can differentiate between CIRs and CMEs

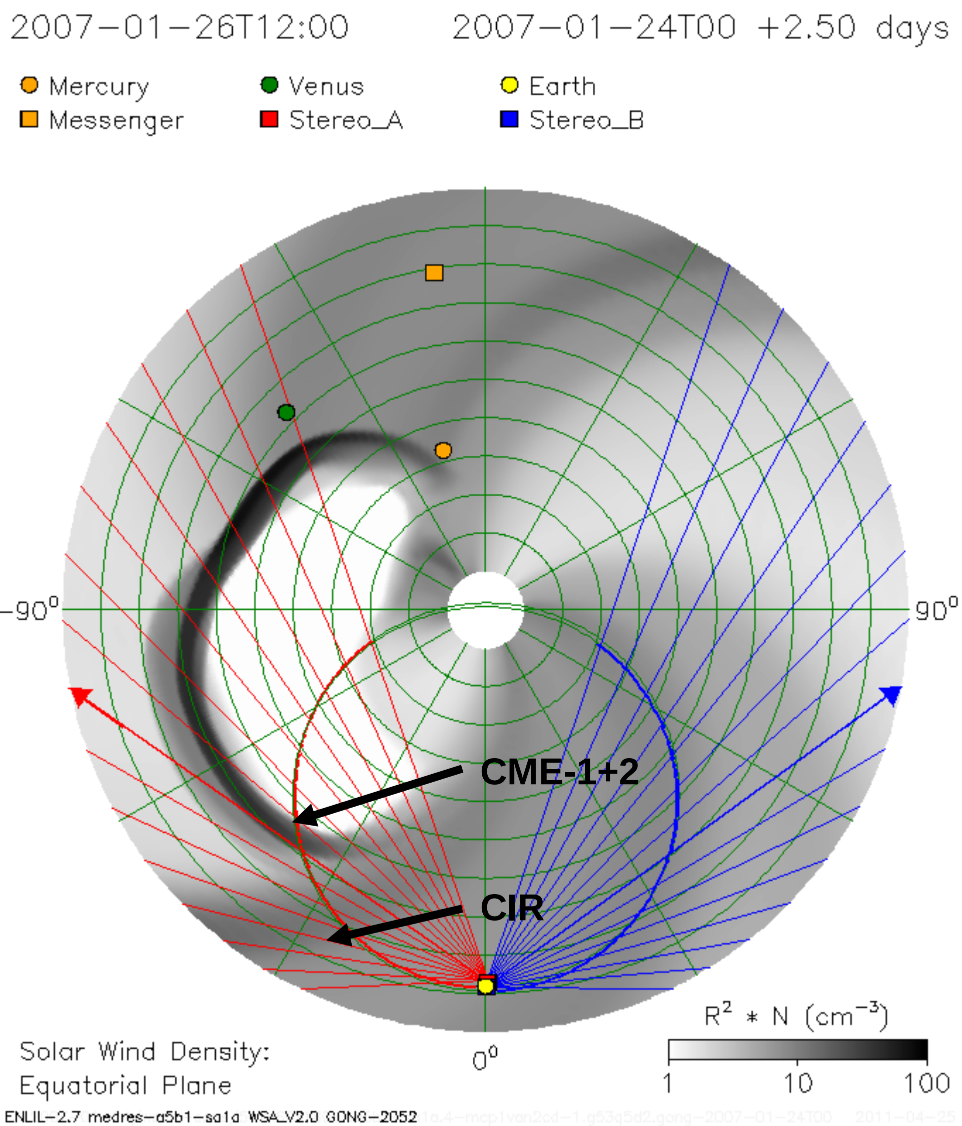
2007 January 24-25 CMEs – Time 2

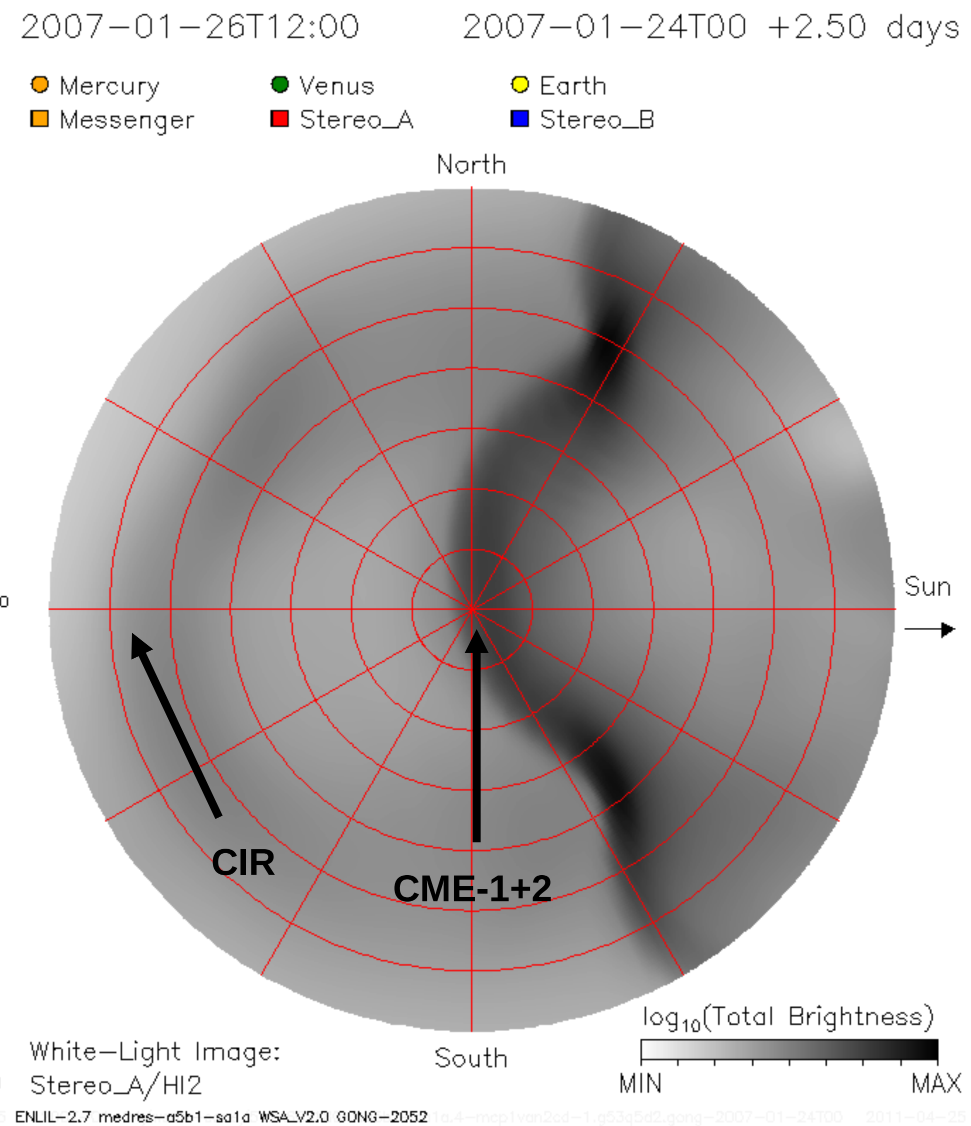




• Modeling + imaging can follow distortions of CMEs by background solar wind

2007 January 24-25 CMEs – Time 3





• Modeling + imaging can track interaction, merging, and amplification of disturbances

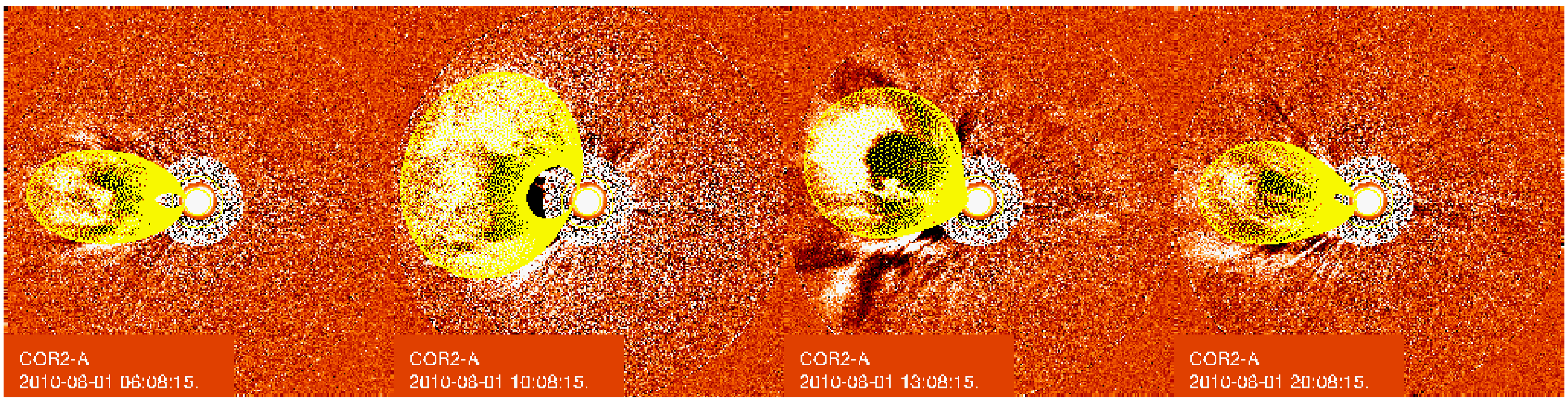
Need for Ensemble Modeling

2010-08-01 – Fitting of CMEs (Case 2)

(Hong Xie, CUA)

The flux rope fit for the 2010-08-01 CMEs. From left to right, the four panels are: STEREO A COR2 images superposed with flux-rope model outline curves (yellow curves) for a) CME 1 at 06:08 UT; b) CME 2 at 10:08 UT; c) CME 3 at 13:08 UT; 4) CME 4 at 20:08 UT.

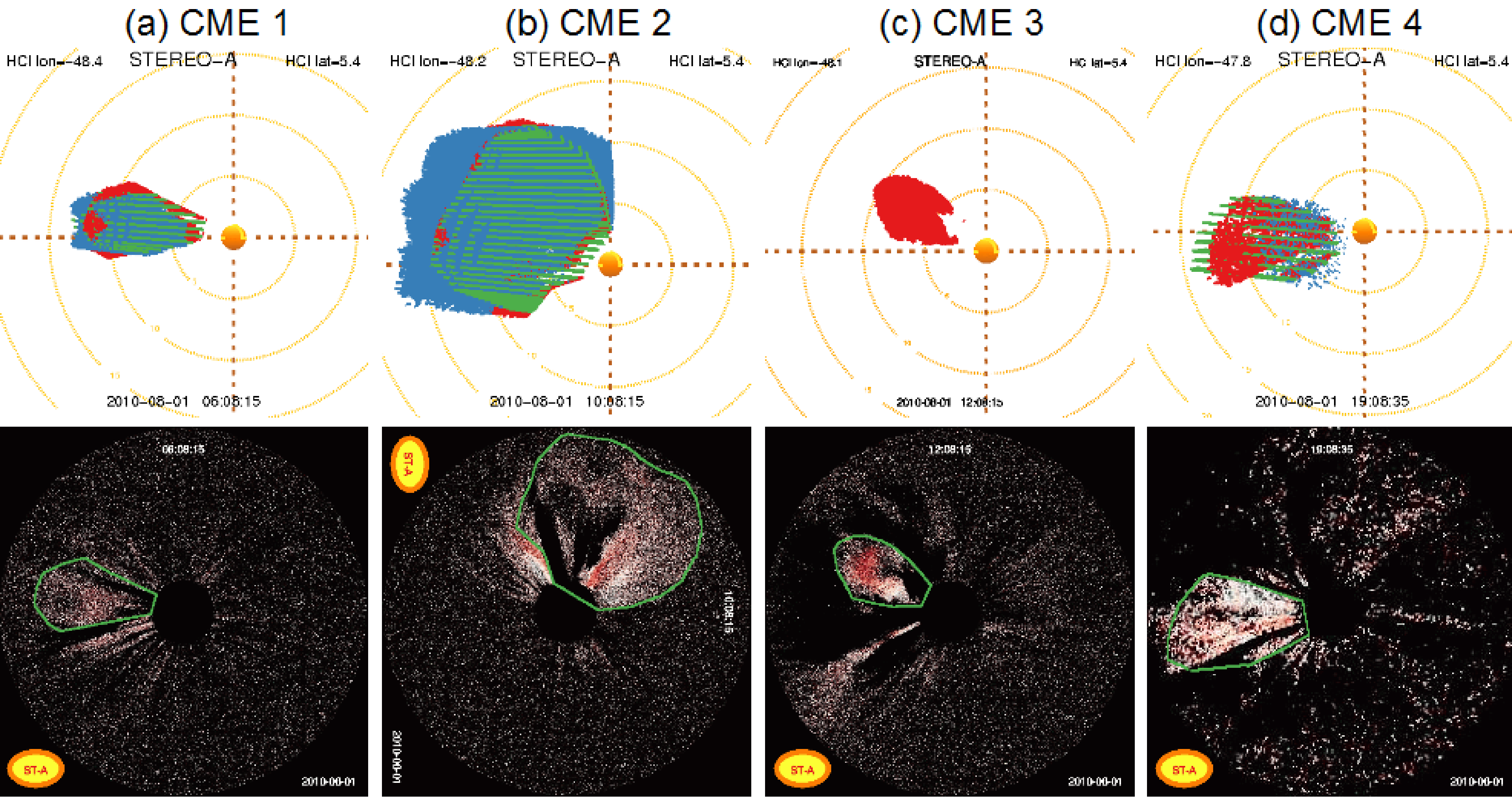
a) CME1 b) CME2 c) CME3 d) CME4



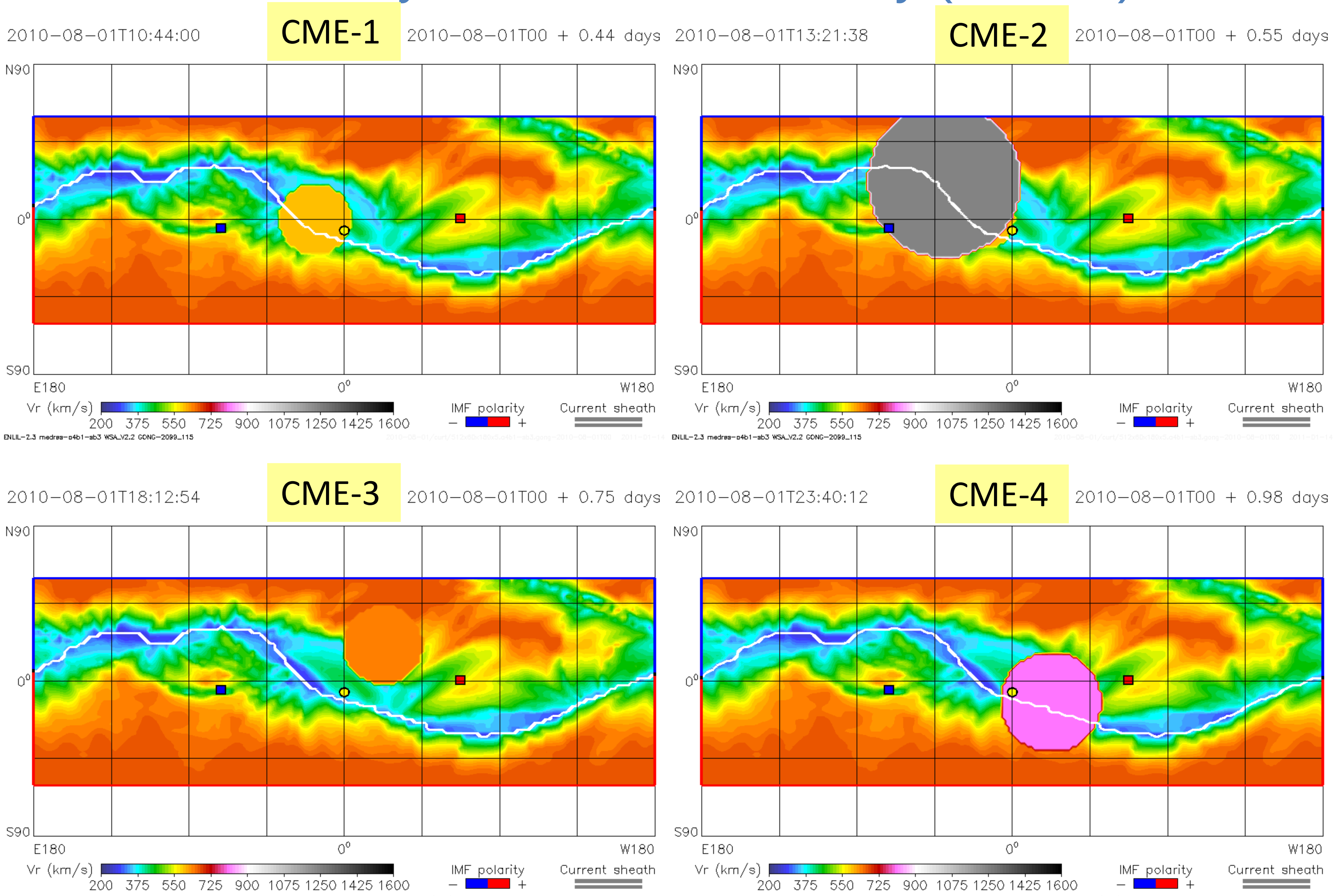
CME 1: onset 03:05 UT at COR1-A ; Source: flare B4.5/N14E14 (Peak 03:50)
CME 2: onset 07:45 UT at COR1-A; Source: flare C3.2/N20E36 (Peak 08:54)
CME 3: onset 08:35 UT at COR1-A; Source: EP ~ 08:00 AIA 304, ~N33W08
CME 4: onset 16:35 at COR1-A; Source EP ~16:40 AIA 304, ~N20W05
(EP = eruptive prominence)

2010-08-01 – Fitting of CMEs (Case 1)

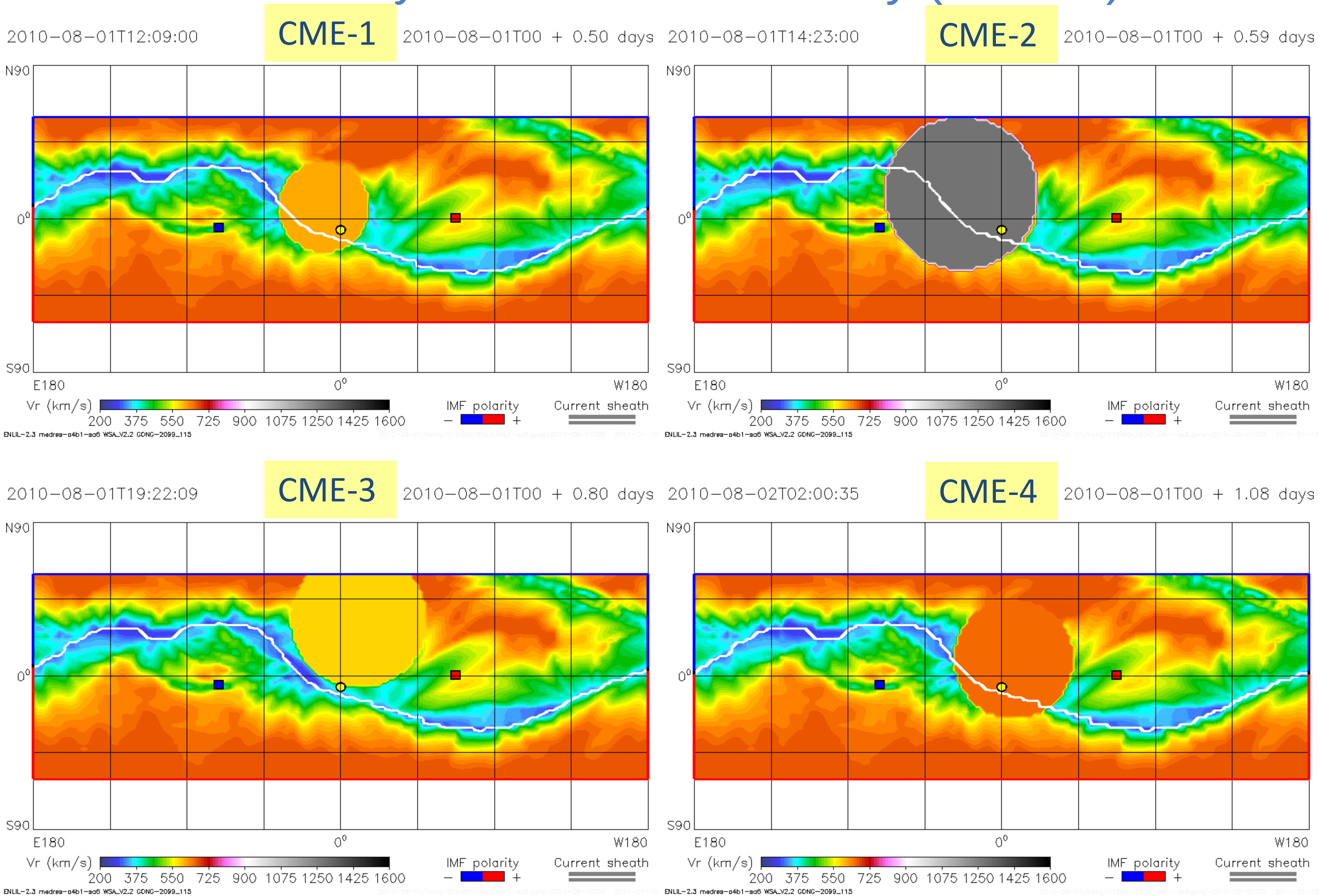
(Curt de Koning, CU/CIRES)



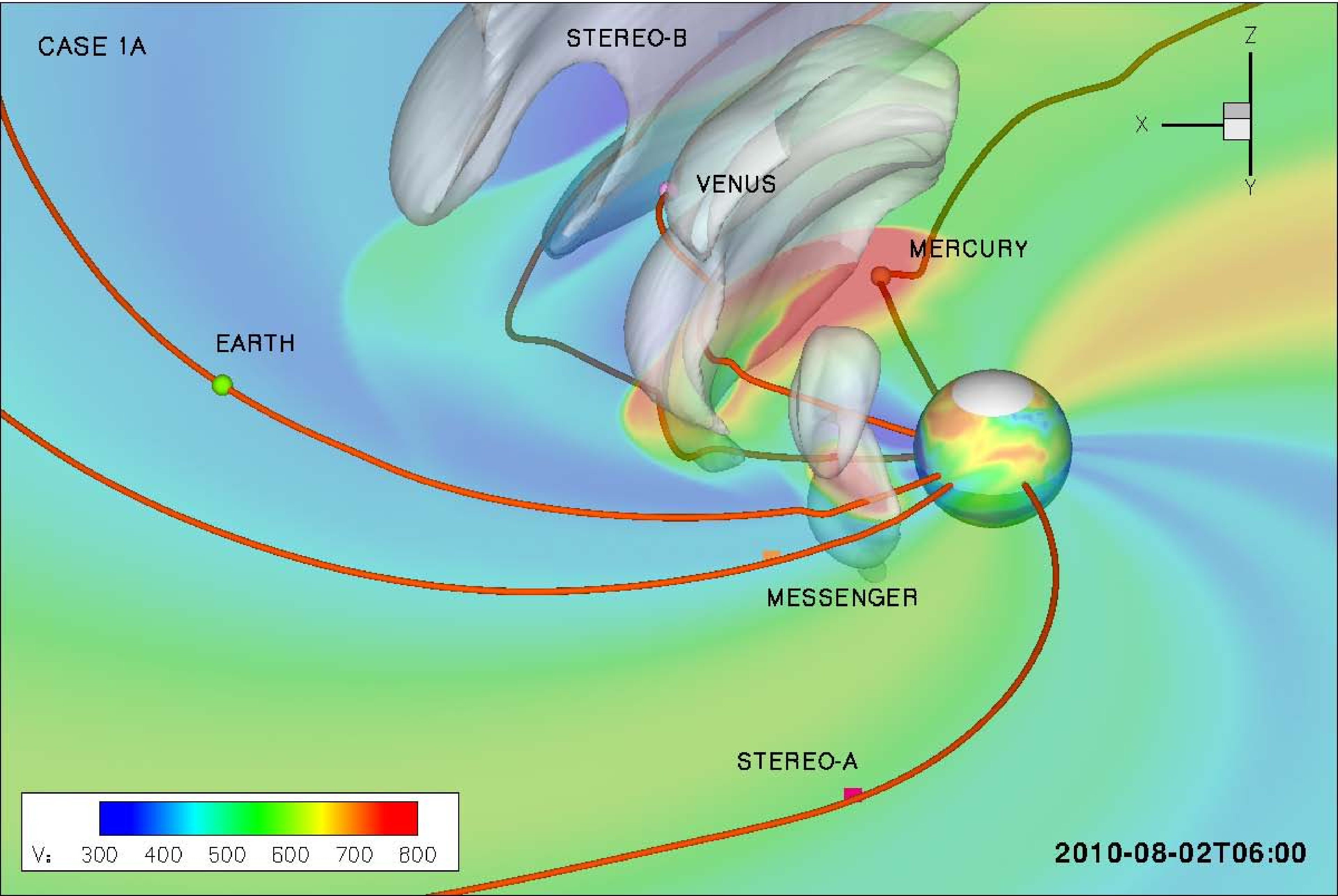
Boundary Conditions – Velocity (Case 1)



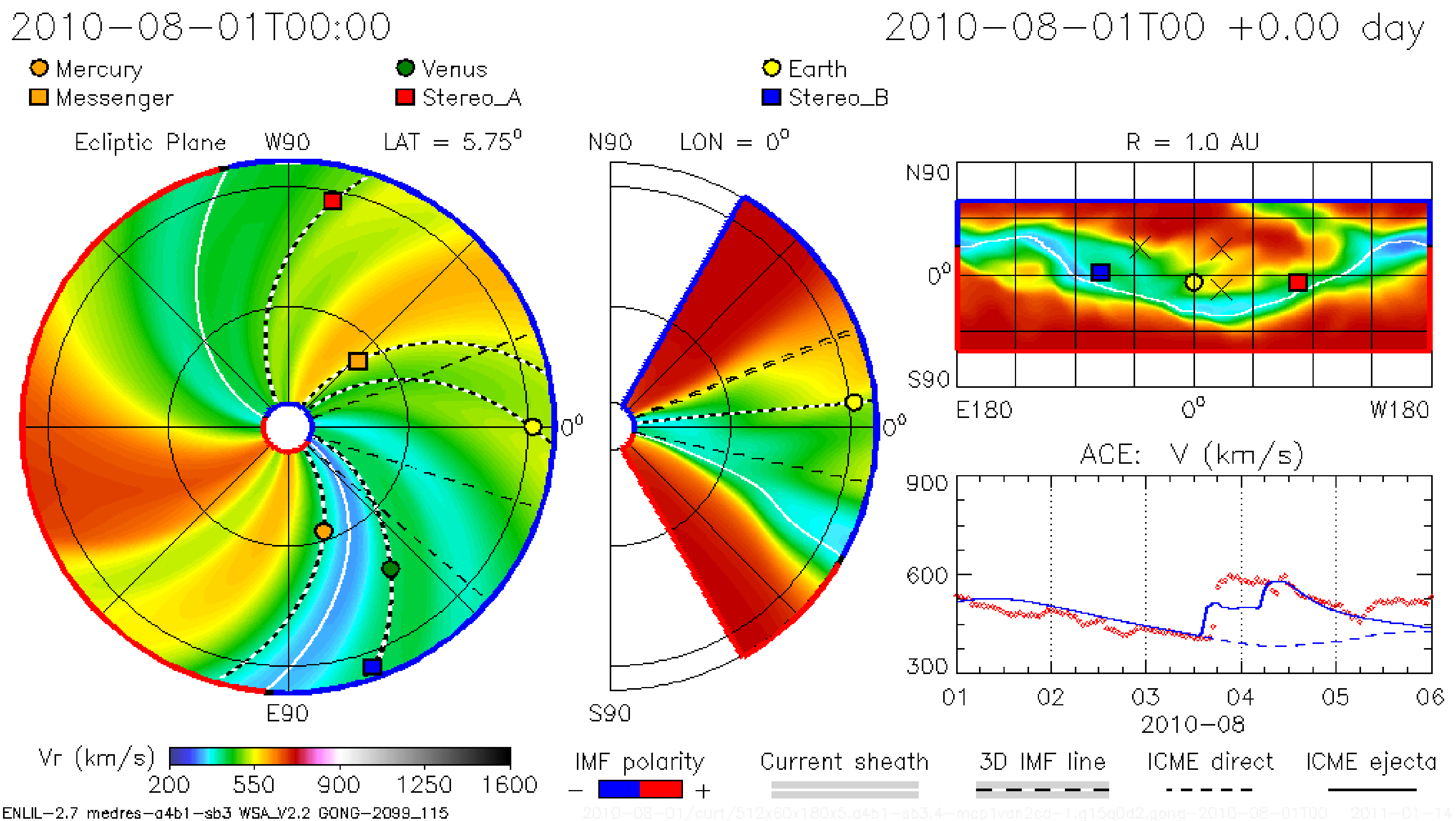
Boundary Conditions – Velocity (Case 2)



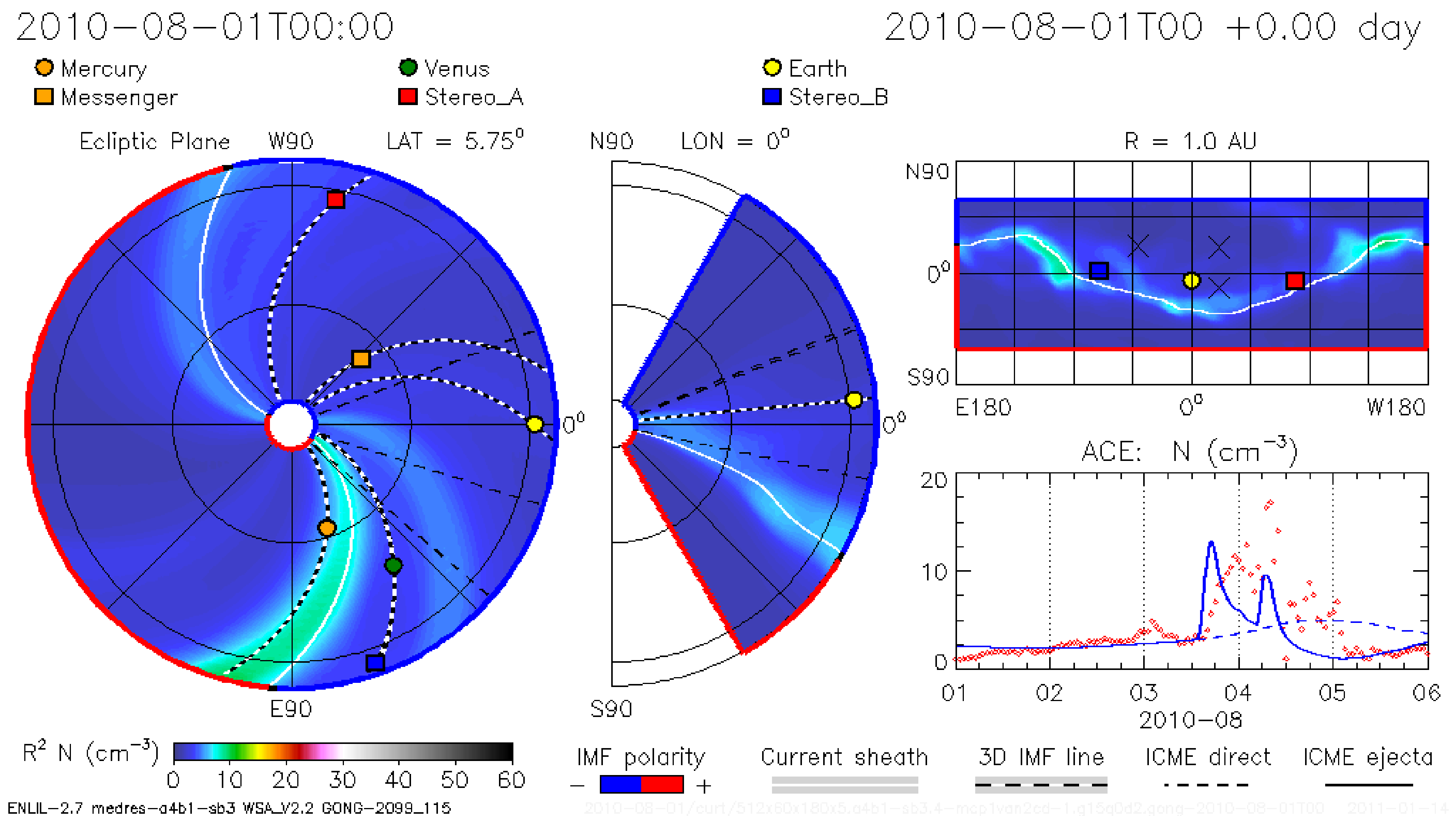
2010-08-01 – Global Solution



Predicted Flow Velocity (Case 1)

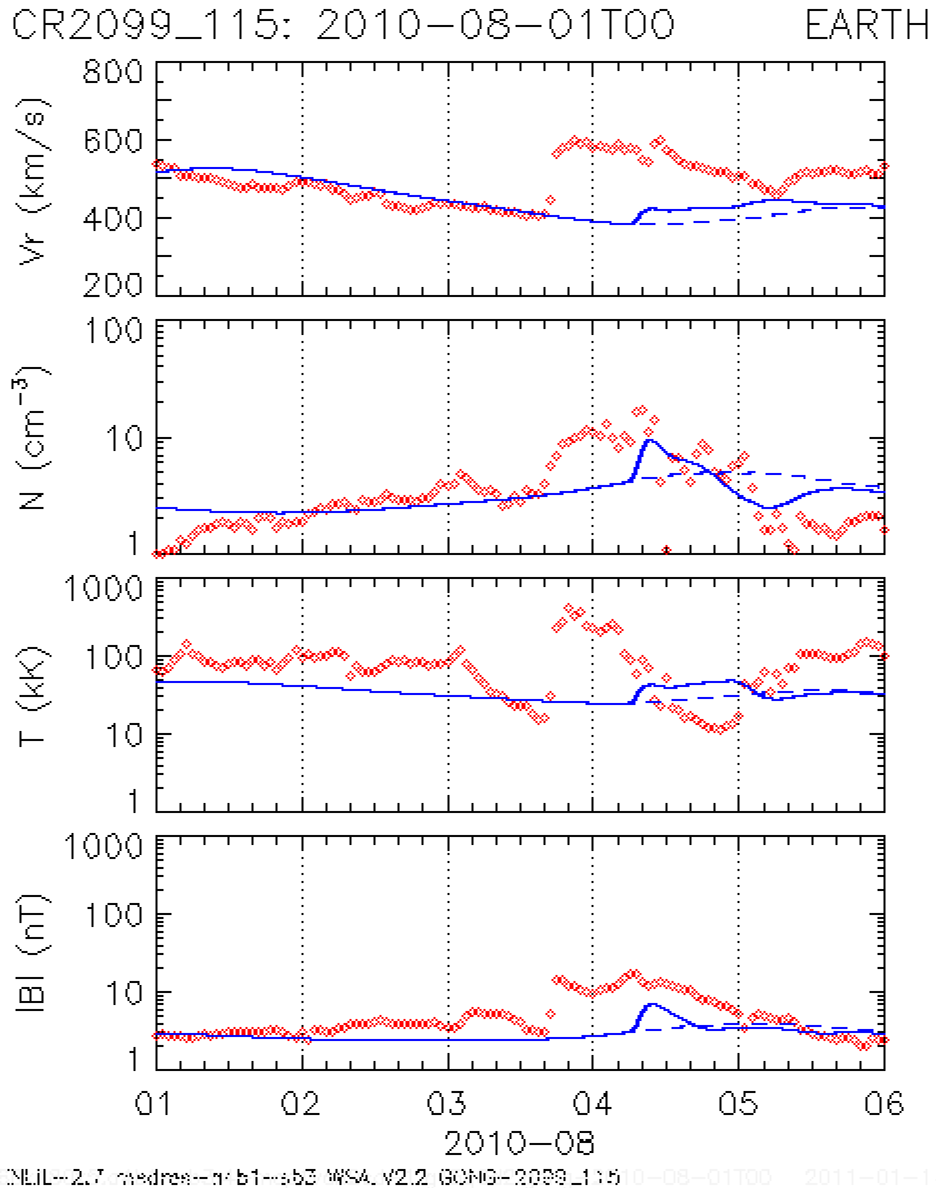


Predicted Proton Density (Case 1)

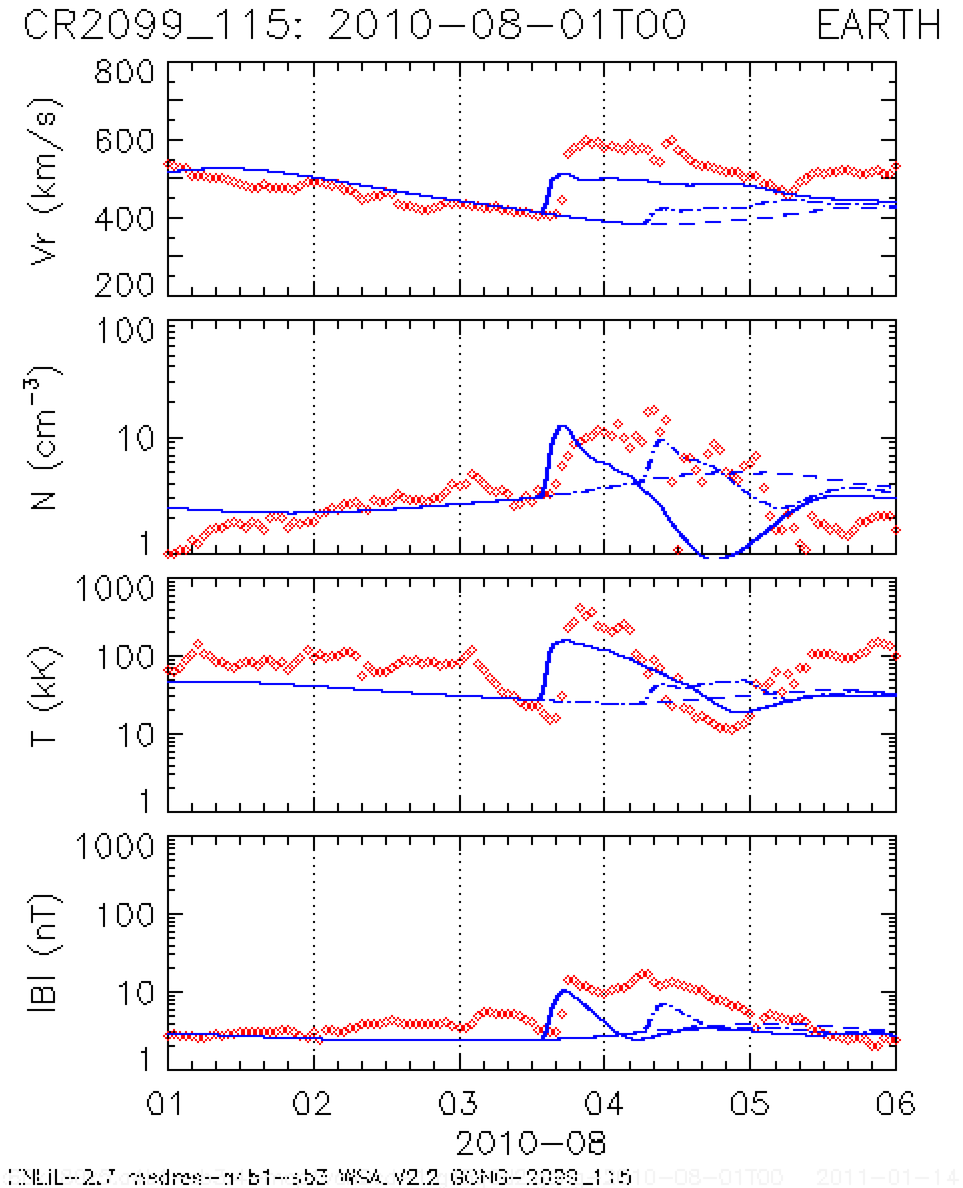


Temporal Profiles – Earth (GLT)

CME 1

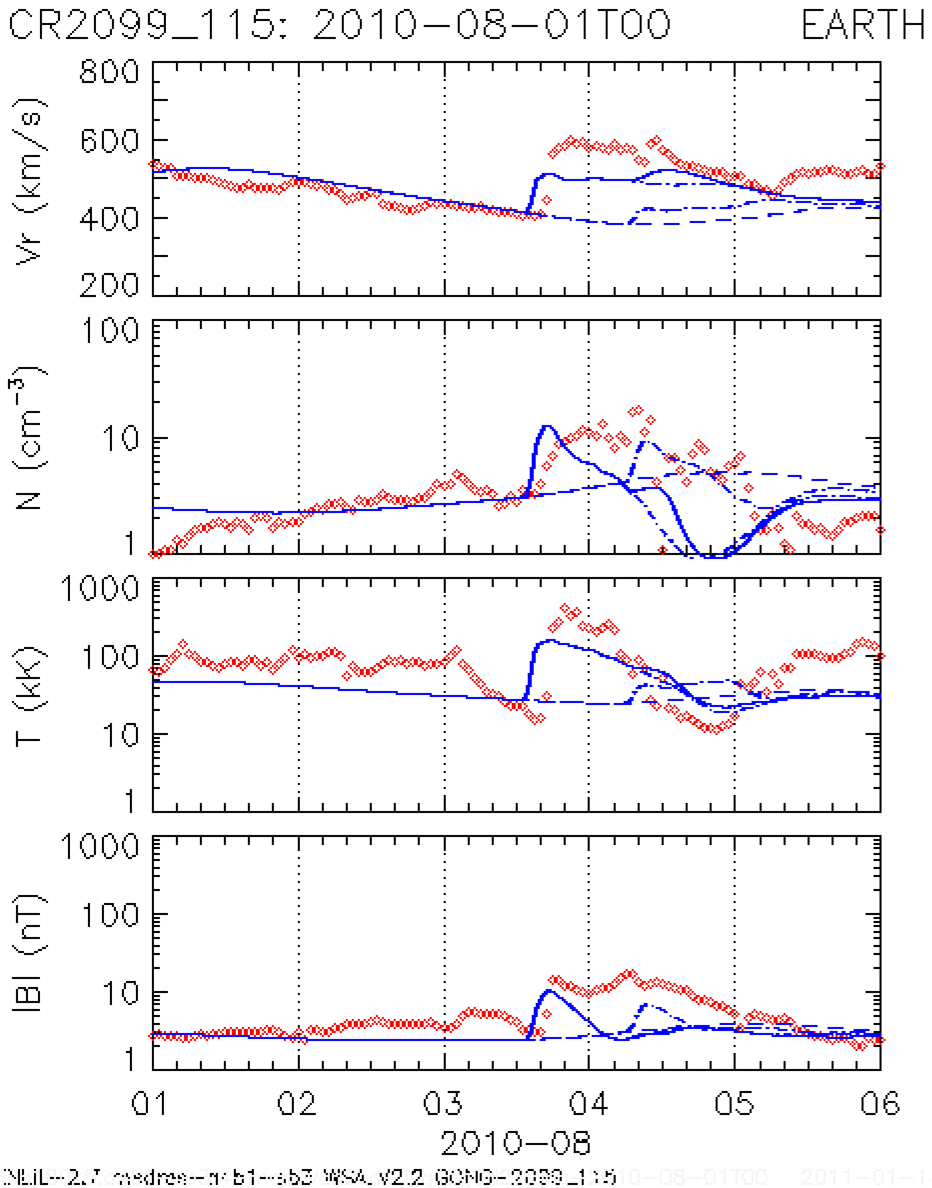


CME 1+2

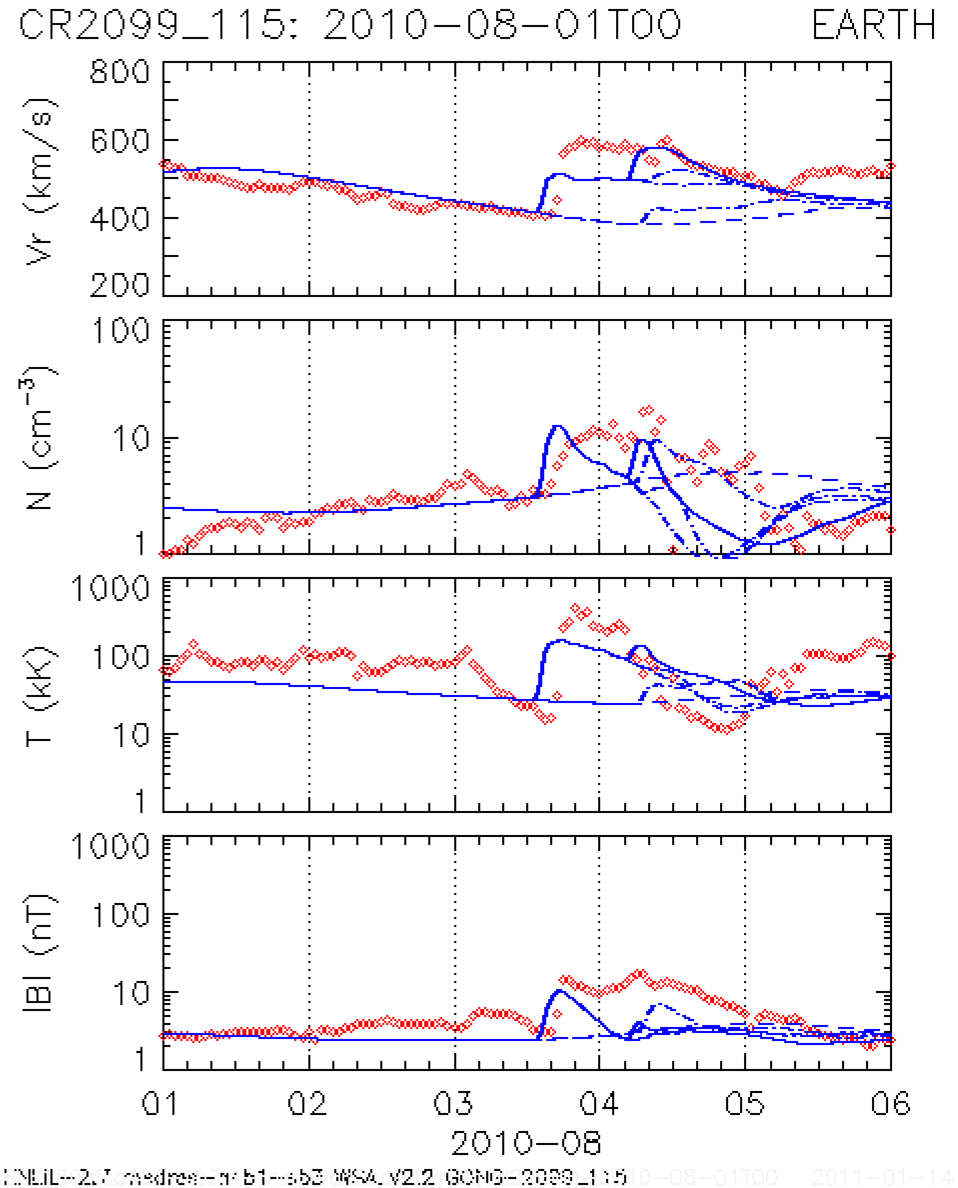


Temporal Profiles – Earth (GLT)

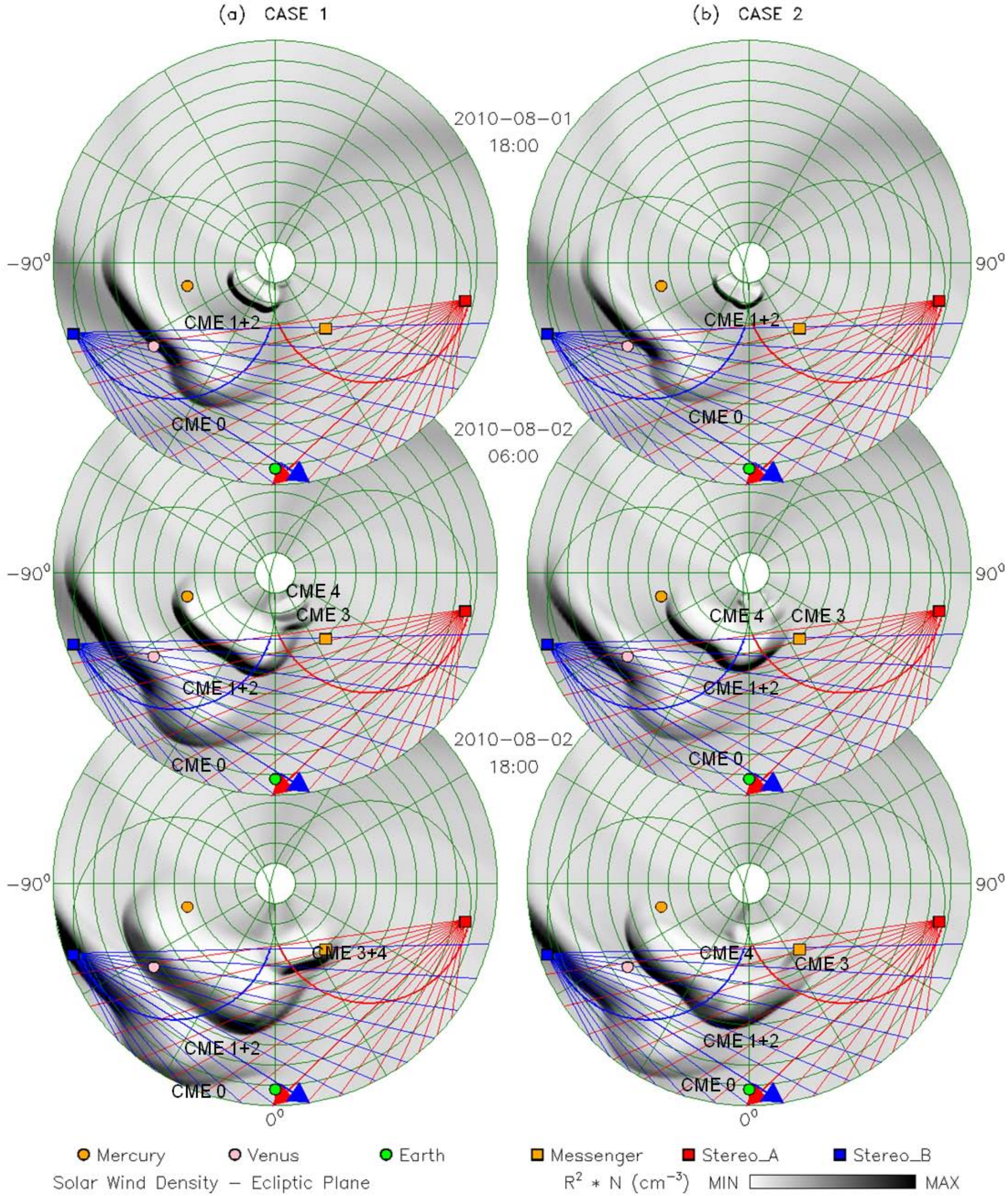
CME 1+2+3



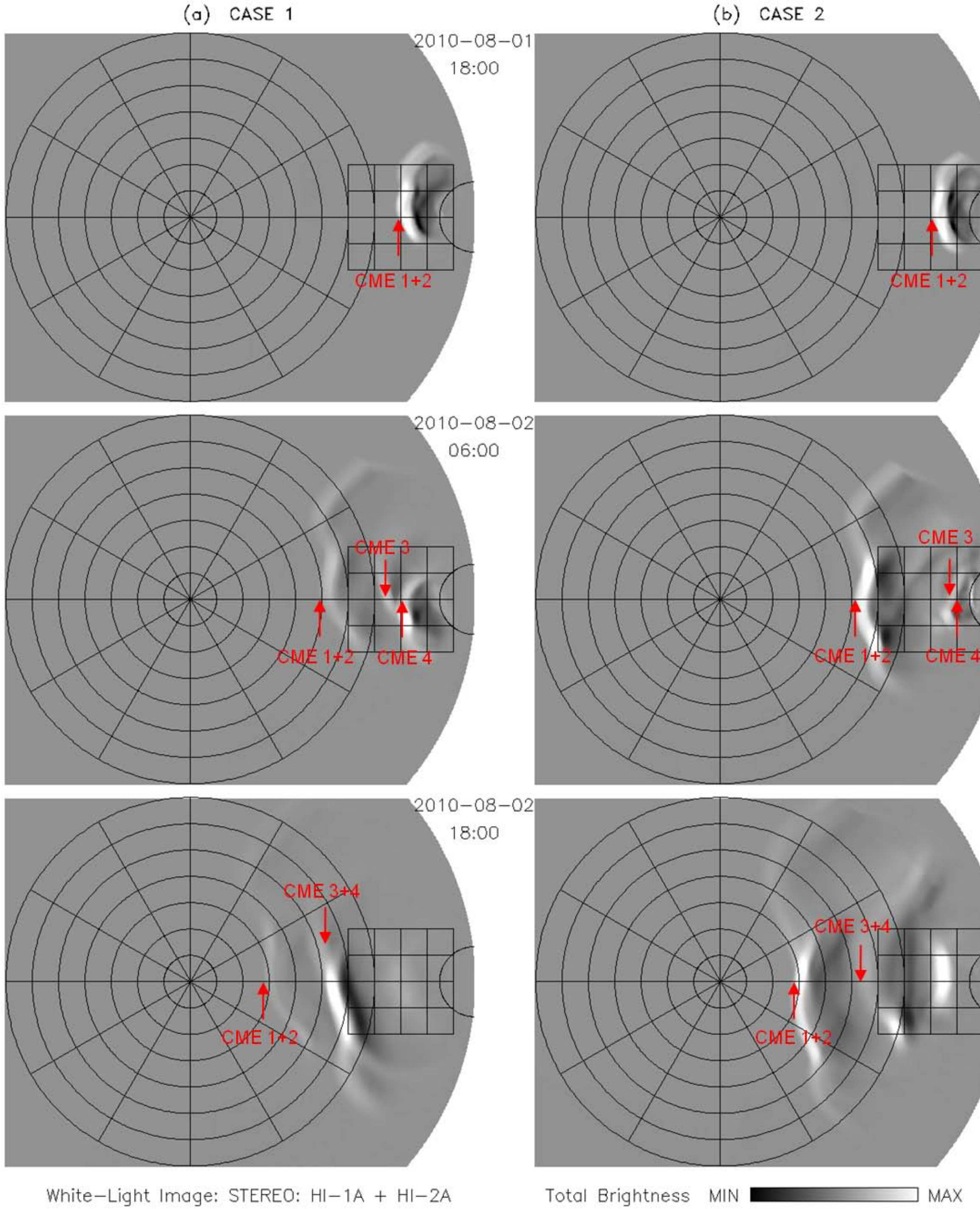
CME 1+2+3+4



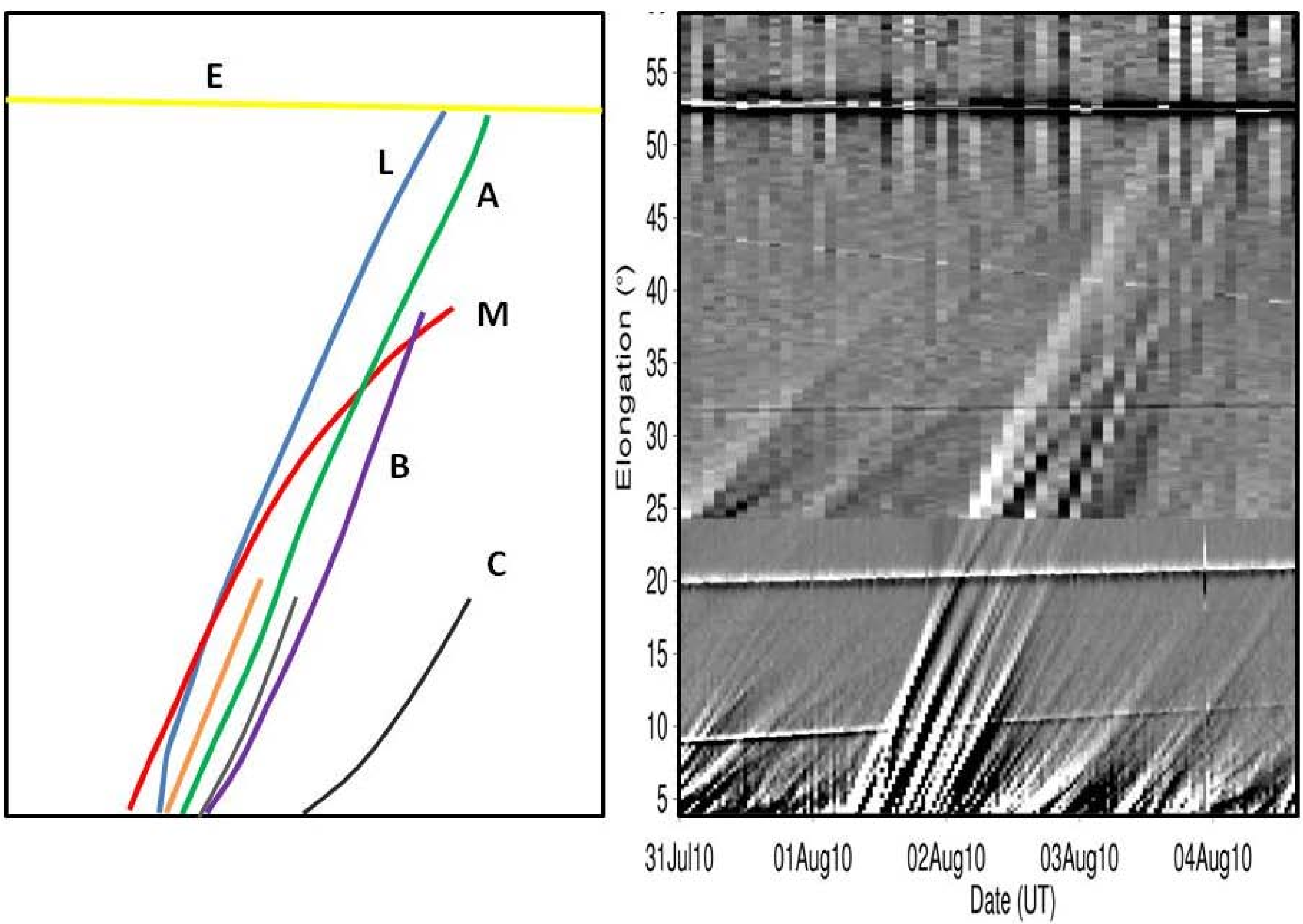
Density Structures



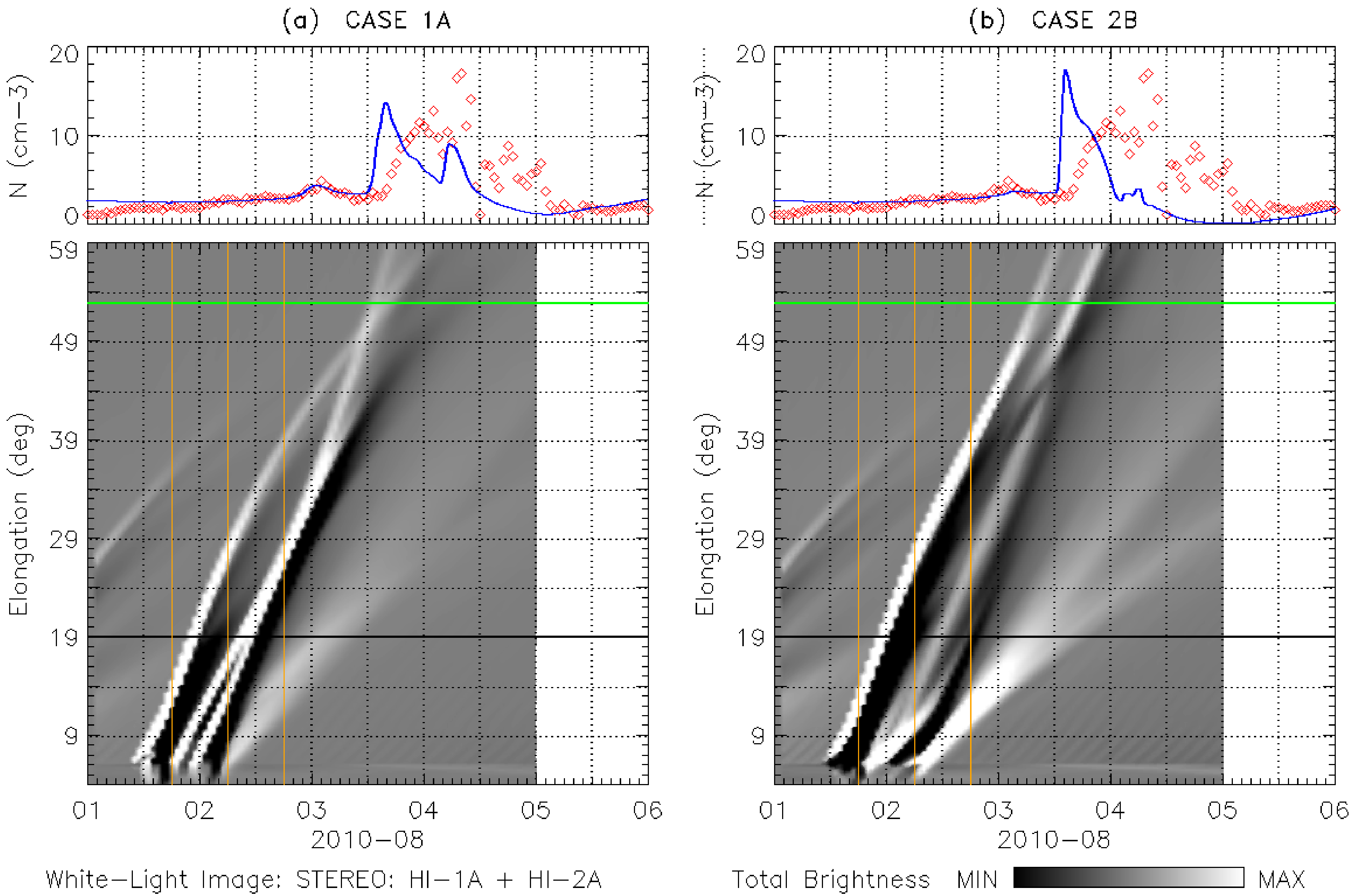
White-Light Images



Observed Elongation-Time Plots (J-maps)



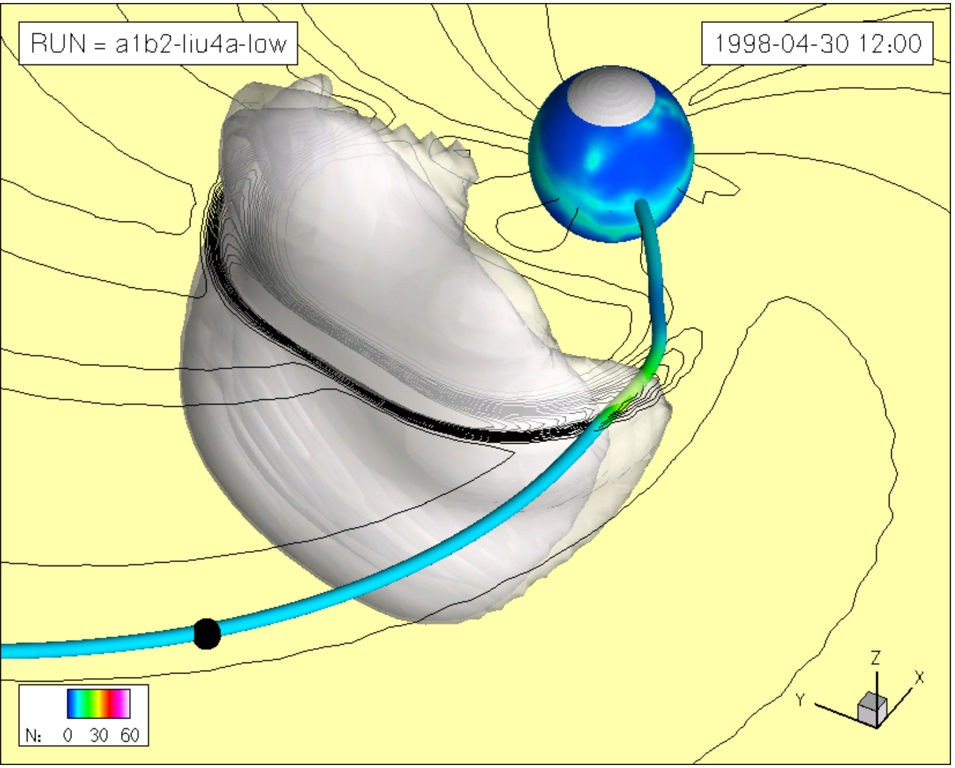
Synthetic Elongation-Time Plots (J-maps)



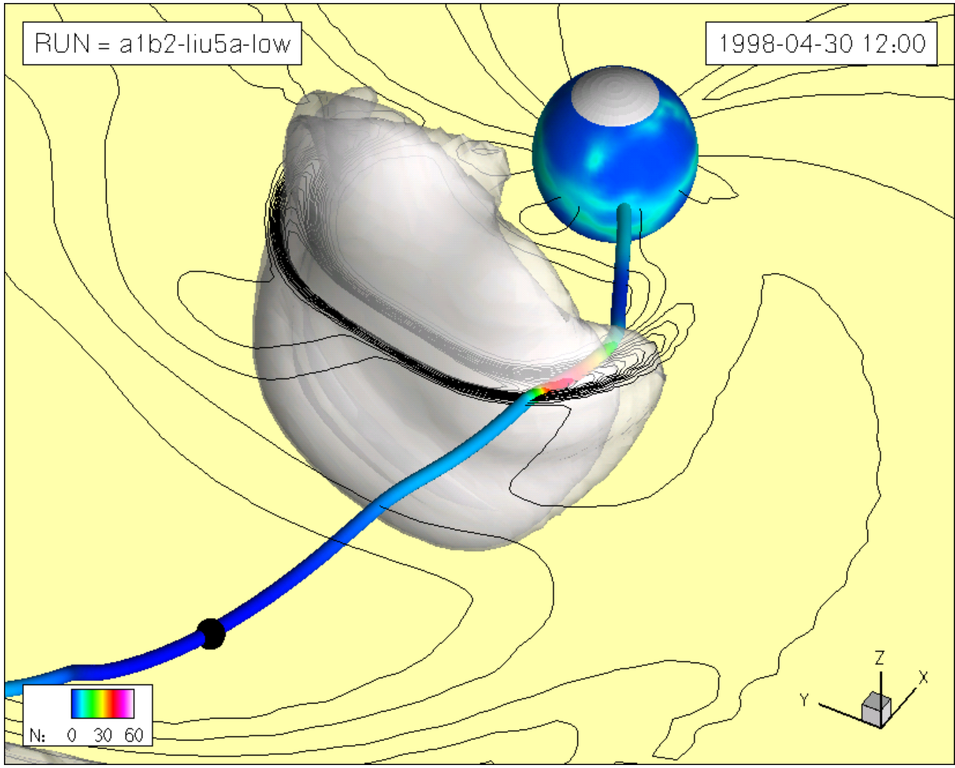
Output for Solar Energetic Particles

ICMEs and IMF Connectivity

ICME in undisturbed SW



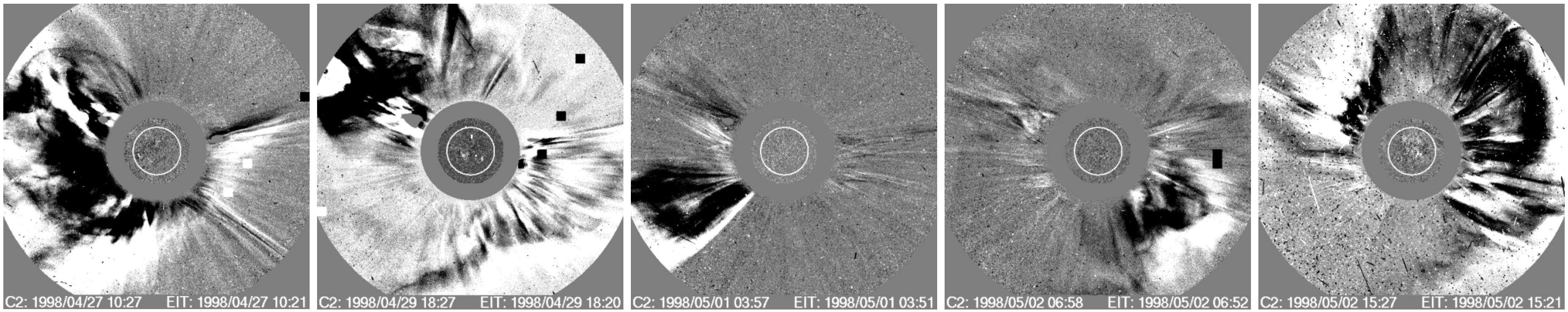
ICME in disturbed SW
by a preceding ICME



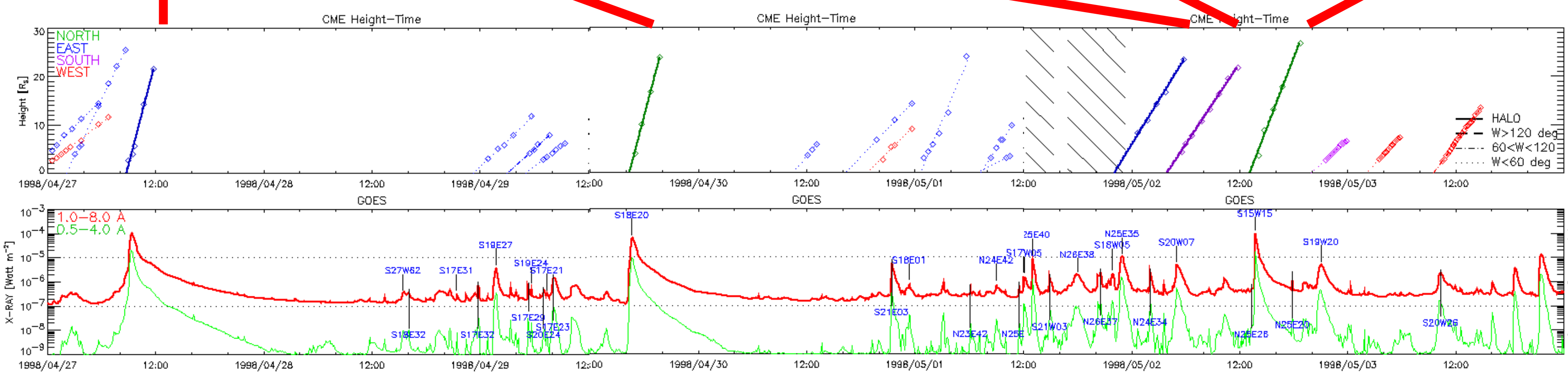
Interplanetary CMEs (white shaded structure), interplanetary magnetic field (IMF) lies (colored by normalized density), during the April/May 1998 events. Geospace is magnetically connected to weak or strong shock front depending on rarefaction caused by preceding ICME.

Multiple Events Challenge

http://cdaw.gsfc.nasa.gov/CME_list/

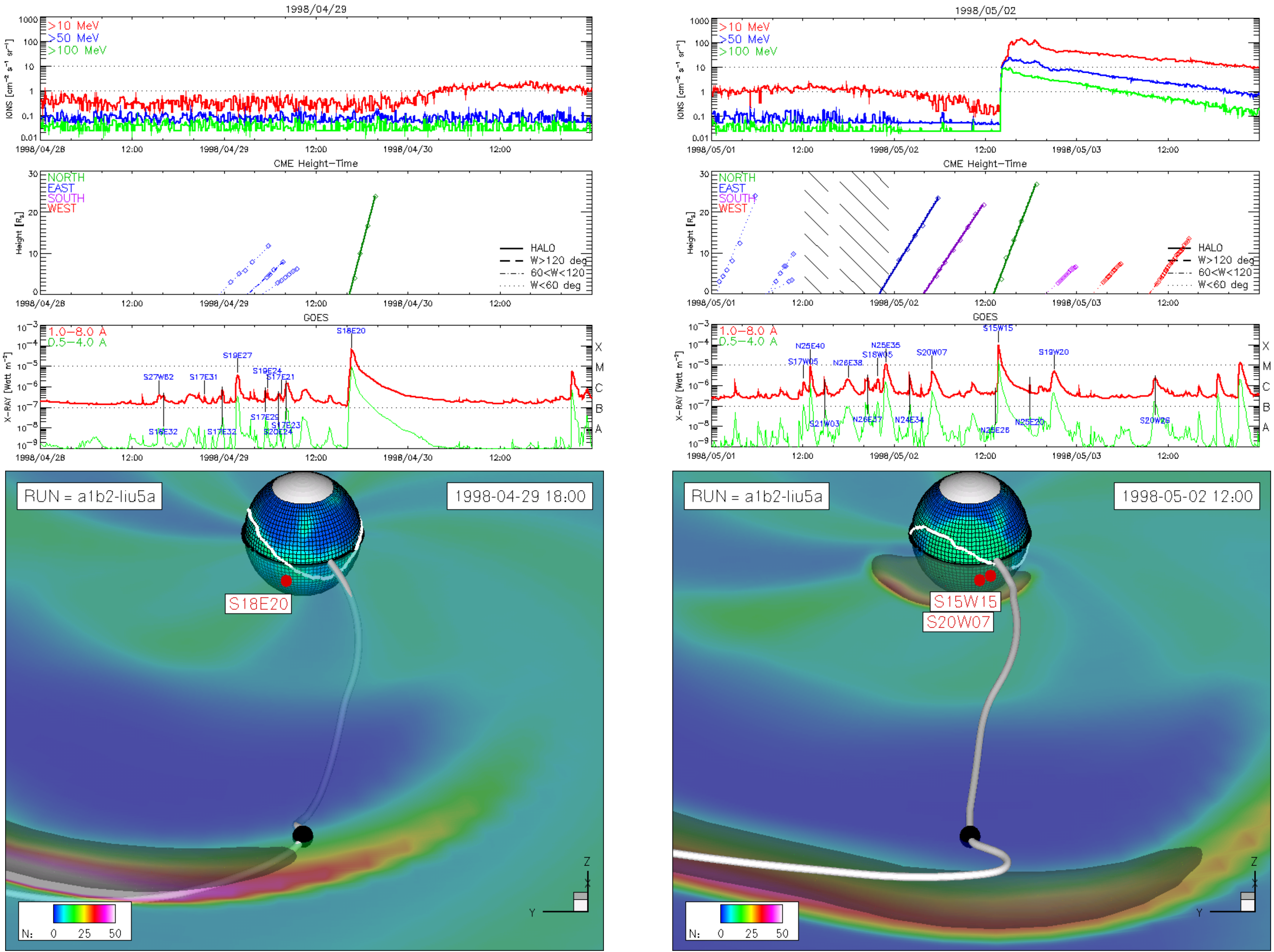


CME-1 CME-2 CME-3 CME-4 CME-5

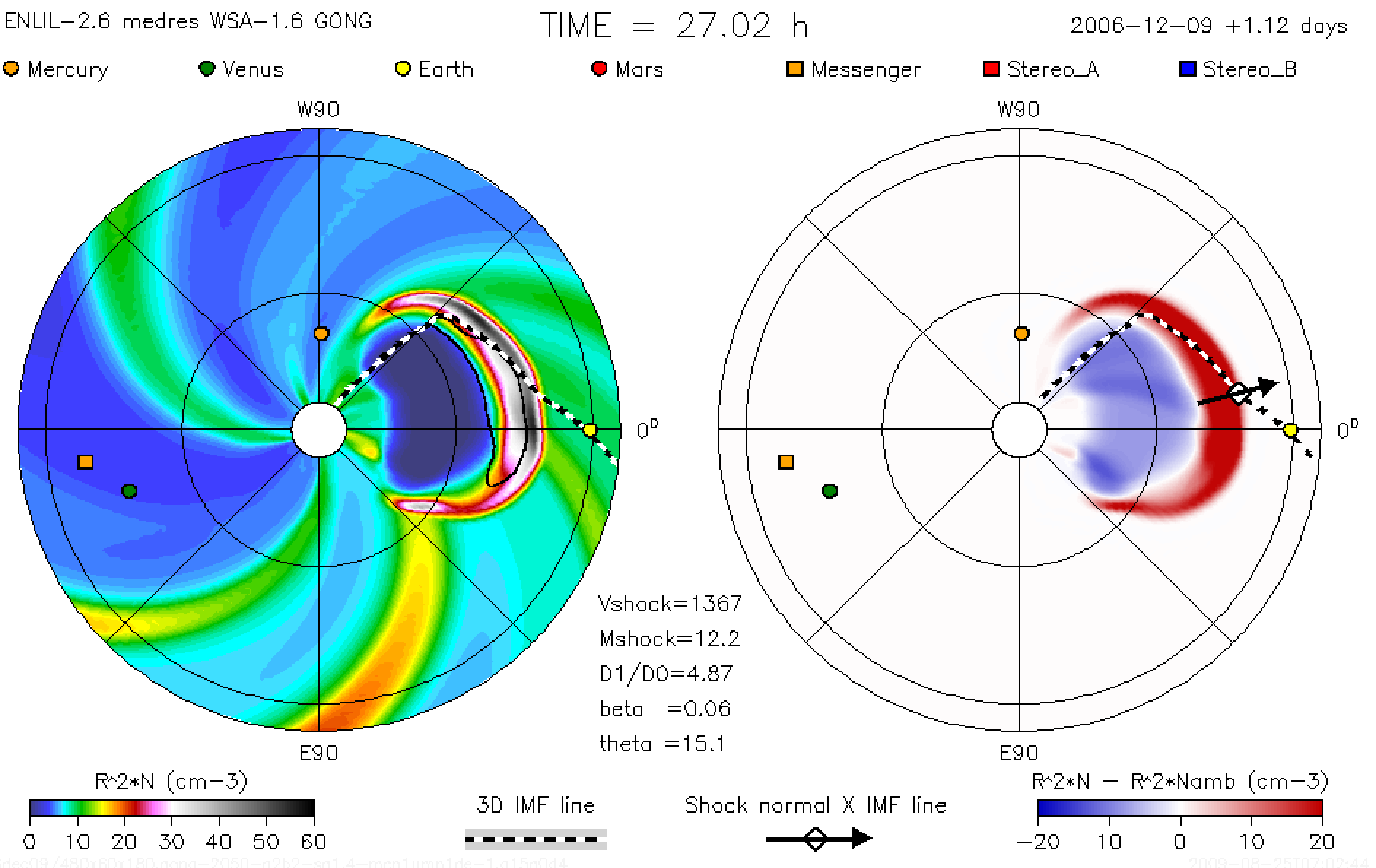


- 5 halo CMEs between April 27 and May 2, 1998
- 18 CMEs between April 27 and May 2, 1998

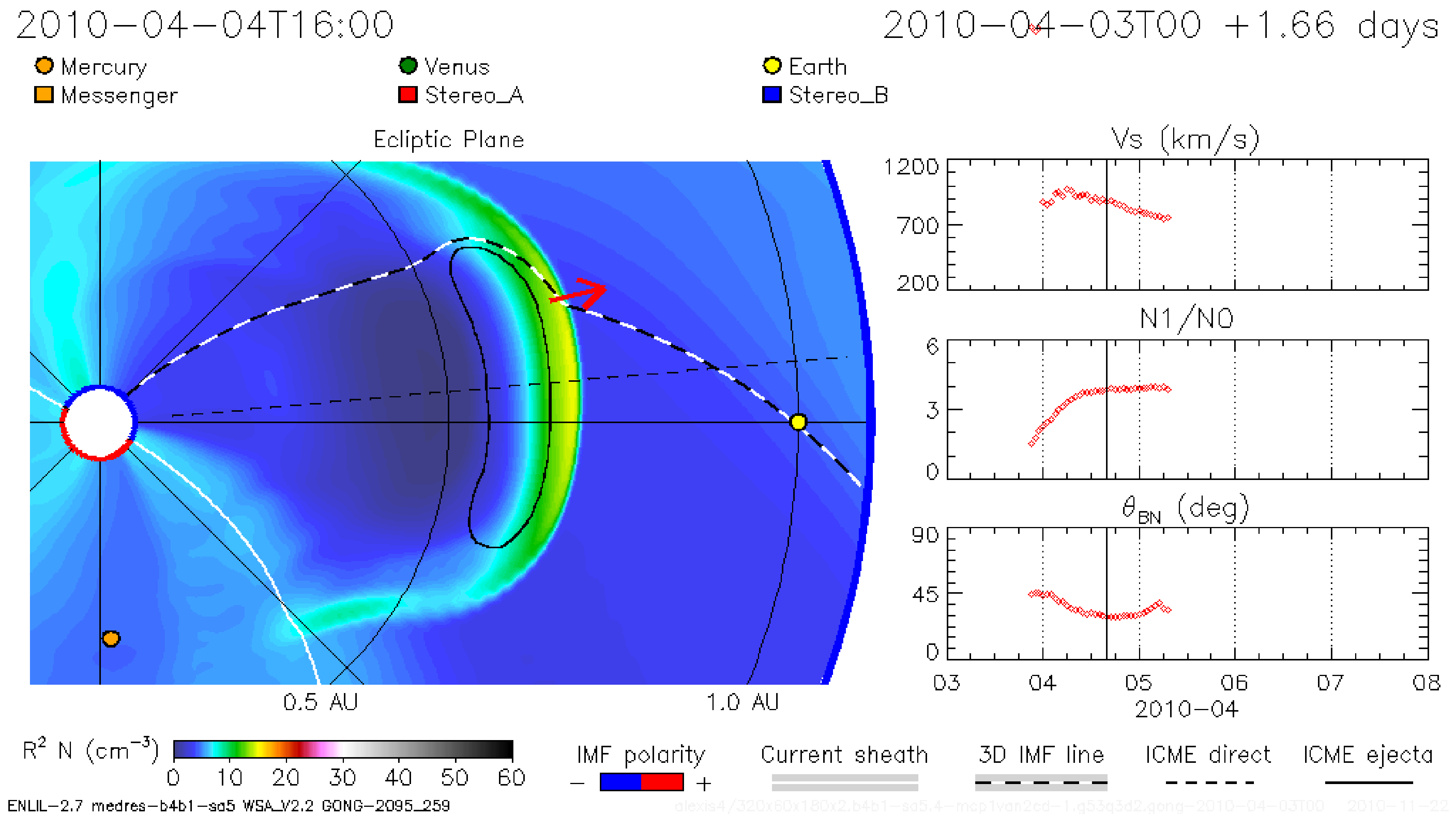
Connectivity of Magnetic Field Line



Shock Tracing – 2006-12-09 Event



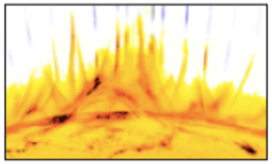
Automatic Detection of Shock Parameters



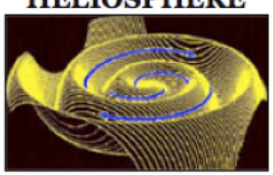
Run-on-Request Service at CCMC

http://ccmc.gsfc.nasa.gov

Models hosted by CCMC

Domain	Model Name	Developer(s)	Institution	Model Class	Services Available				
					Runs on Request	Instant Run	Real Time Run	Widget	Source Code on ftp
COUPLED SOLAR - HELIOSPHERE	**CORHEL MAS/WSA/ENLIL**	J. Linker, Z. Mikic, R. Lionello, P. Riley, N. Arge, D. Odstrcil	PSI, AFRL, U.Colorado	physics-based MHD	X				
	SWMF/SC/IH	Tamas Gombosi et al.	CSEM	Physics-based MHD	X				
COUPLED MAGNETOSPHERE	**SWMF/BATS-R-US with RCM**	Tamas Gombosi et al., R. Wolf et al.	CSEM	Physics-based MHD	X				
SOLAR 	**CORHEL MAS/WSA/ENLIL**	J. Linker, Z. Mikic, R. Lionello, P. Riley, N. Arge, D. Odstrcil	PSI, AFRL, U.Colorado	physics-based MHD	X				
	PFSS	J. Luhmann et al.	SSL/UC Berkeley	Potential Magnetic Field	X		X	X	
	WSA/PF with CS	Nick Arge	AFRL	Potential-based			X	X	
	SWMF/SC/IH	Tamas Gombosi et al.	CSEM	Physics-based MHD	X				

Models hosted by CCMC

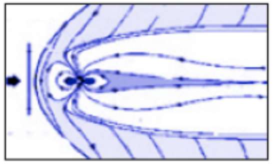
	ANMHD	Bill Abbett, Dave Bercik, George Fisher, Yuhong Fan	UC Berkeley	physics-based MHD	X				
	CORHEL MAS/WSA/ENLIL	J. Linker, Z. Mikic, R. Lionello, P. Riley, N. Arge, D. Odstrcil	PSI, AFRL, U.Colorado	physics-based MHD	X				
	SWMF/SC/IH	Tamas Gombosi et al.	CSEM	Physics-based MHD	X				
	ENLIL	D. Odstrcil	Univ. of Colorado at Boulder	Physics-based MHD	X		X	X	
	ENLIL with Cone Model	D. Odstrcil	Univ. of Colorado at Boulder	Physics-based MHD	X				
HELIOSPHERE 	Heliospheric Tomography	B. Jackson, P. Hick	CASS/UCSD	Data Assimilative	X				
	Exospheric Solar Wind	H.Lamy, V.Pierrard	IASB	Physics-based Kinetic	X				
				Physics-Based Lagrangian					

Models hosted by CCMC

	EMMREM	N. Schwadron, L. Townsend, R. Squier, F. Cucinotta, M. H. Kim, K. Kozarev, R. Hatcher, M. PourArsalan	Boston Univ., U. Tenn, NASA JSC	Kinetic Model for Primary Transport (Energetic Particle Radiation Environment Model); Physics-based Secondary Transport Model (EMMREM looping version of BaRYoN TRaNsport BRYNTRN Code)					
	Global Magnetosphere:								
	BATS-R-US	Dr. Tamas Gombosi et al.	CSEM	Physics-based MHD	X		X	X	
	SWMF/BATS-R-US with RCM	Tamas Gombosi et al., R. Wolf et al.	CSEM	Physics-based MHD	X				
	OpenGGCM	Joachim Raeder, Timothy Fuller-Rowell	Space Science Center, UNH	Physics-based MHD	X				

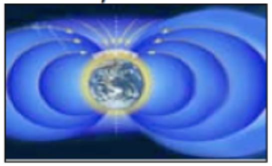
Models hosted by CCMC

MAGNETOSPHERE



GUMICS	Pekka Janhunen et.al.	FMI	Physics-based MHD	X				
LFM-MIX	John Lyon, Slava Merkin, Mike Wiltberger, Peter Schmitt	Dartmouth College/Boston University	physics-based MHD					
WINDMI	W. Horton, M. L. Mays, E. Spencer and I. Doxas	Univ. of Texas at Austin	physics-based		X	X		
Inner Magnetosphere:								
Fok Ring Current	Mei-Ching H. Fok	NASA, GSFC	Physics-based	X			X	
AE-8/AP-8 RADBELT	Contact Person: D. Bilitza, NASA/GSFC	NSSDC, GSFC, NASA	Statistical		X			X
Geomagnetic Field Models:								
IGRF	Susan Macmillan, Stefan Maus	IAGA Working Group on IGRF	Statistical		X			X
Tsyganenko Model	Nikolai Tsyganenko	Univ. of St.-Petersburg, Russia	Statistical		X			X

Models hosted by CCMC

	Ionosphere/Thermosphere:								
	SAMI2	Joseph Huba, Glenn Joyce, Marc Swisdak	NRL and Icarus Research, Inc.	Physics-based	X				
	CTIP	Timothy Fuller-Rowell et al	NOAA SEC	Physics-based	X				
	ABBYNormal	J. Vincent Eccles et al.	Space Environment Corporation	Physics-based	X	X	X		
IONOSPHERE/THERMOSPHERE 	**USU-GAIM**	R.W. Schunk, L. Scherliess, J.J. Sojka, D.C. Thompson, L. Zhu	Utah State University	Physics-based data assimilation	X				
	IRI	D. Bilitza, NASA/GSFC	URSI/COSPAR Working Group on IRI	Statistical		X			X
	Ionosphere Electrodynamics:								
	Weimer	Daniel R. Weimer	Solana Scientific Inc.	Statistical		X	X	X	
	Atmosphere:								
	MSISE	A. E. Hedin	retired from. NASA, GSFC	Statistical		X			X

Ambient Solar Wind Parameters

Basic Mode – Association with the Coronal Model and Resolution

Name	Title	Default	Range
cr	Carrington Rotation number	1922	1890 – present
resolution	Numerical grid resolution	low	low | medium

Advanced Mode – Free Parameters at the Inner Boundary

Name	Title	Default	Range
vfast	Radial flow velocity of fast stream (km/s)	650.	600. – 700.
dfast	Number density of fast stream (cm^{-3})	150.	100. – 200.
tfast	Temperature of fast stream (MK)	0.6	0.5 – 0.8
bfast	Radial magnetic field of fast stream (nT)	150.	100. – 200.
gamma	Ratio of specific heats	1.5	1.05 – 2.
xalpha	Fraction of alpha particles (rel. to protons)	0.	0. – 0.1
dvexp	Exponent in $N\ V^{dvexp}$ = const	2.	1. – 2.
nptot	=1 (=2) if P_{the} (P_{tot}) = const	1	1 | 2

Cone Model Parameters

Basic Mode – Observationally Based Parameters

Name	Title	Default	Range
ncloud	Number of clouds specified	1	0 – 5
ldates	Date(s) when cloud center at inner boundary	1997-05-12	yyyy-mm-dd
ltimes	Time(s) when cloud center at inner boundary	15:30	hh:mm
vcld	Cloud velocity (km/s)	700.0	500. – 2000.
x2cld	Cloud center co-latitude (deg)	87.0	0. – 180.
x3cld	Cloud center longitude (deg)	181.0	90. – 270.
rcld	Cloud radius (deg)	25.0	0. – 90.

Advanced Mode – Free Parameters at the Inner Boundary

Name	Title	Default	Range
dcld	Cloud density over fast stream value	4.	1. – 10.
tcld	Cloud temperature over fast stream value	1.	0.5 – 10.
xcld	Cloud trailing elongation over spherical shape	1.	1. – 5.
ncld	=1 (2) for trapezoidal (spherical) shape	1	1 | 2

Thank You