

# Numerical Simulations of STEREO ICMEs

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<sup>1</sup>*University of Colorado/CIRES, Boulder, CO*

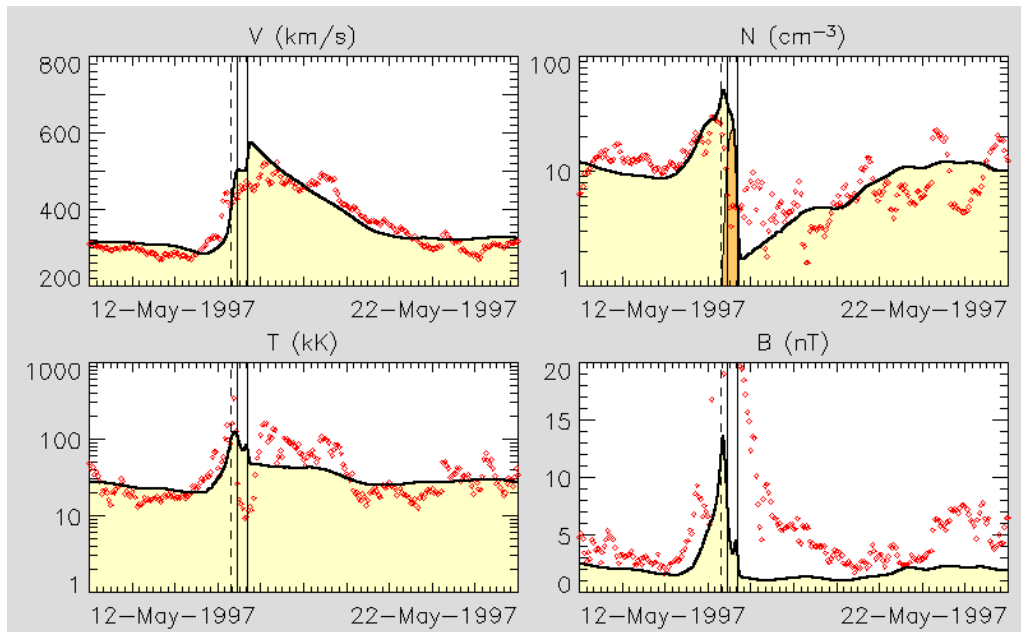
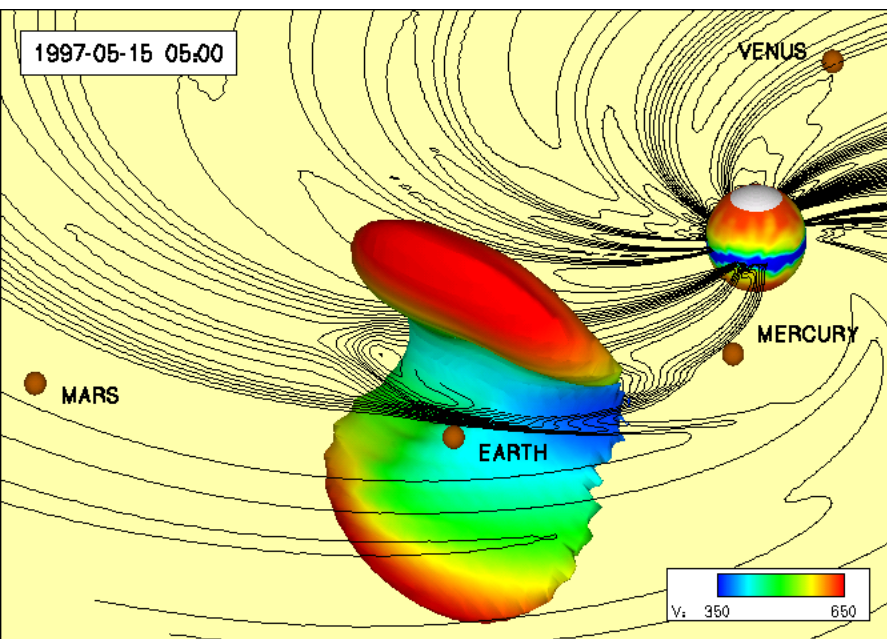
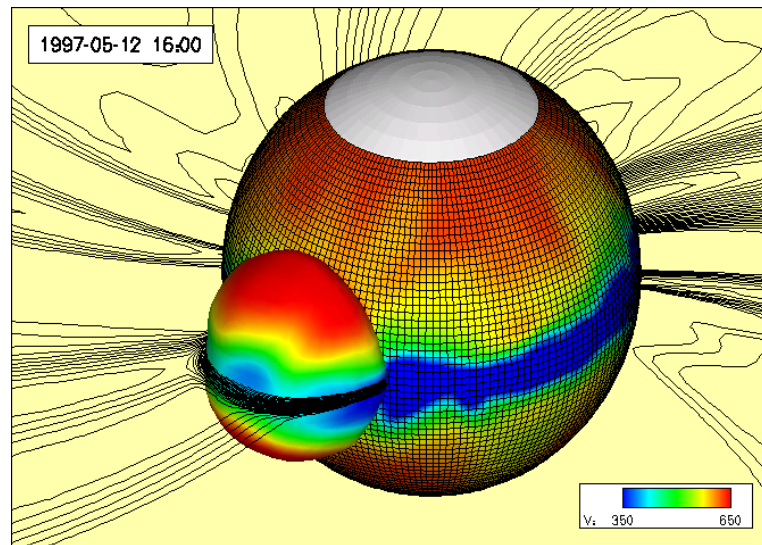
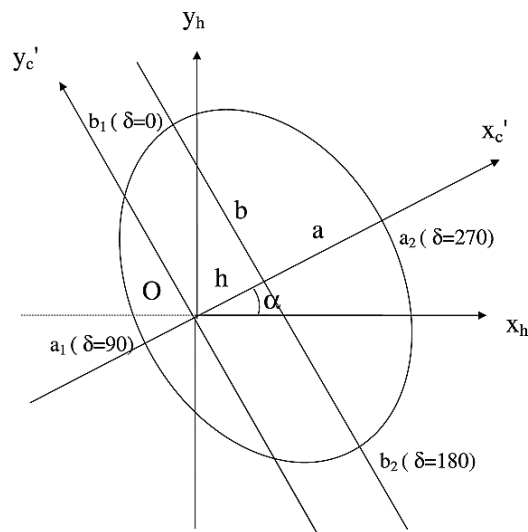
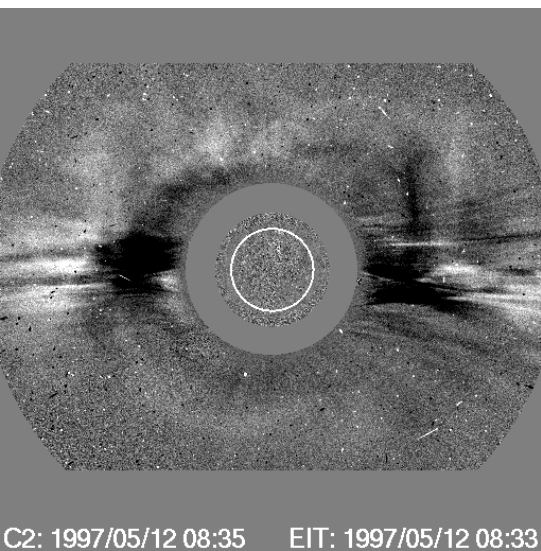
<sup>2</sup>*NOAA/Space Weather Prediction Center, Boulder, CO*

<sup>3</sup>*Naval Research Laboratory, Washington, DC*

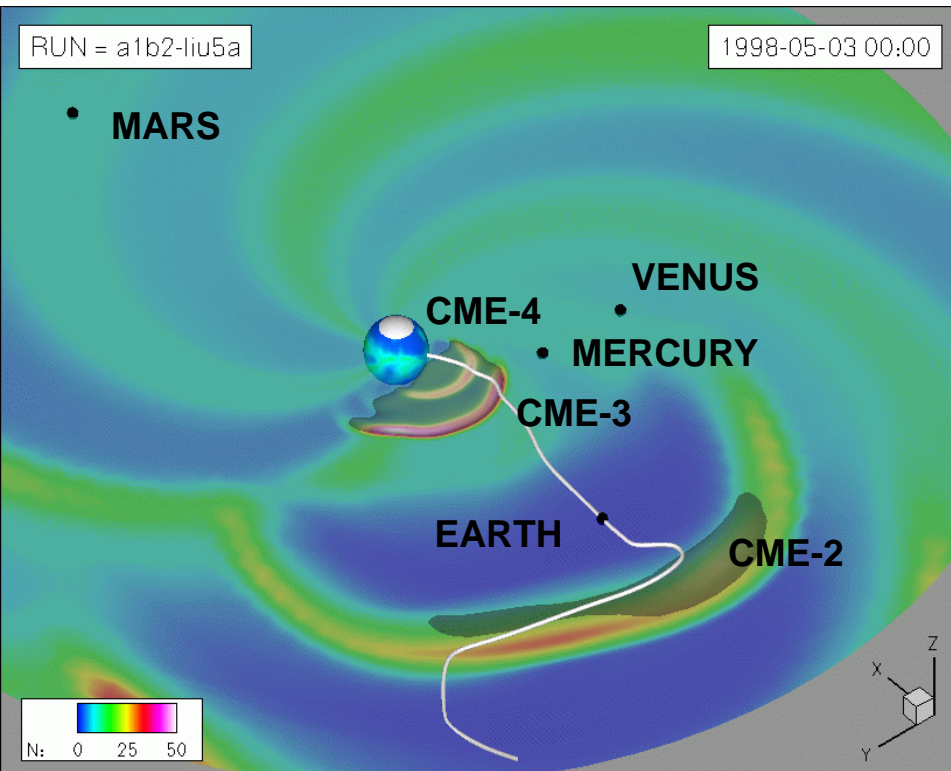
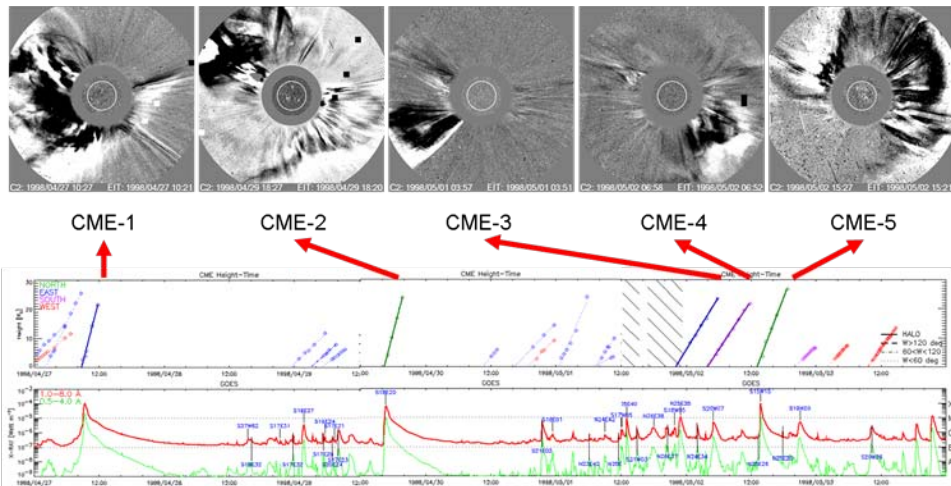


STEREO-SWG Workshop, Pasadena, CA, February 3-5, 2009

# Simulation of Heliospheric Disturbances – Cone Model



# April/May, 1998 CME Events



# Using Cone Models

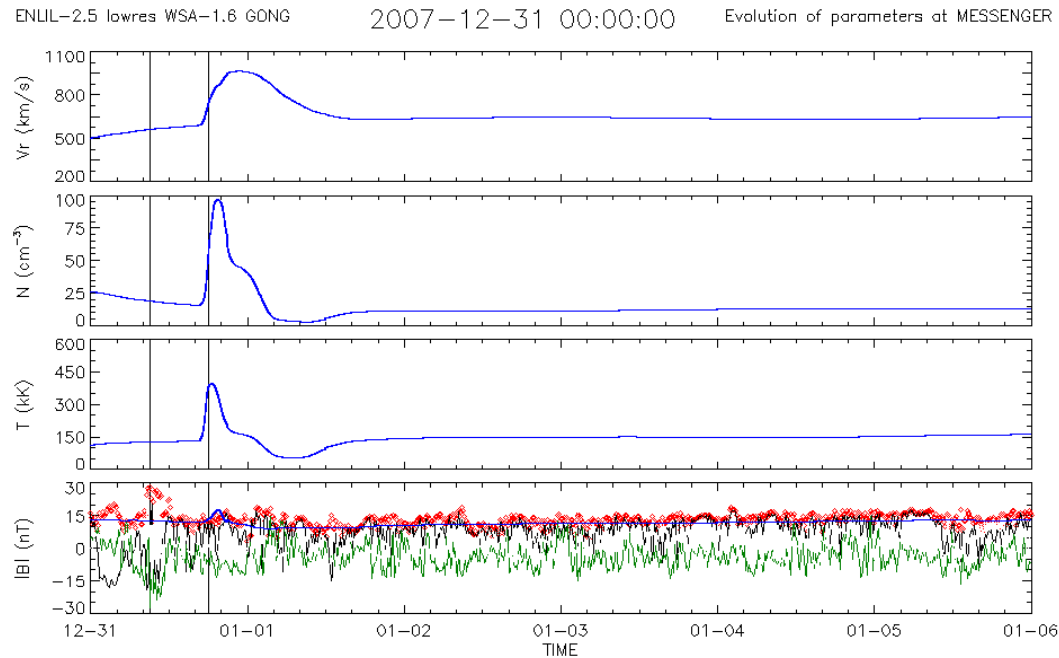
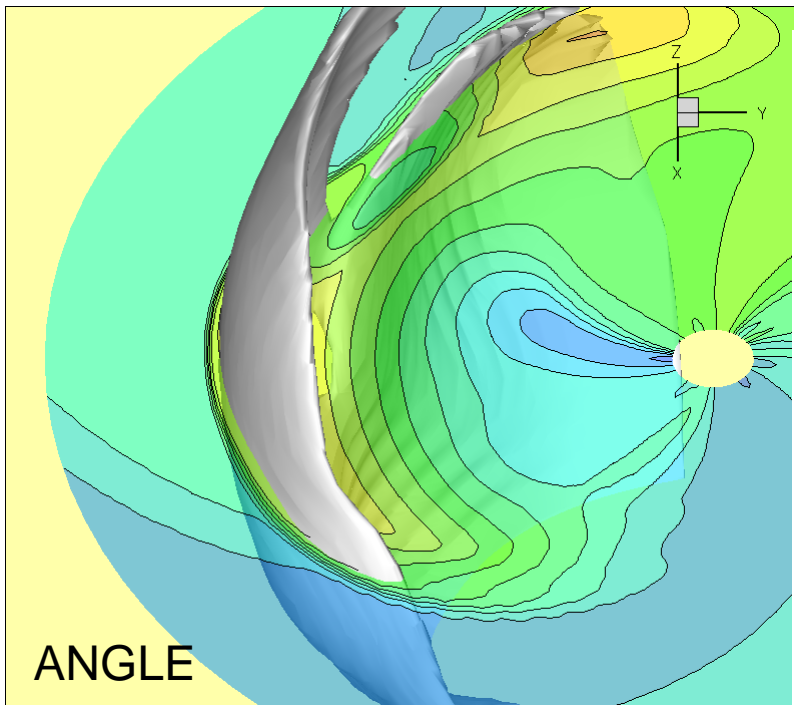
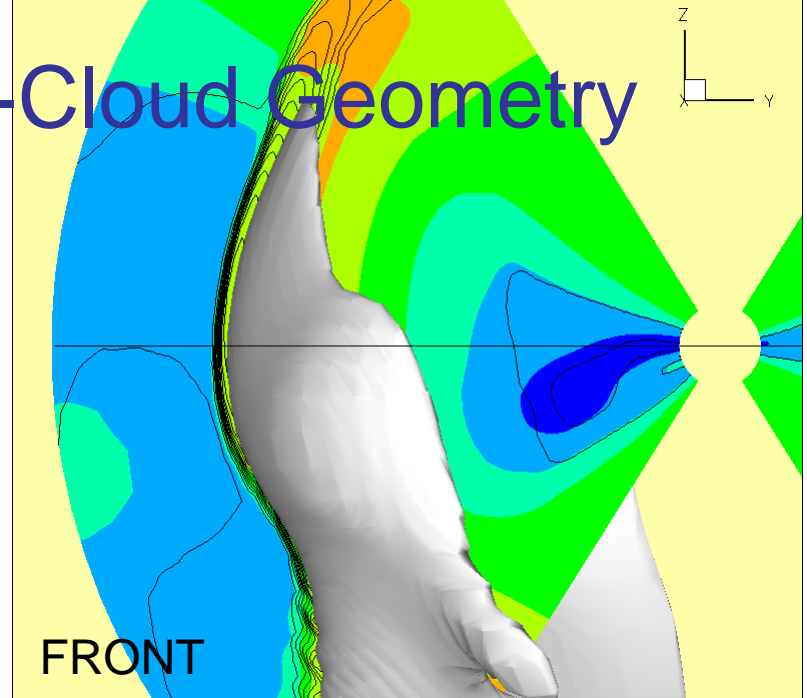
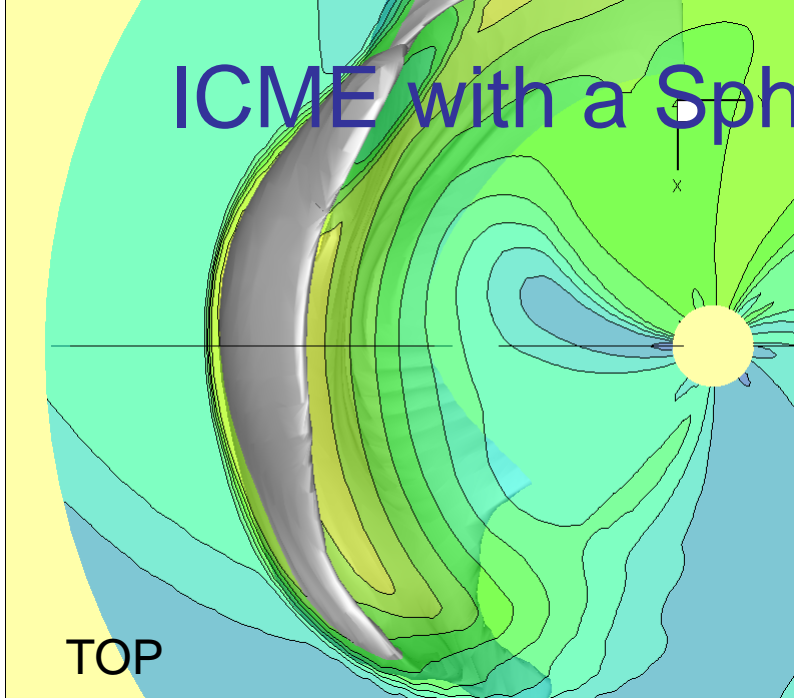
## PLUS

- observationally based
- simple specification
- numerically robust
- more accurate than empirical formulae
- global context for transient and background structures
- interplanetary shocks and IMF line connectivity

## MINUS

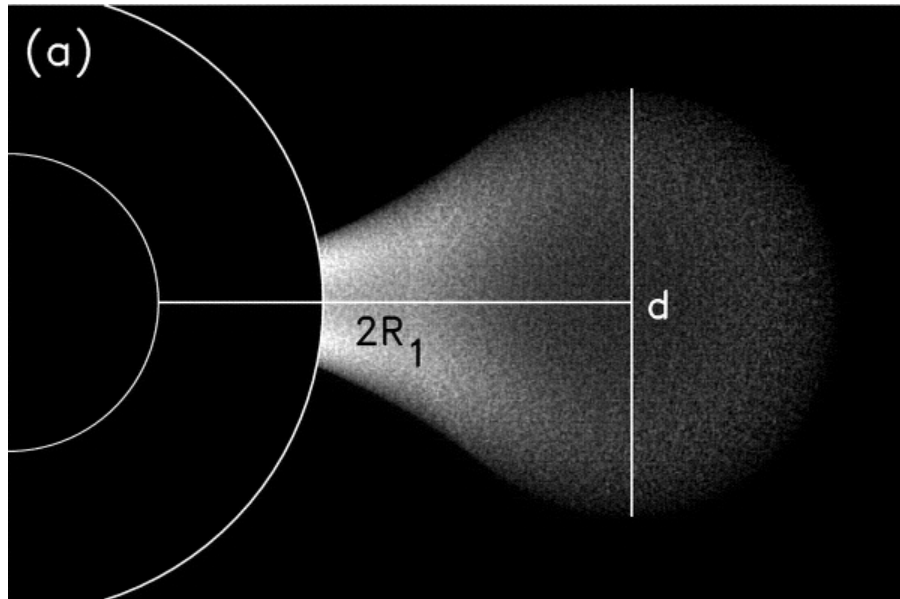
- absence of internal magnetic structure
- initial effect on surrounding solar wind
- reverse shock
- shock stand-off distance

# ICME with a Spherical-Cloud Geometry

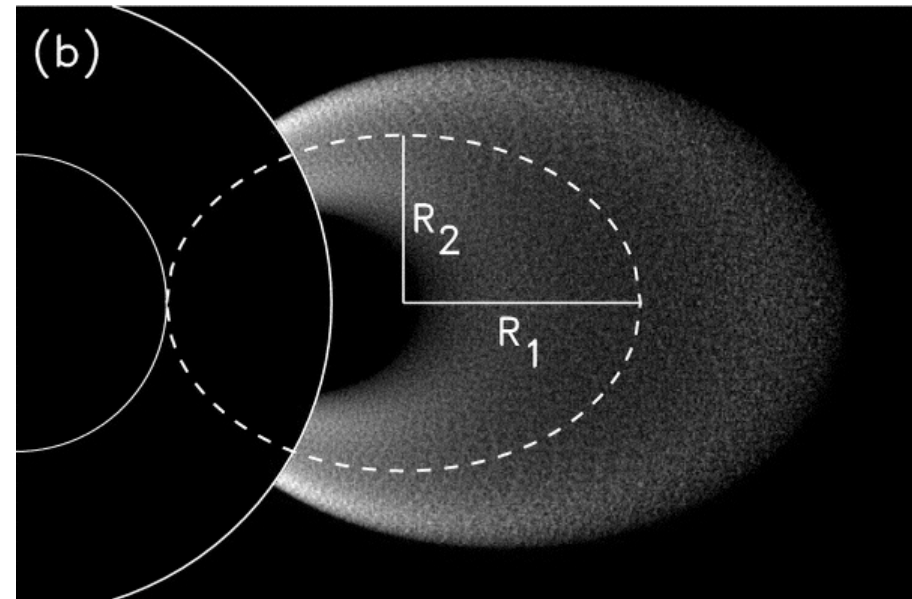


# Eruptive Flux Rope (EFR) Model

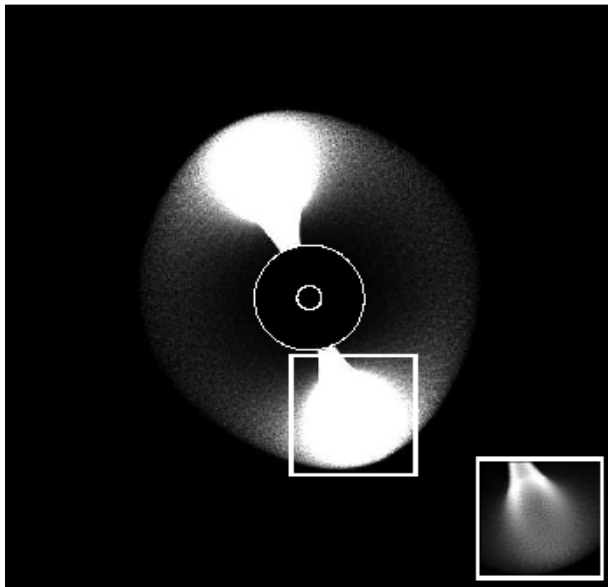
Axial view



Broadside view

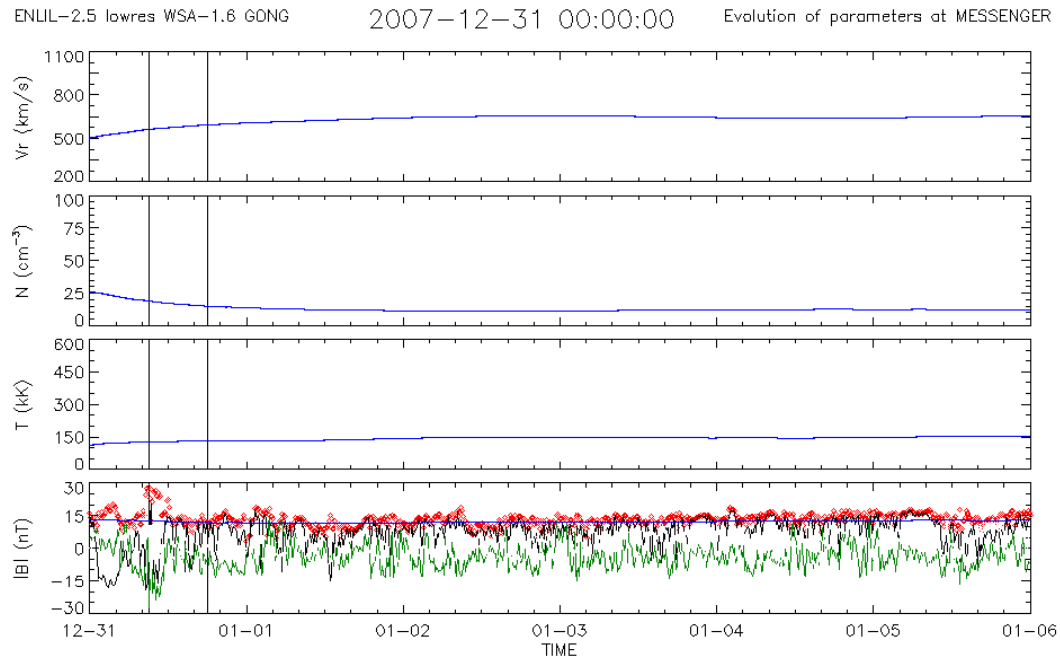
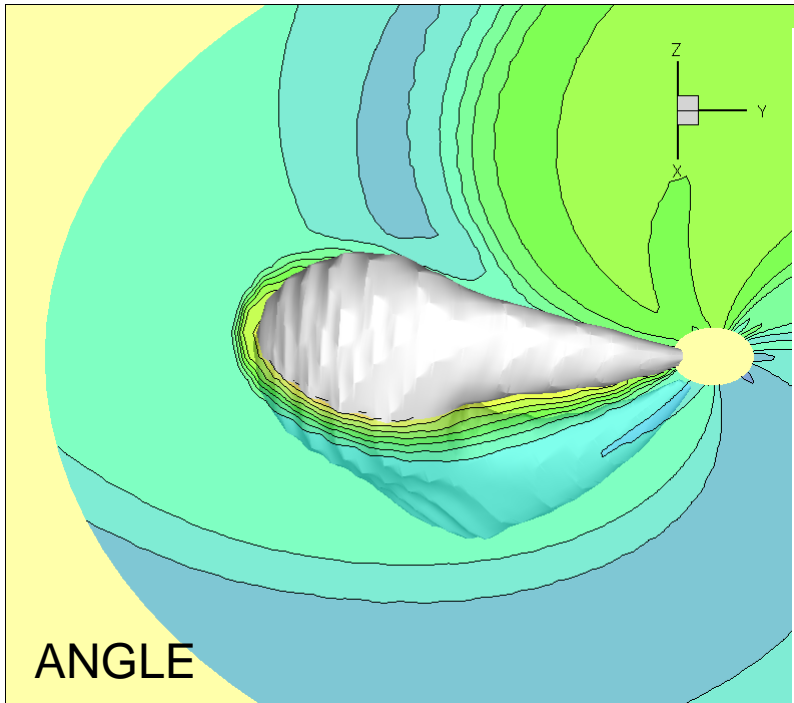
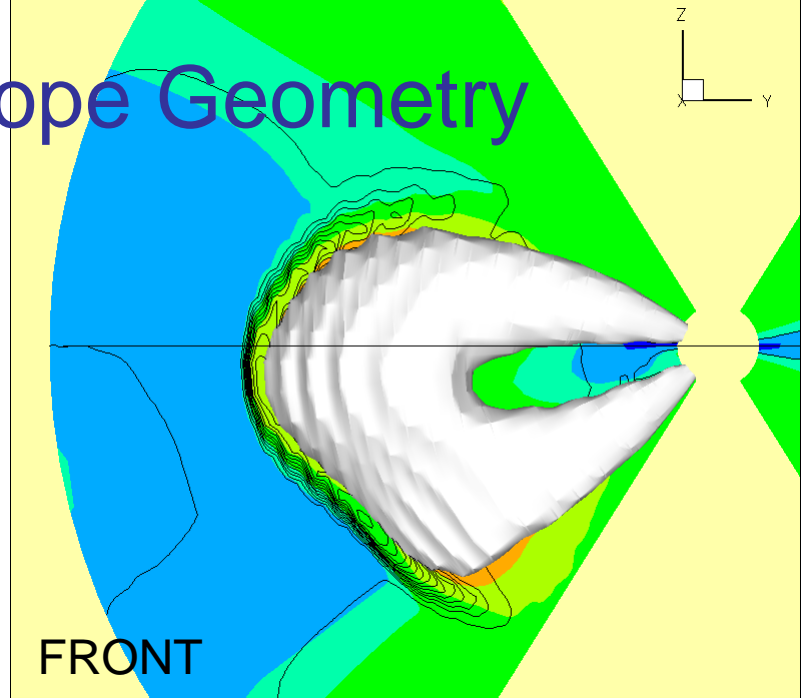
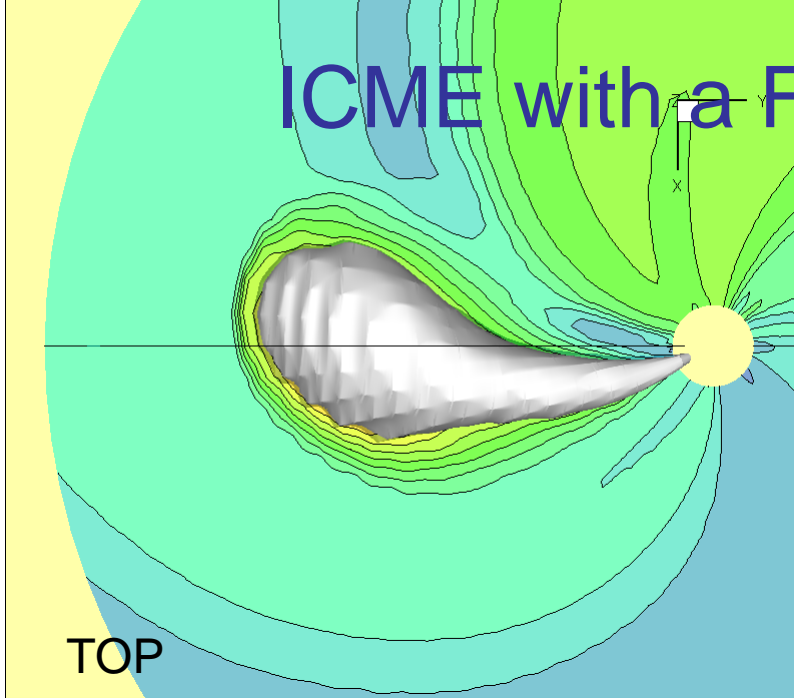


Front view



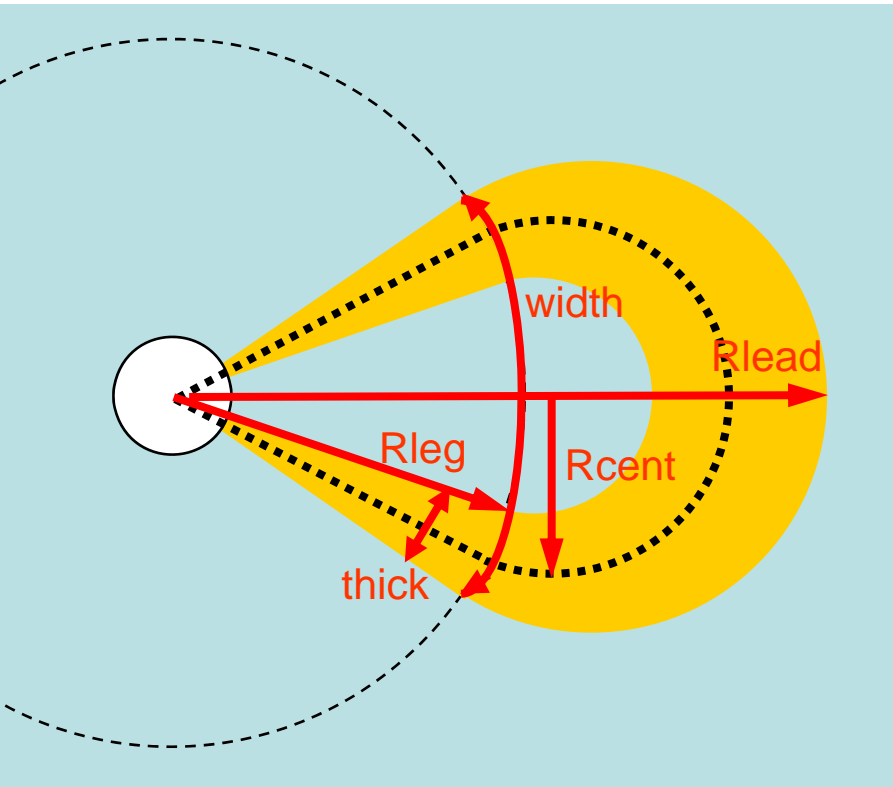
*Chen, 1996;*  
*Krall et al., 2000;*  
*Krall and Chen, 2004;*  
*Xie et al., 2008*

# ICME with a Flux-Rope Geometry

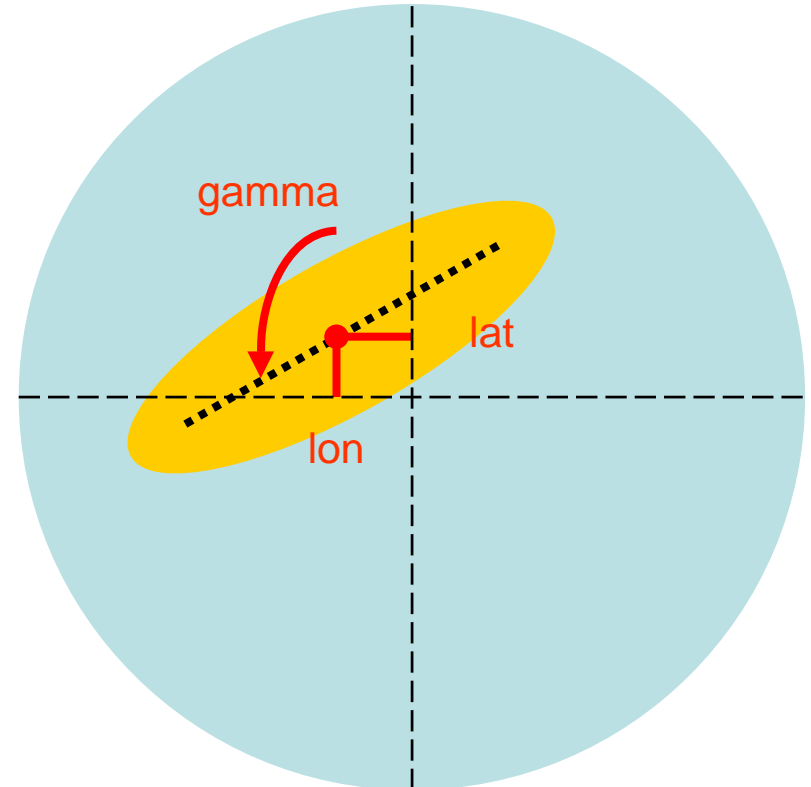


# ICME – Hydrodynamic Rope Model

SIDE VIEW



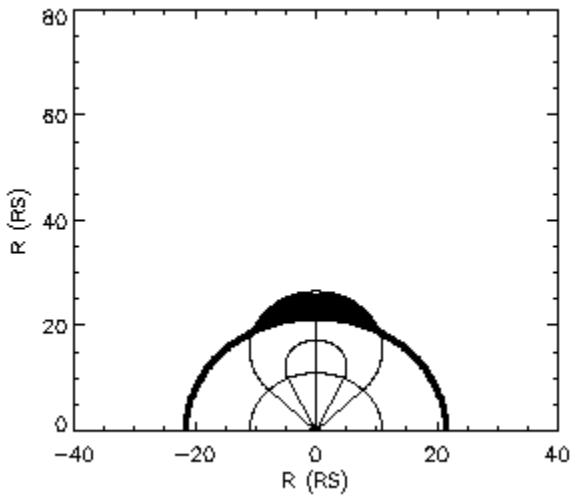
FRONT VIEW



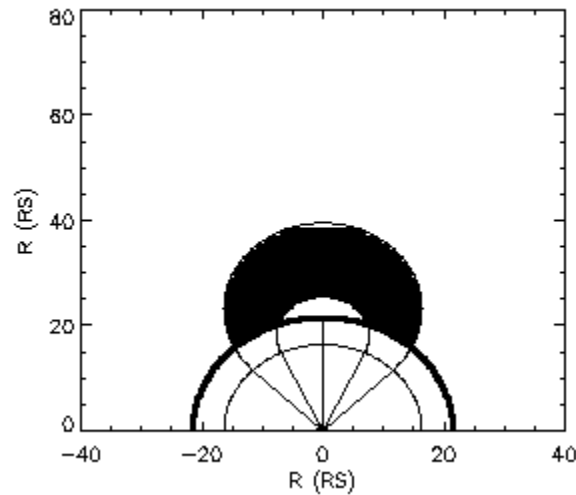
- Thernisien et al. (2008) – fitting STEREO coronagraph observations
- Spatial structure  $\rightarrow$  time dependent boundary conditions

# Launching the Hydrodynamic Rope Model

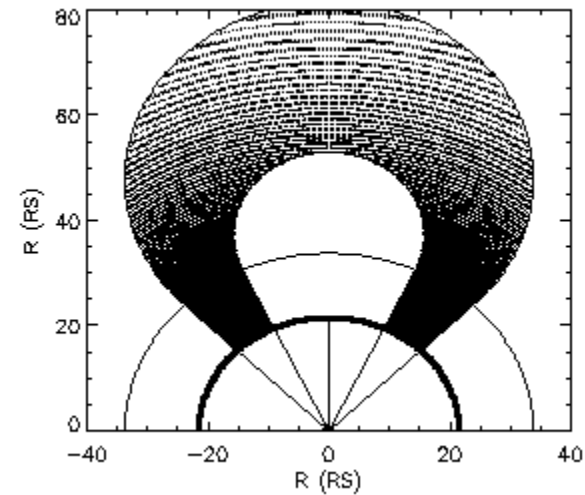
Emerging cap



Emerging main body



Emerging legs

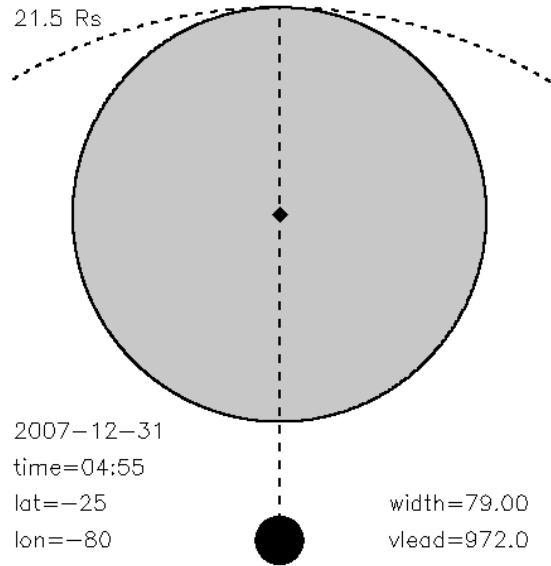


- Self-similarity achieved by linear decrease of the speed
- Leg-structures may last few days

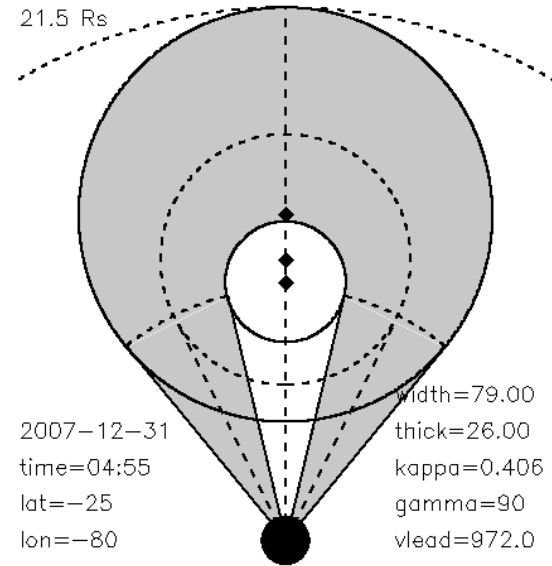


# 2007 December 31 CME

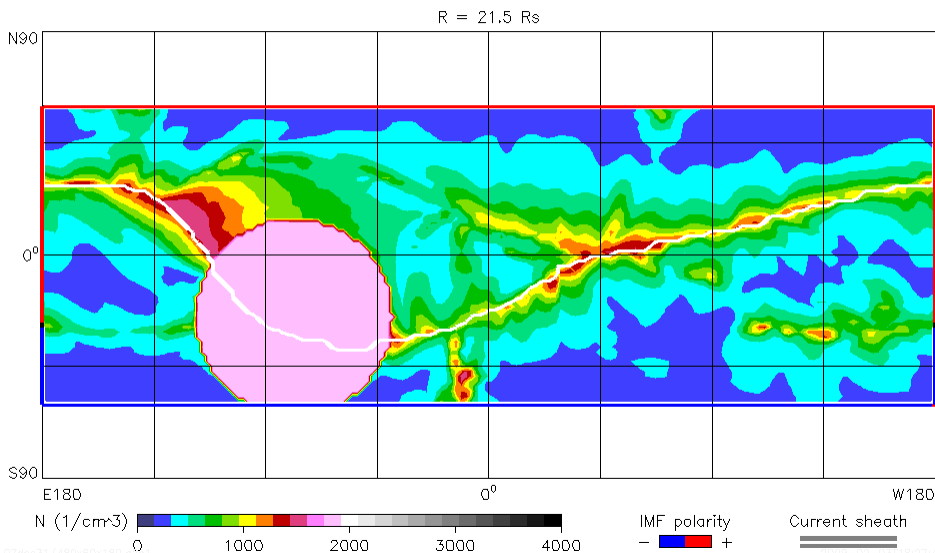
## Cone Model



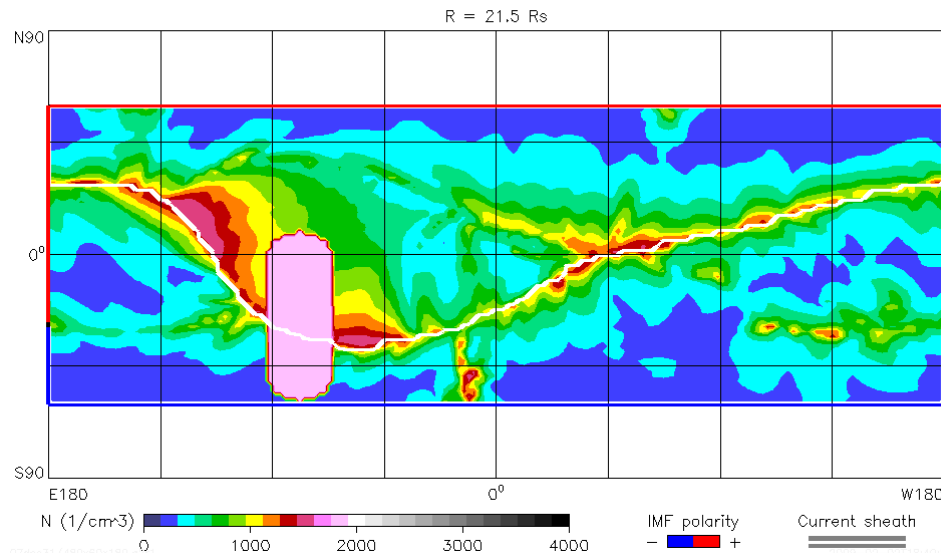
## Rope Model



ENLIL-2.5 medres WSA-1.6 GONG 2007-12-31 07:41:26 2007-12-31 + 0.32 days

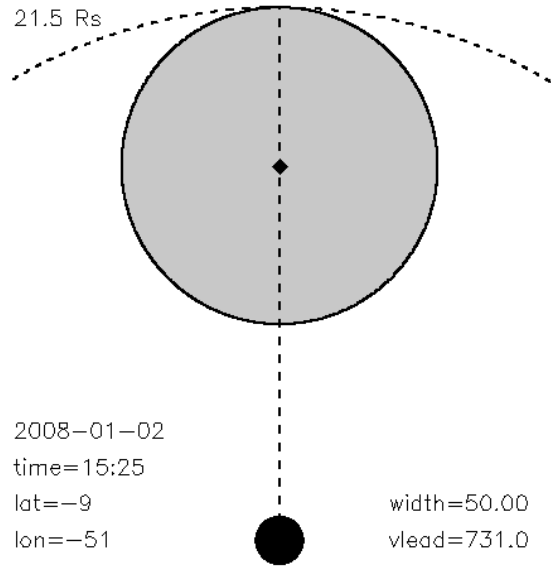


ENLIL-2.5 medres WSA-1.6 GONG 2007-12-31 06:49:57 2007-12-31 + 0.28 days

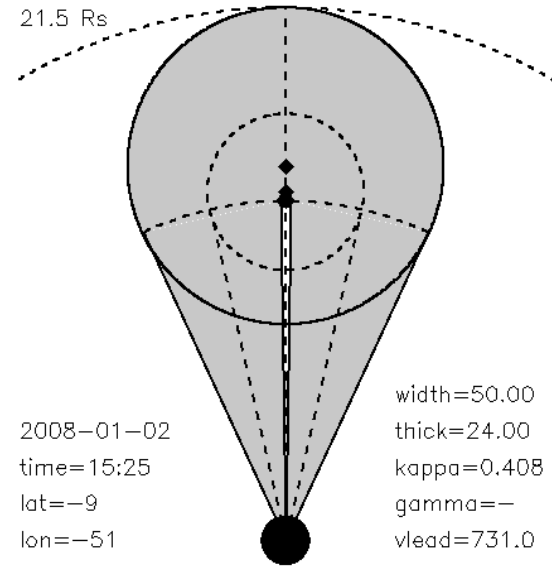


# 2008 January 2 CME

## Cone Model



## Rope Model

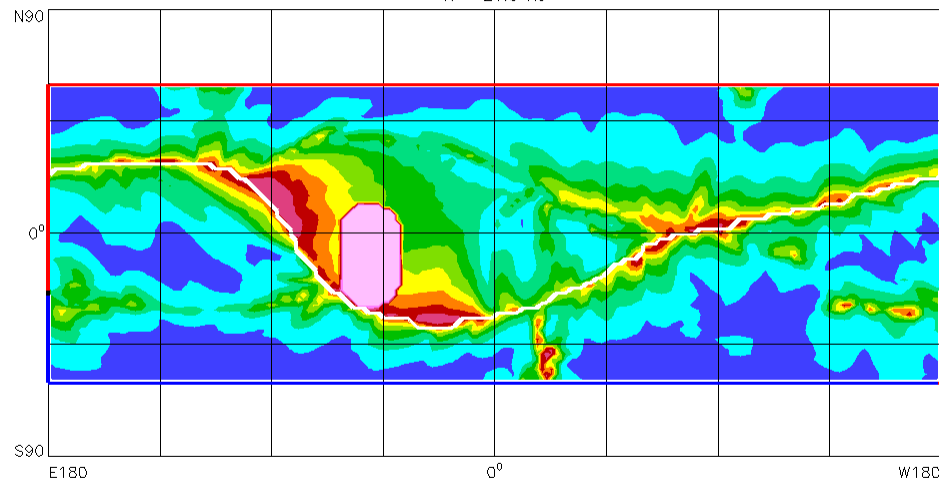
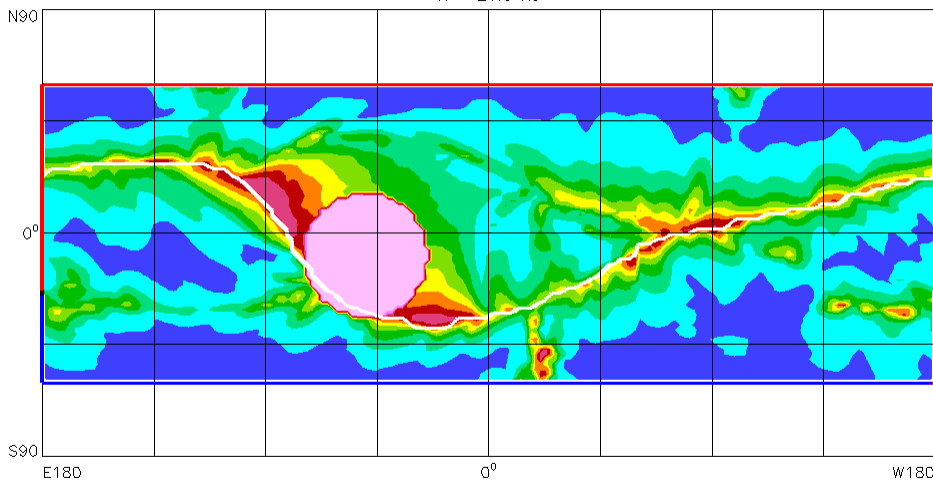


ENLIL-2.5 medres WSA-1.6 GONG 2008-01-02 17:45:04 2008-01-02 + 0.73 days

ENLIL-2.5 medres WSA-1.6 GONG 2008-01-02 16:42:43 2008-01-02 + 0.69 days

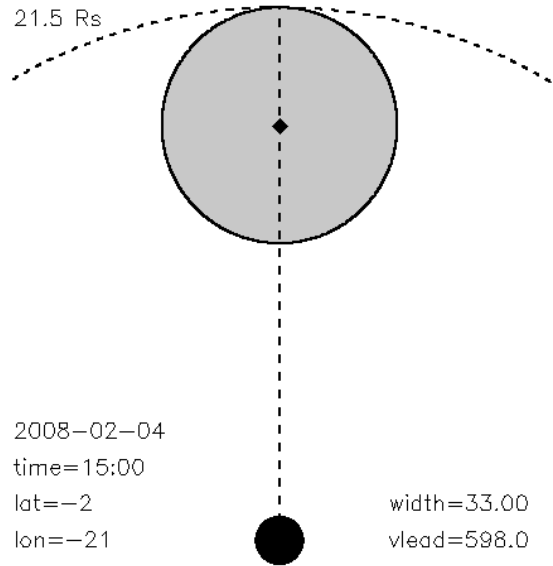
R = 21.5 Rs

R = 21.5 Rs

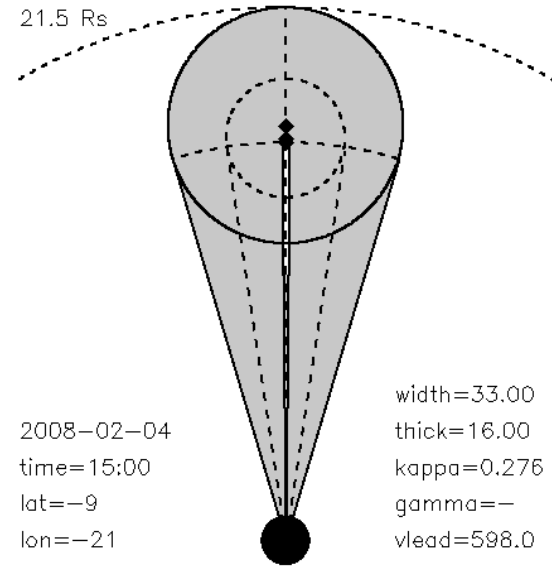


# 2008 February 4 CME

## Cone Model



## Rope Model

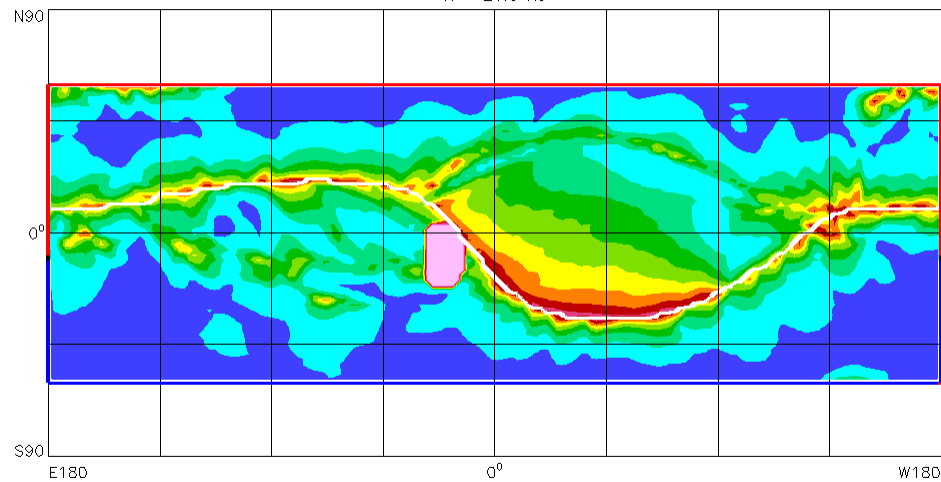
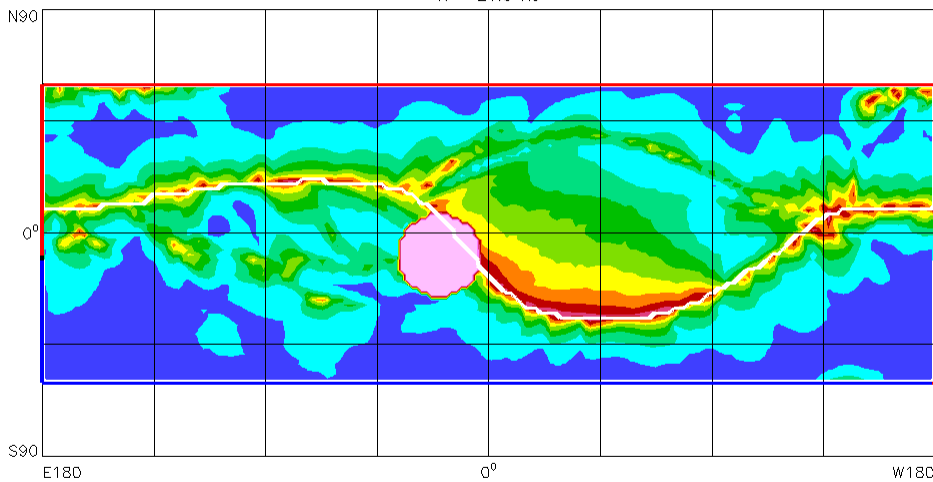


ENLIL-2.5 medres WSA-1.6 GONG 2008-02-04 16:53:00 2008-02-04 + 0.70 days

ENLIL-2.5 medres WSA-1.6 GONG 2008-02-04 15:56:33 2008-02-04 + 0.66 days

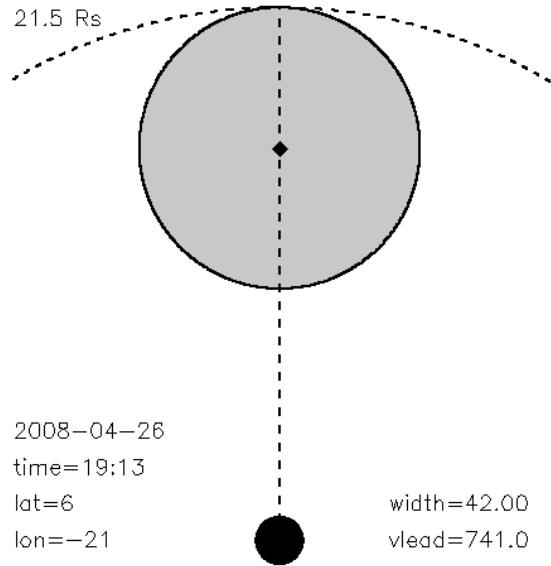
R = 21.5 Rs

R = 21.5 Rs

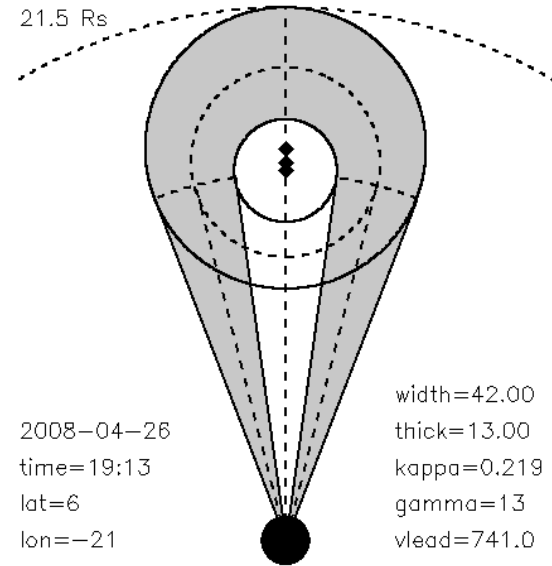


# 2008 April 26 CME

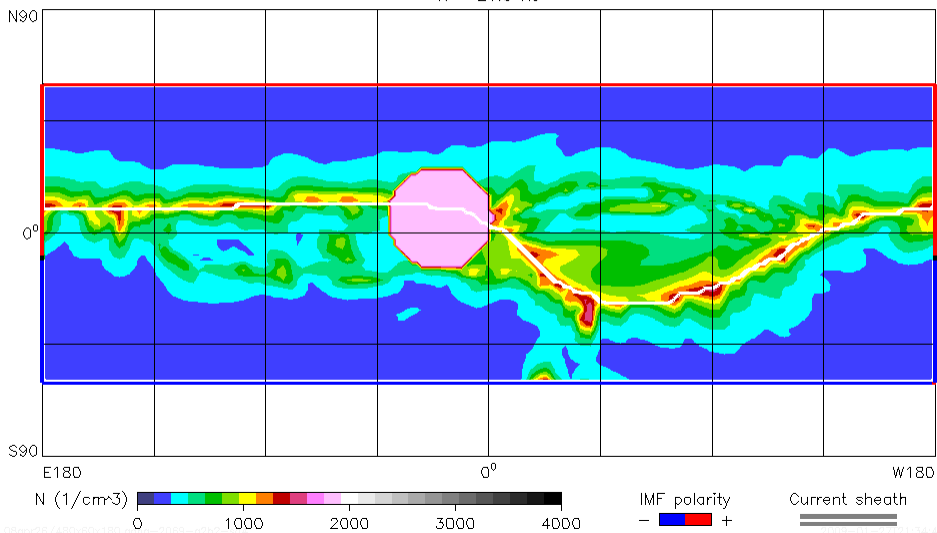
## Cone Model



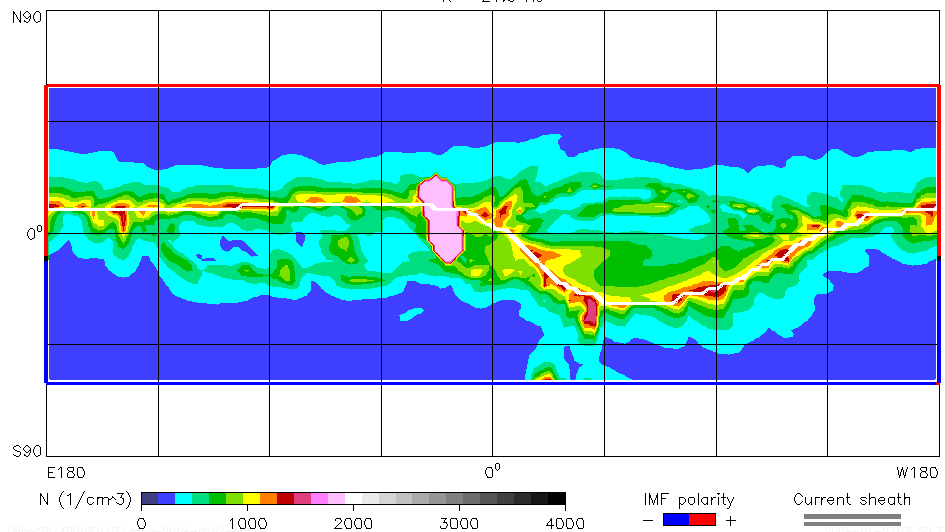
## Rope Model



ENLIL-2.5 medres WSA-1.6 GONG 2008-04-26 21:09:04 2008-04-26 + 0.88 days  
R = 21.5 Rs

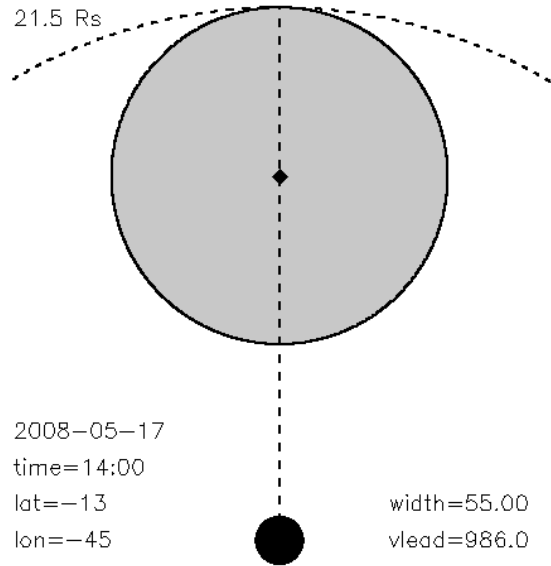


ENLIL-2.5 medres WSA-1.6 GONG 2008-04-26 20:14:14 2008-04-26 + 0.84 days  
R = 21.5 Rs

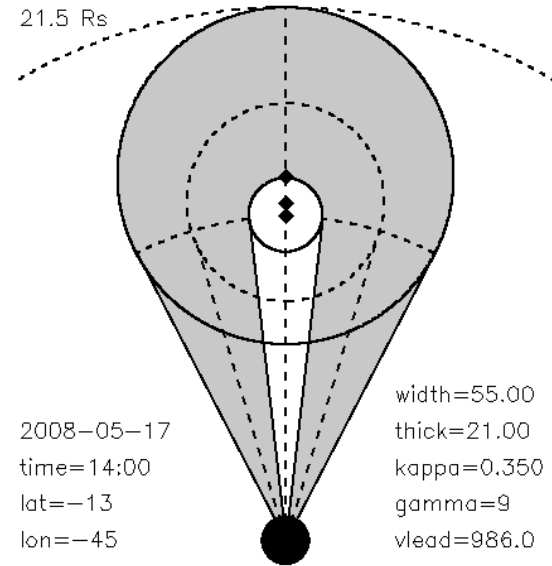


# 2008 May 17 CME

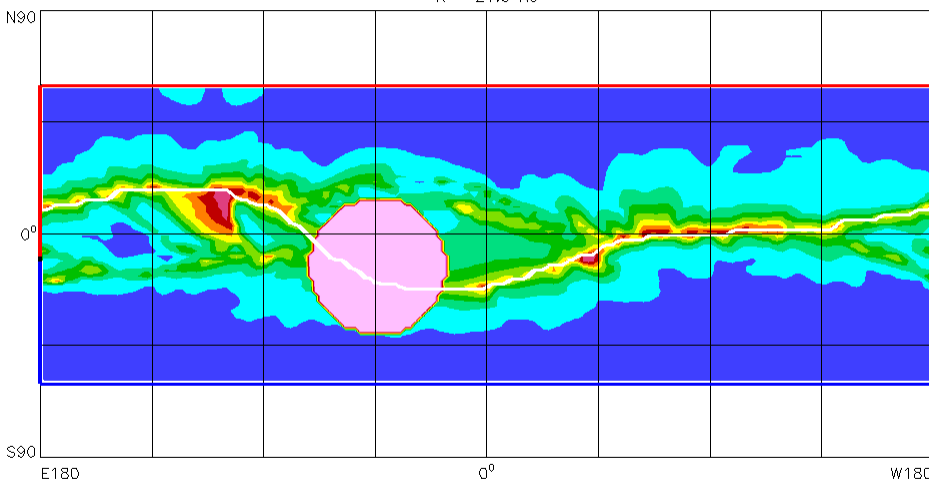
## Cone Model



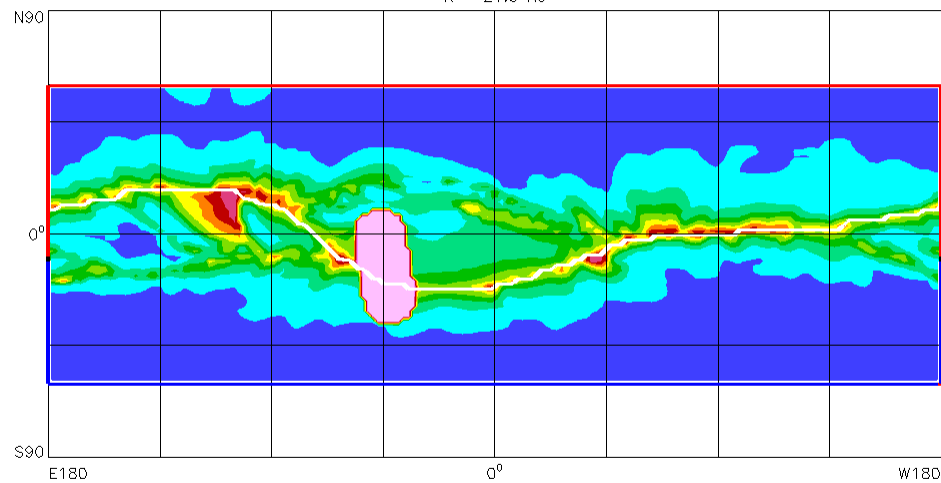
## Rope Model



ENLIL-2.5 medres WSA-1.6 GONG 2008-05-17 15:54:13 2008-05-17 + 0.66 days  
R = 21.5 Rs

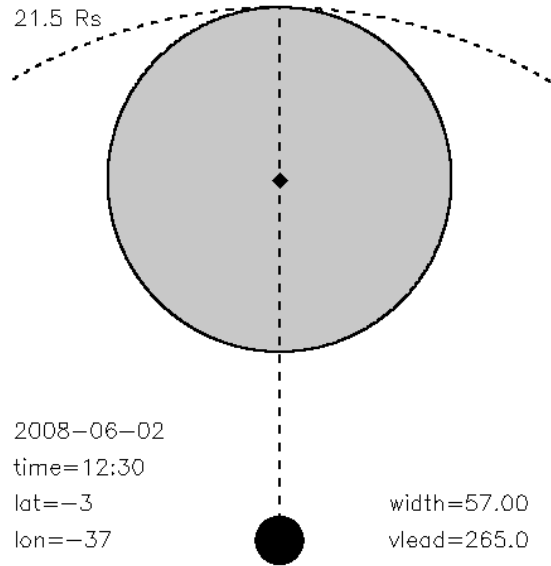


ENLIL-2.5 medres WSA-1.6 GONG 2008-05-17 15:05:32 2008-05-17 + 0.62 days  
R = 21.5 Rs

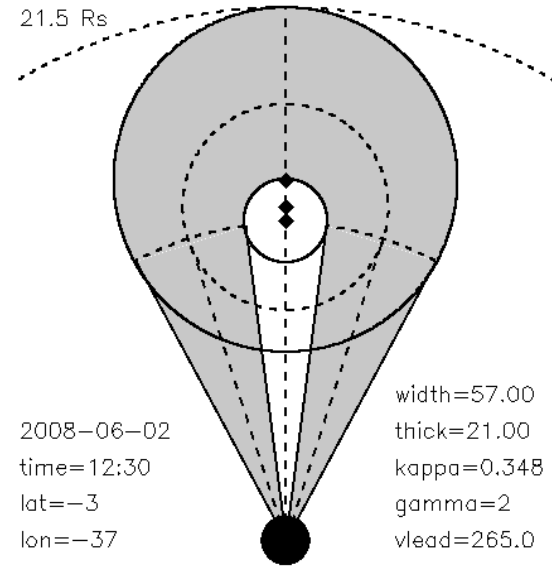


# 2008 June 2 CME

## Cone Model

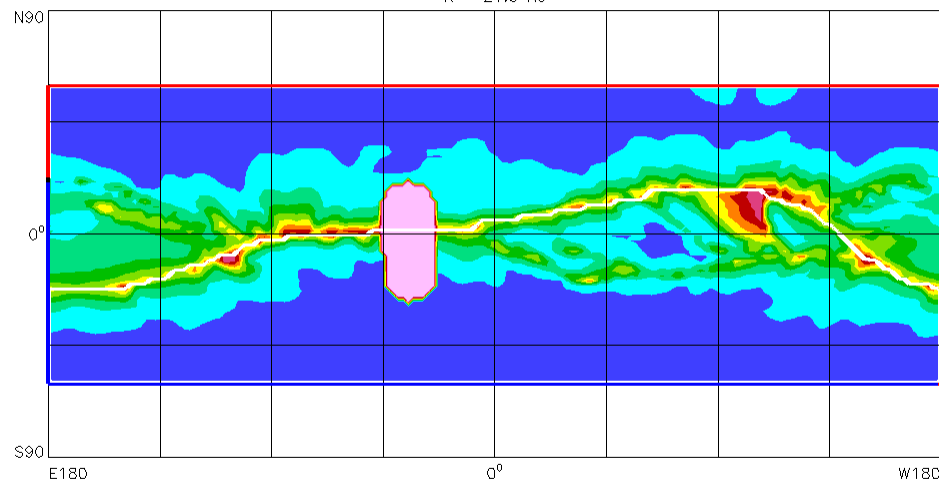
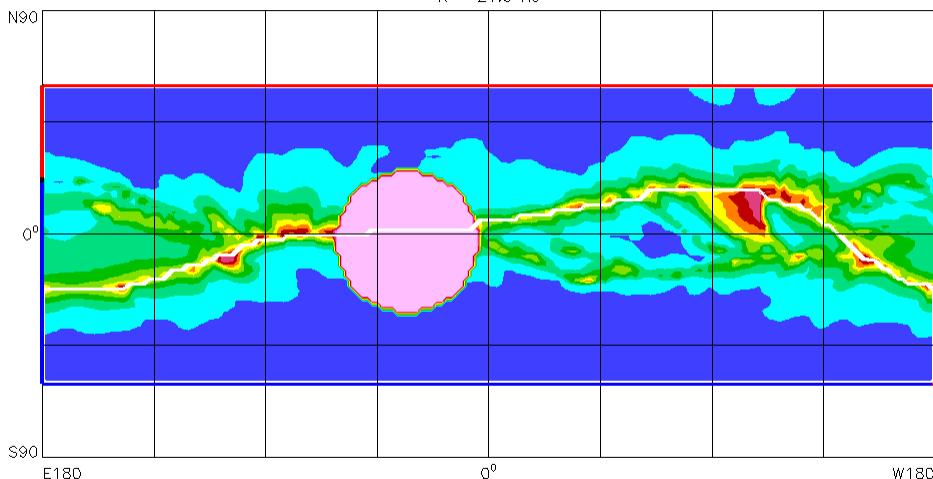


## Rope Model



ENLIL-2.5 medres WSA-1.6 GONG 2008-06-02 19:50:28 2008-06-02 + 0.82 days  
R = 21.5 Rs

ENLIL-2.5 medres WSA-1.6 GONG 2008-06-02 16:46:14 2008-06-02 + 0.69 days  
R = 21.5 Rs

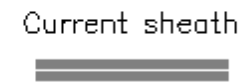
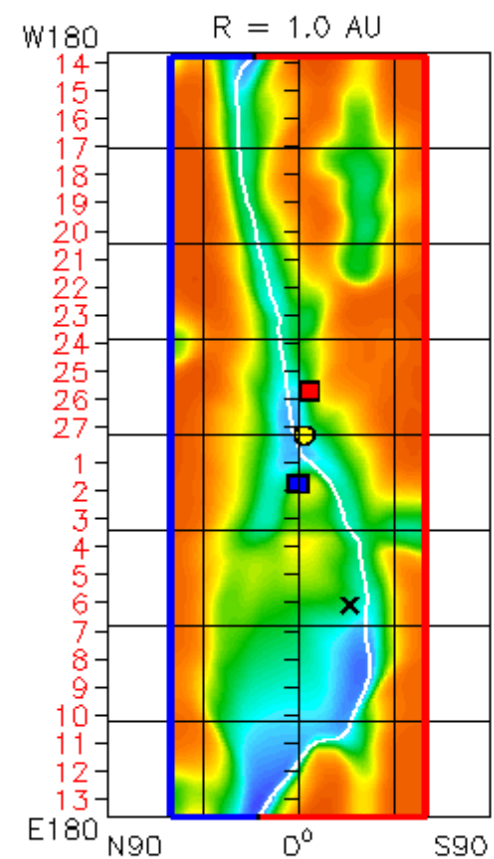
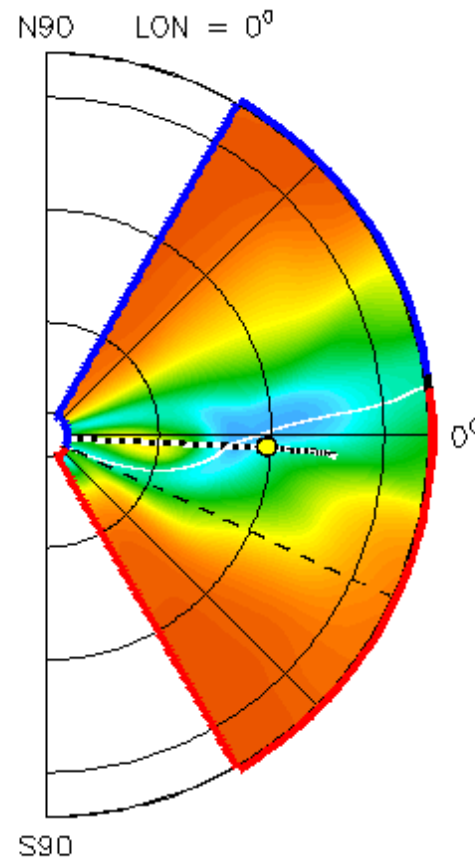
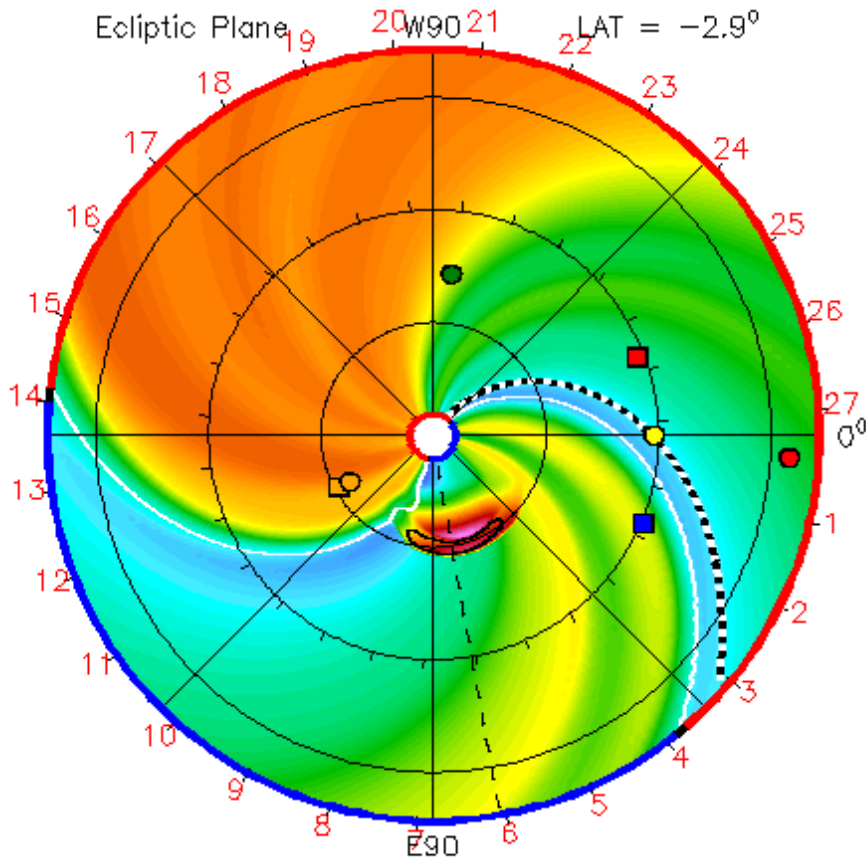


# 2007 December 31 CME – Cone Model

2008-01-01 04:01:04

2007-12-31 +1.16 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

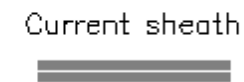
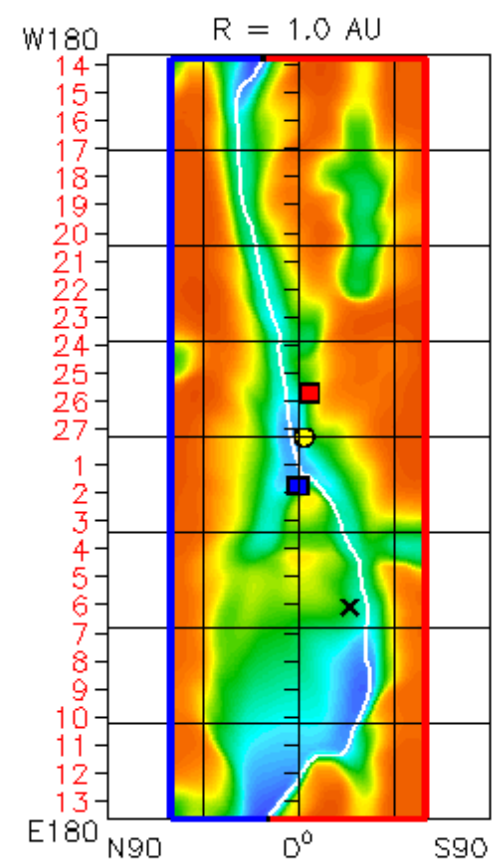
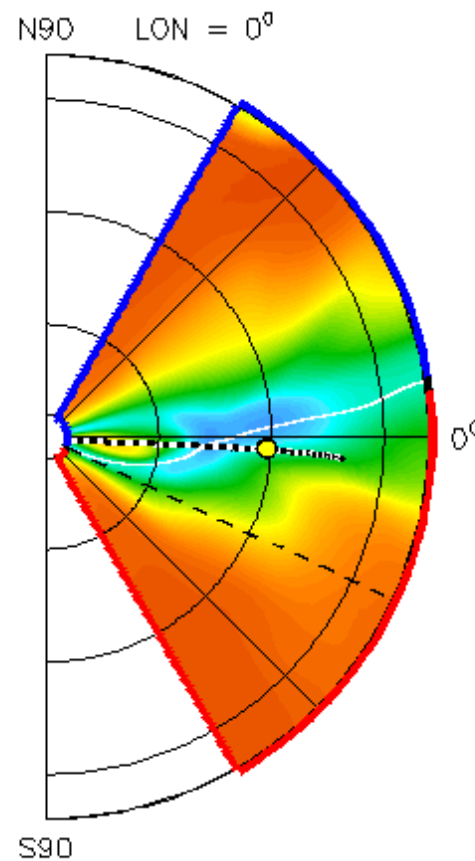
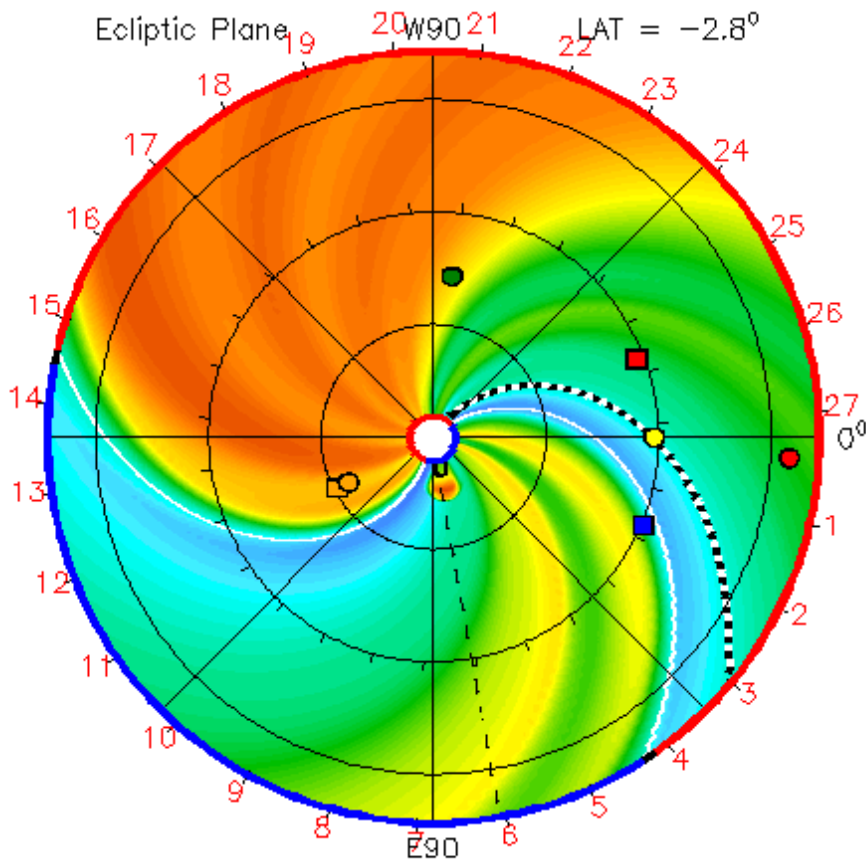


# 2007 December 31 CME – Rope Model

2007-12-31 16:02:47

2007-12-31 +0.66 days

● Mercury   
 ● Venus   
 ● Earth   
 ● Mars   
 ■ Messenger   
 ■ Stereo\_A   
 ■ Stereo\_B



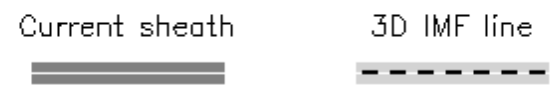
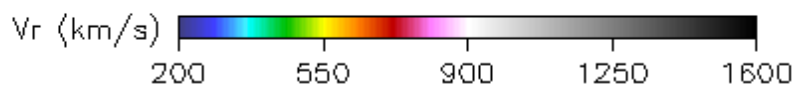
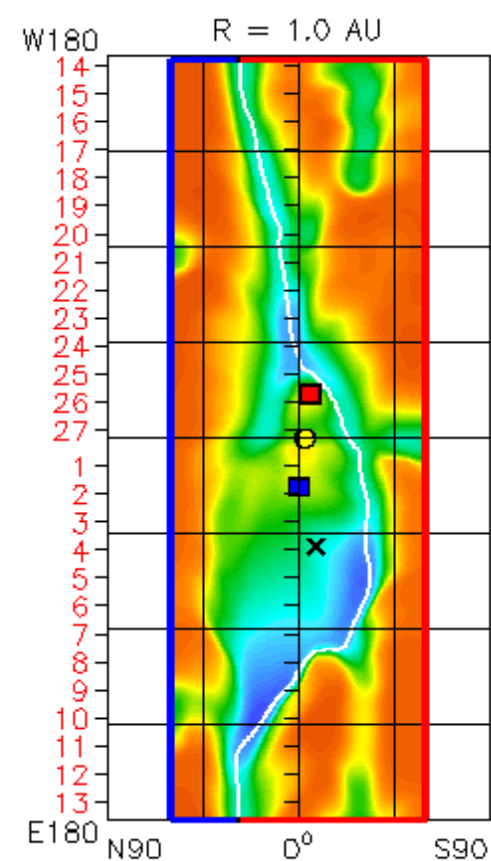
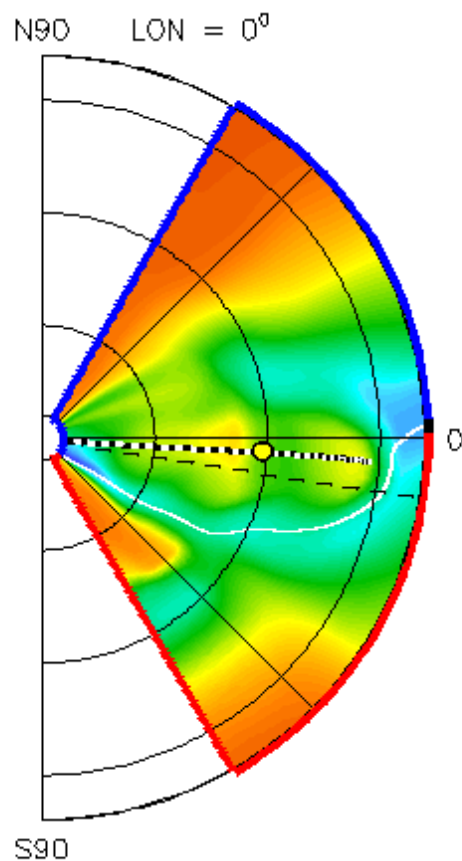
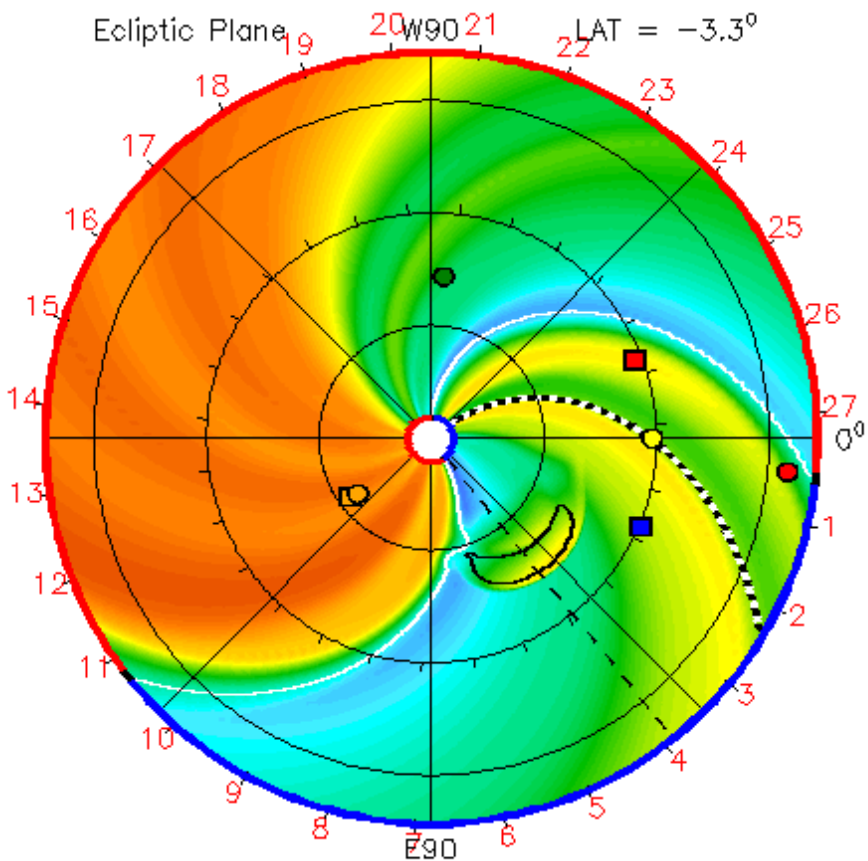


# 2008 January 2 CME – Cone Model

2008-01-04 12:00:05

2008-01-02 +2.50 days

● Mercury   
 ● Venus   
 ● Earth   
 ● Mars   
 ■ Messenger   
 ■ Stereo\_A   
 ■ Stereo\_B

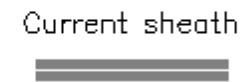
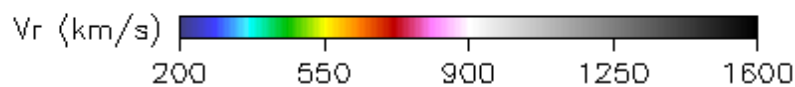
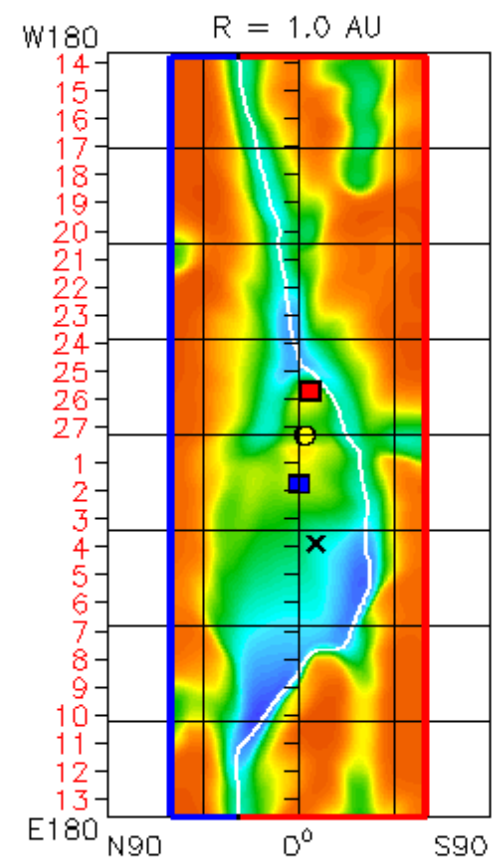
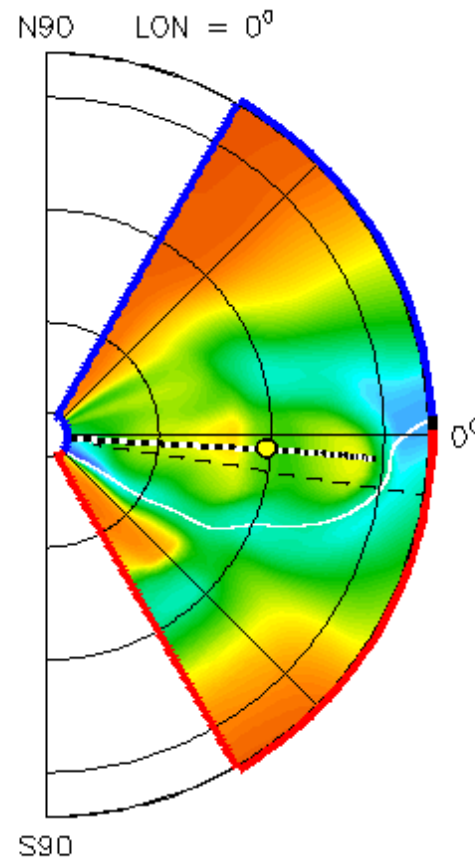
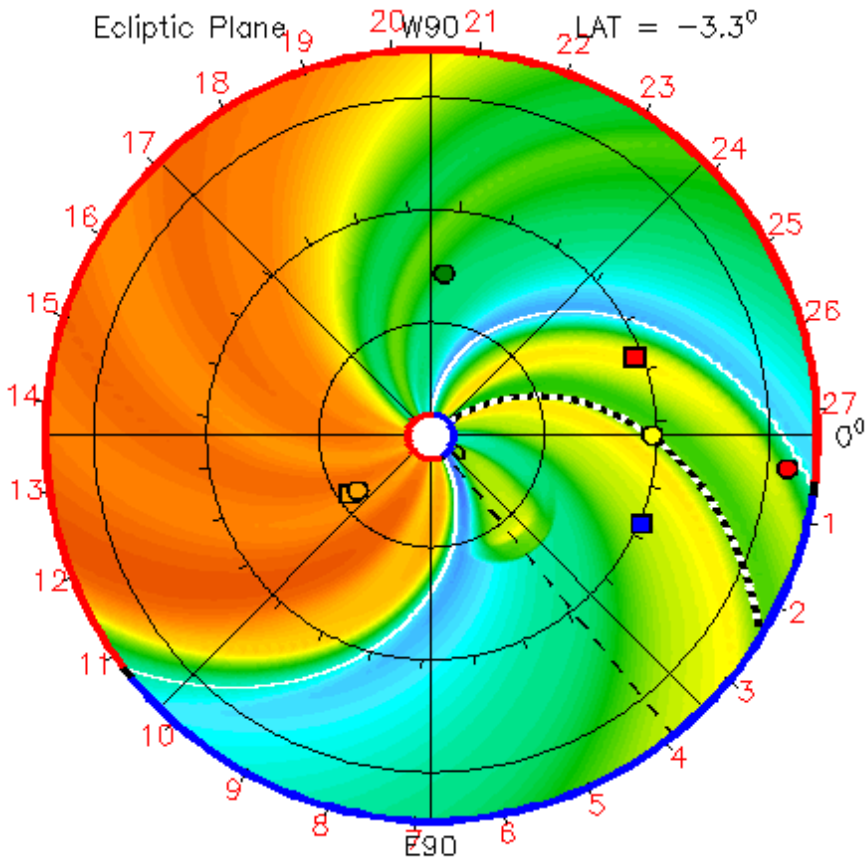


# 2008 January 2 CME – Rope Model

2008-01-04 10:00:49

2008-01-02 +2.41 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

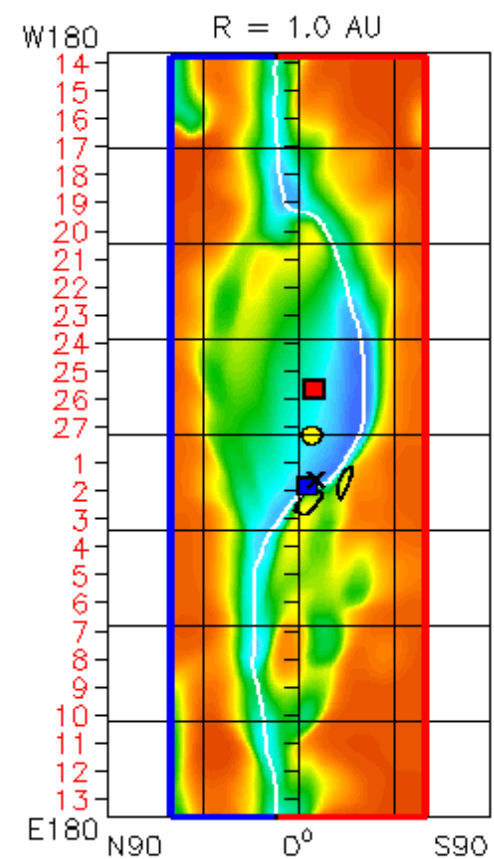
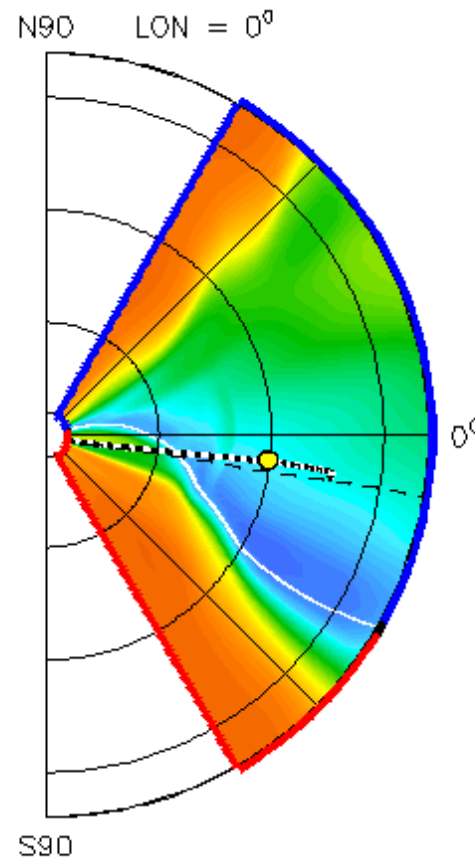
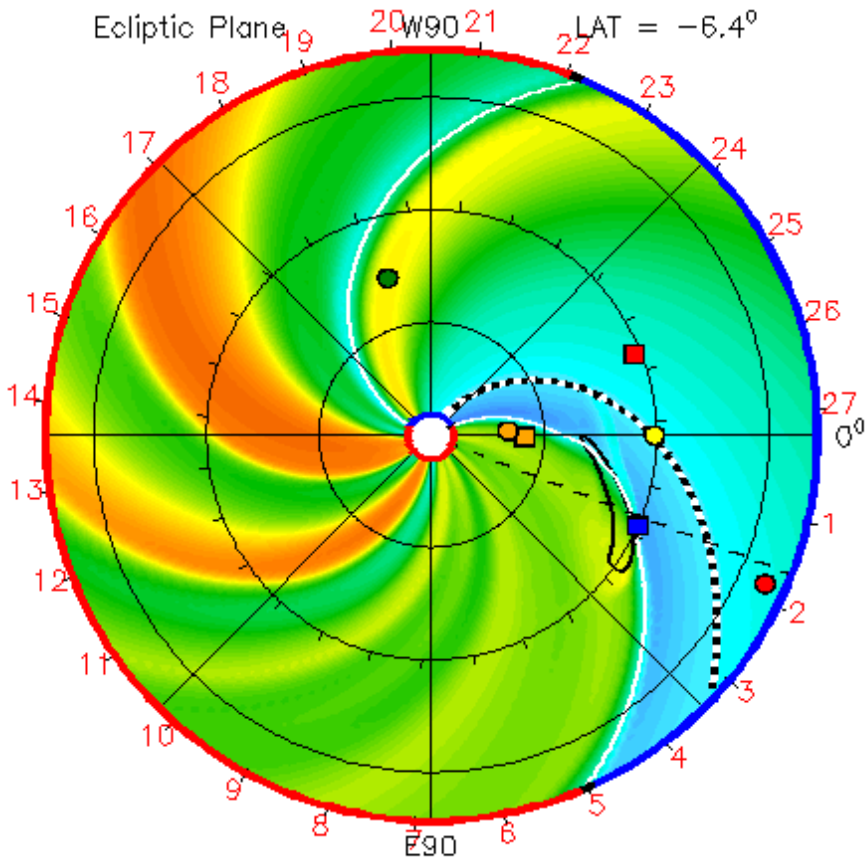


# 2008 February 4 CME – Cone Model

2008-02-07 10:01:12

2008-02-04 +3.41 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

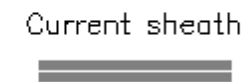
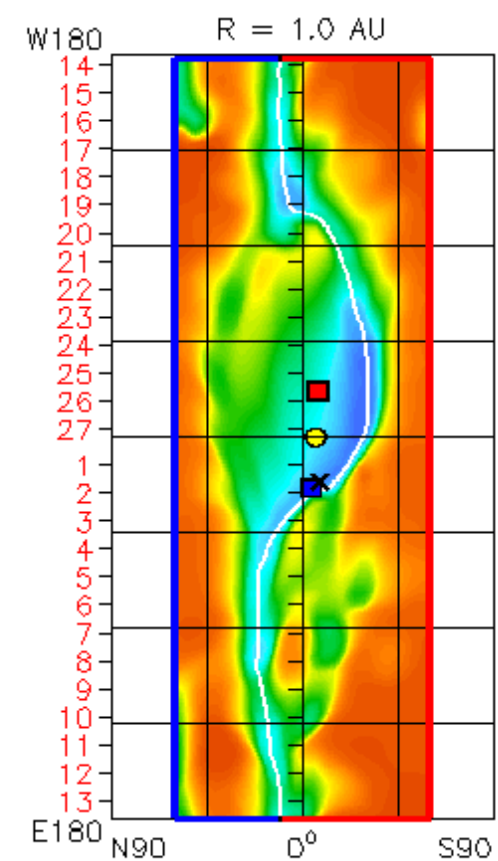
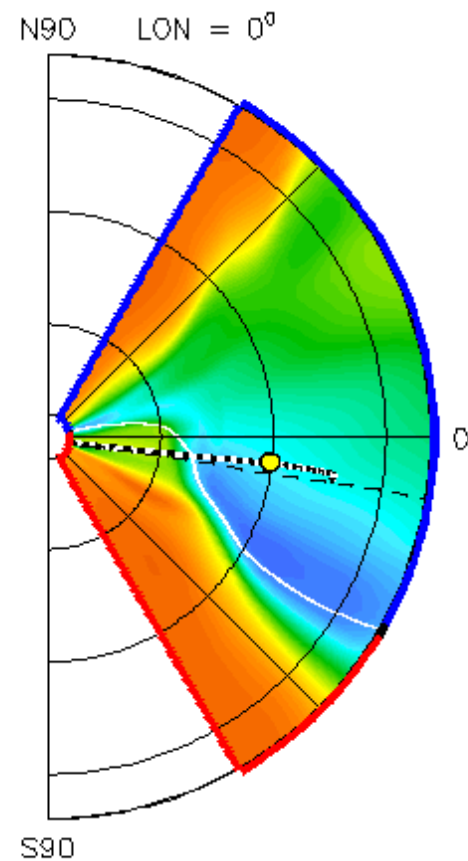
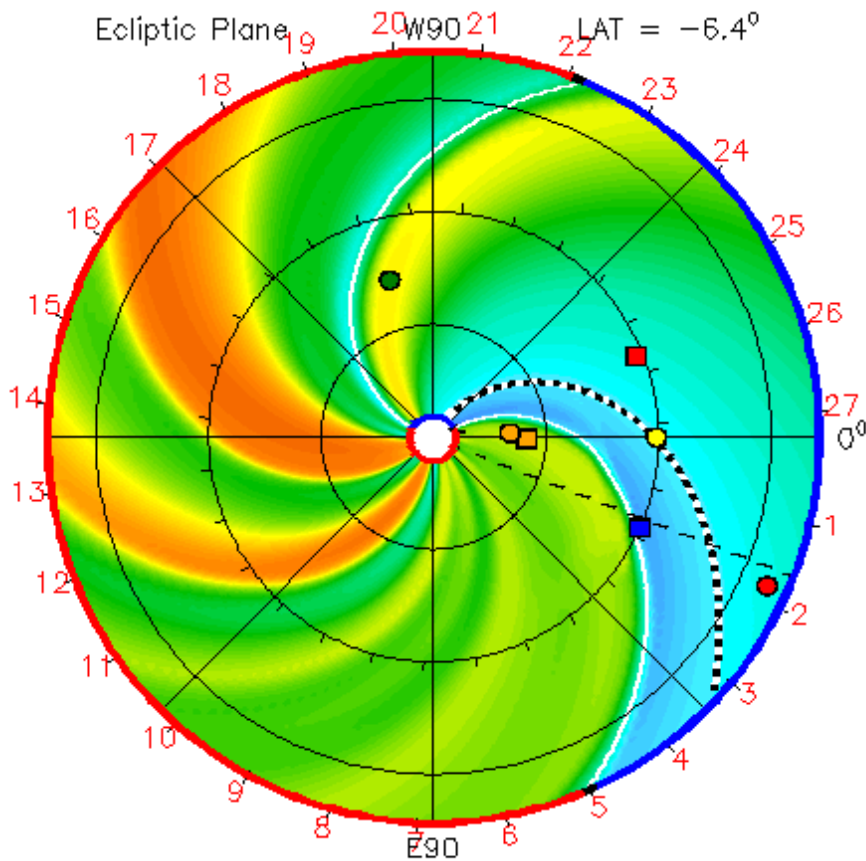


# 2008 February 4 CME – Rope Model

2008-02-07 10:03:02

2008-02-04 +3.41 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

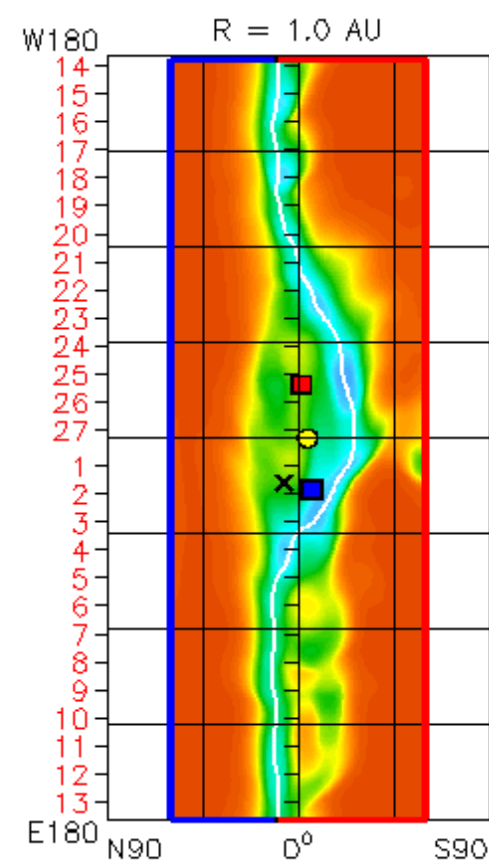
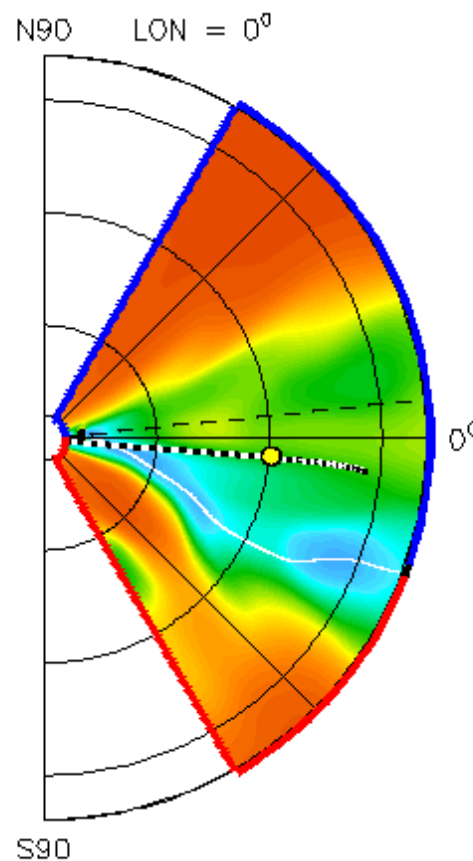
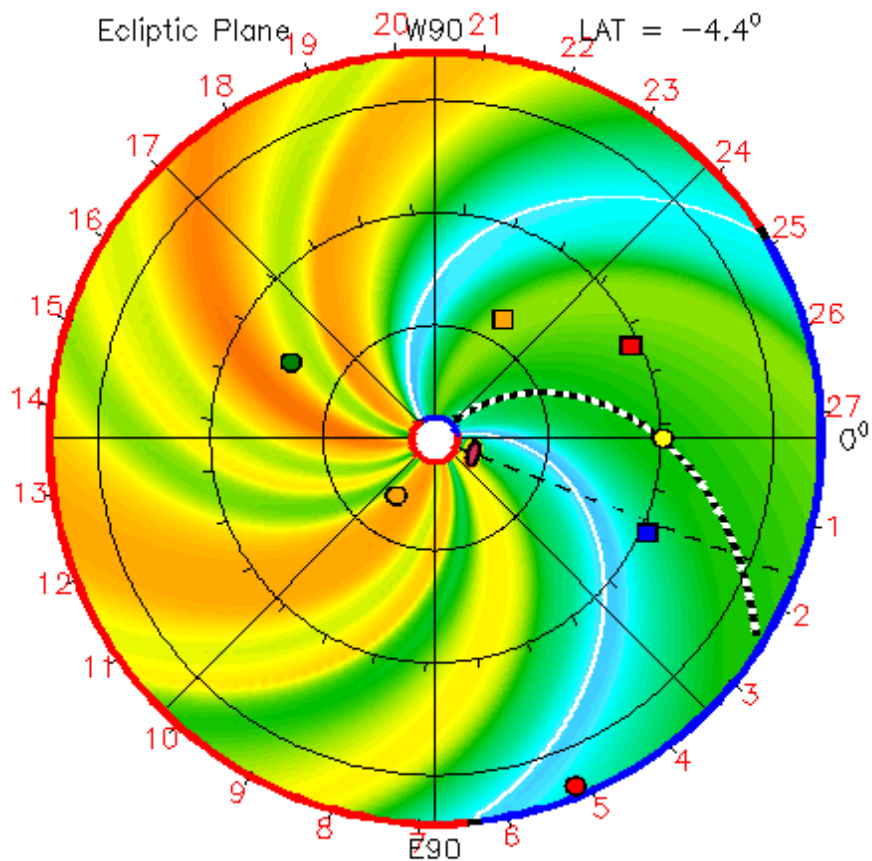


# 2008 April 26 CME – Cone Model

2008-04-27 02:02:51

2008-04-26 +1.08 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B



Current sheath



3D IMF line

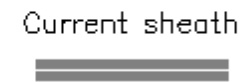
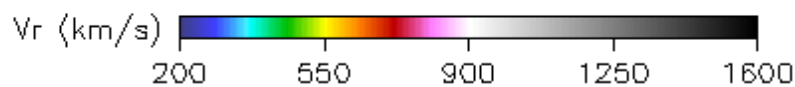
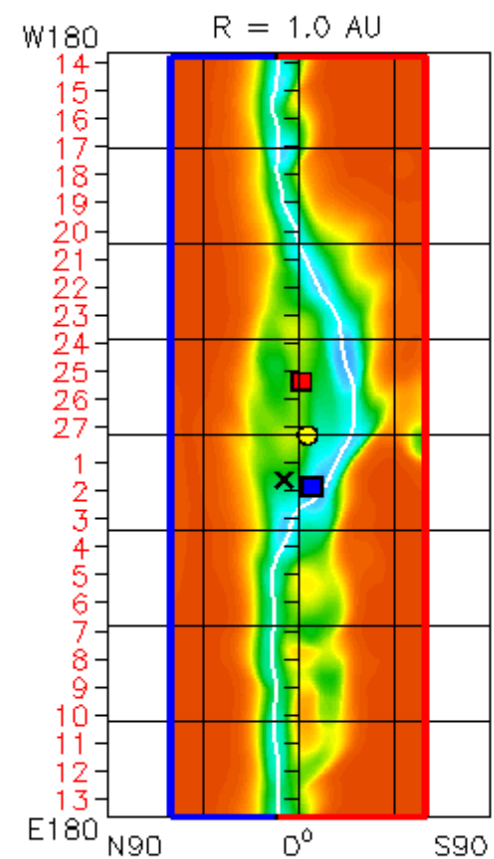
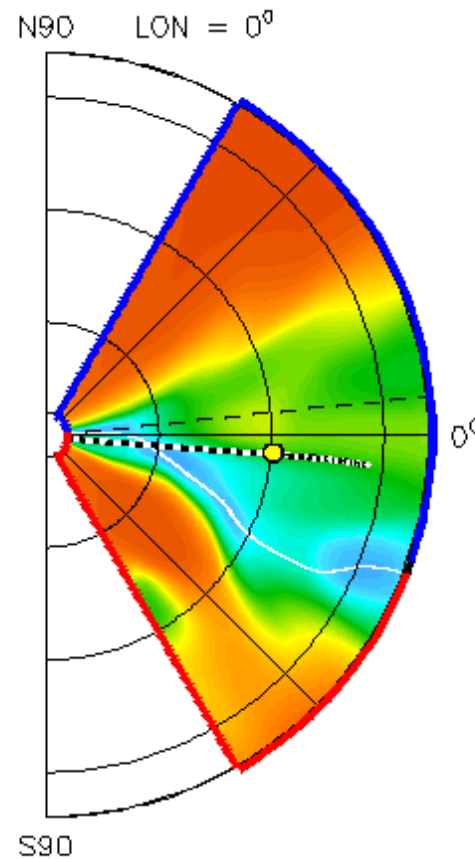
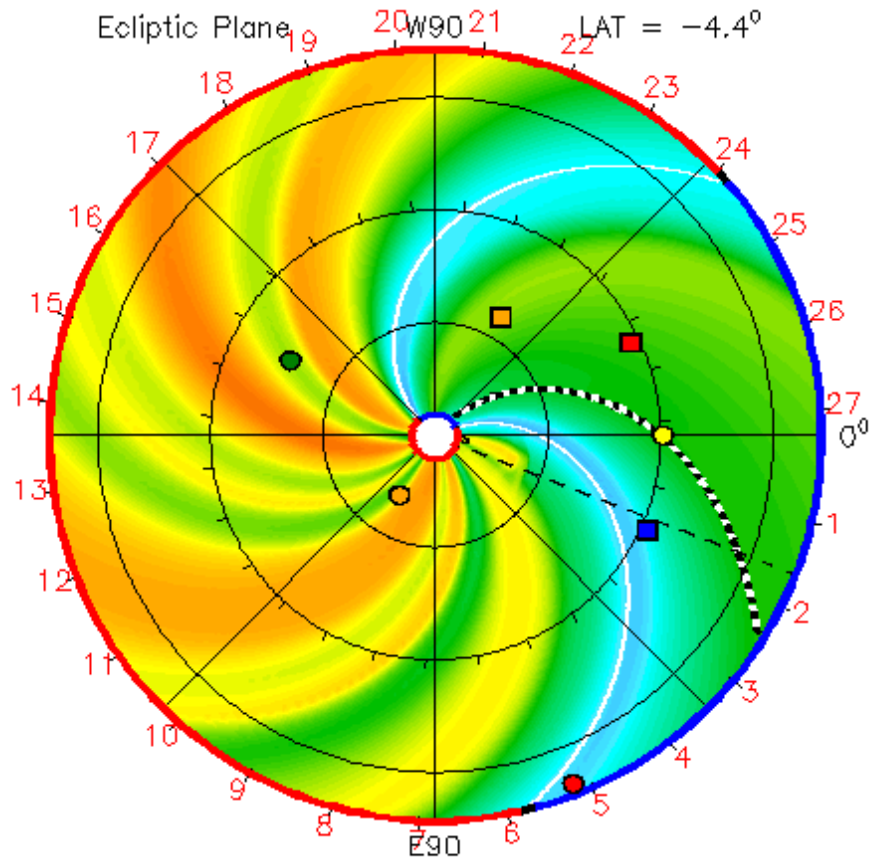


# 2008 April 26 CME – Rope Model

2008-04-27 18:02:30

2008-04-26 +1.75 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

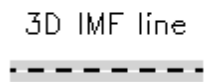
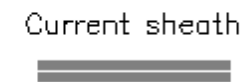
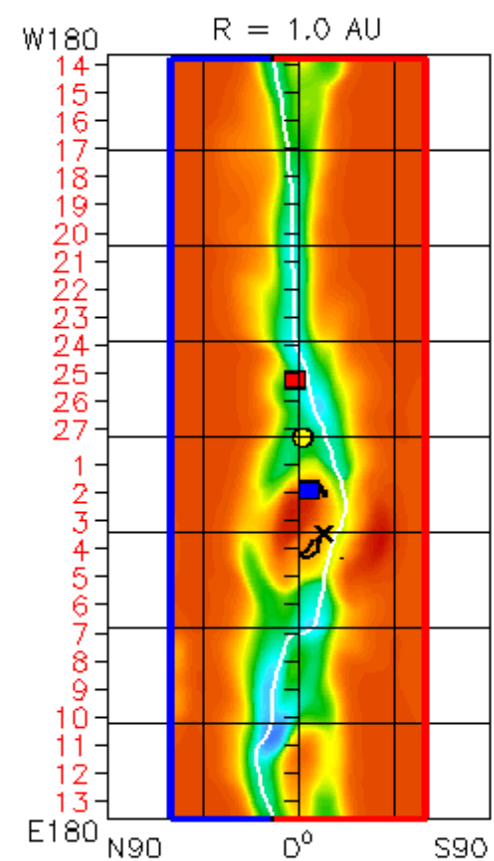
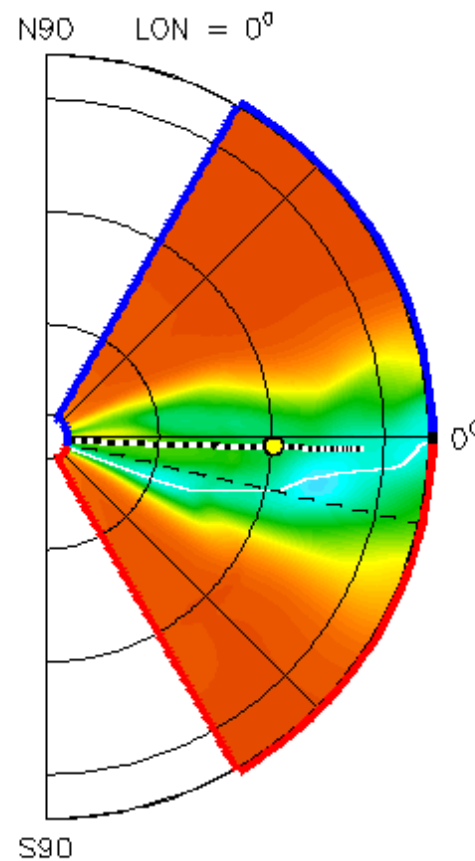
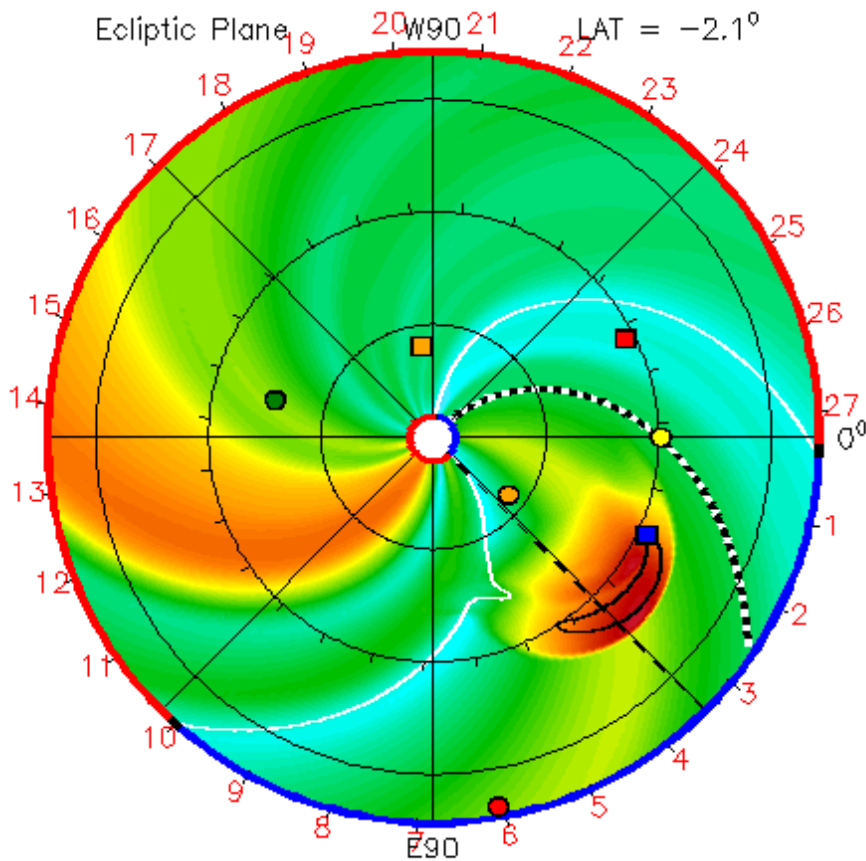


# 2008 May 17 CME – Cone Model

2008-05-19 22:01:50

2008-05-17 +2.91 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

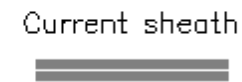
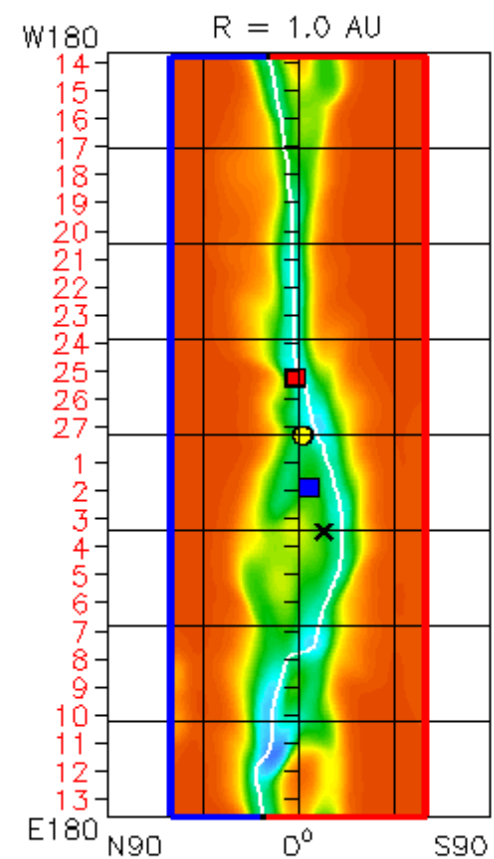
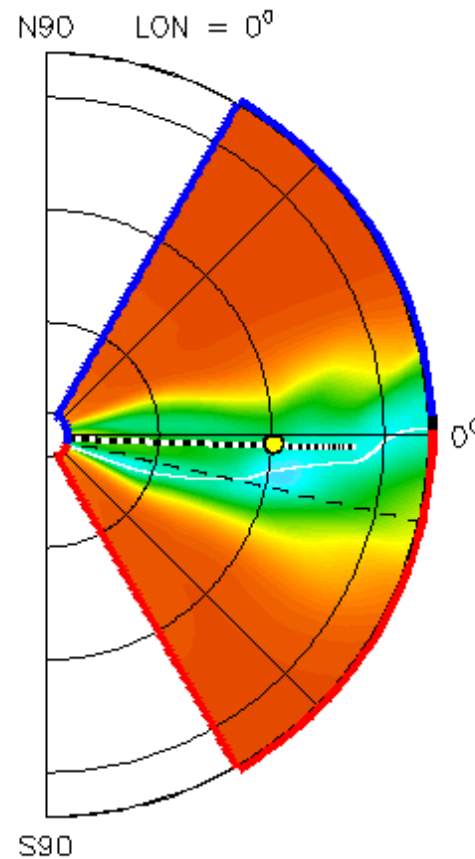
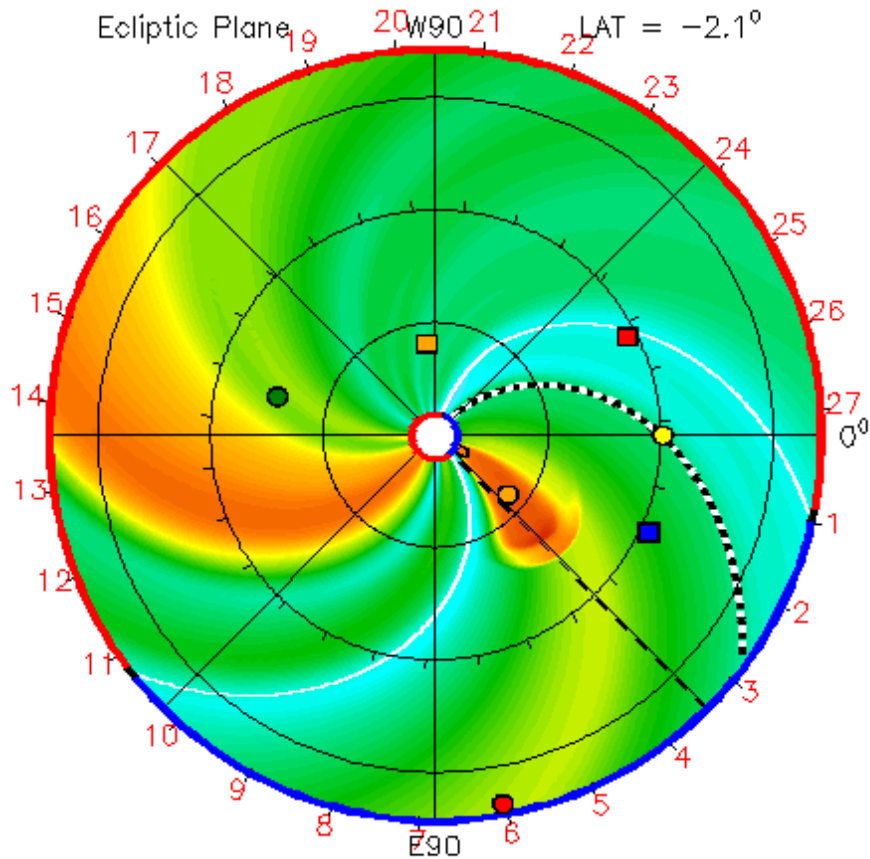


# 2008 May 17 CME – Rope Model

2008-05-19 04:00:38

2008-05-17 +2.16 days

● Mercury   
 ● Venus   
 ● Earth   
 ● Mars   
 ■ Messenger   
 ■ Stereo\_A   
 ■ Stereo\_B



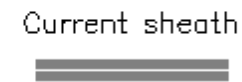
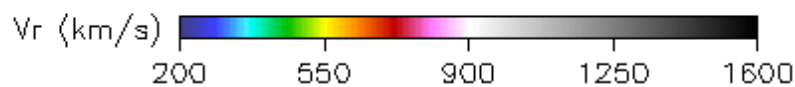
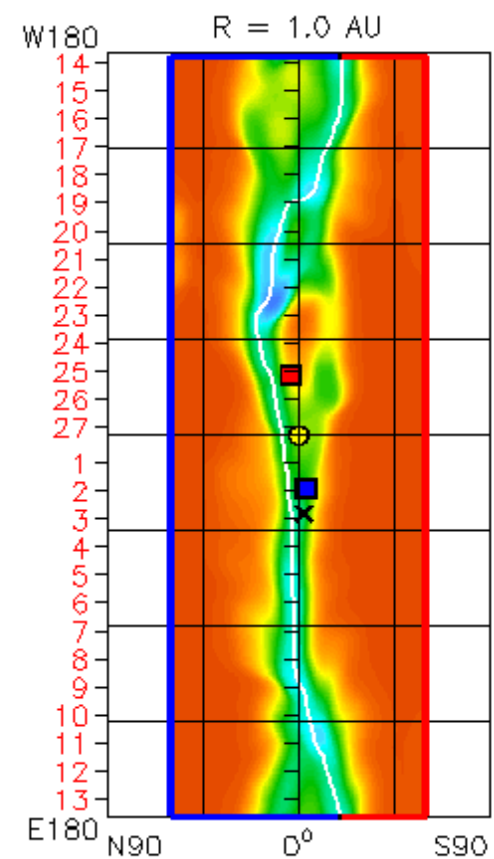
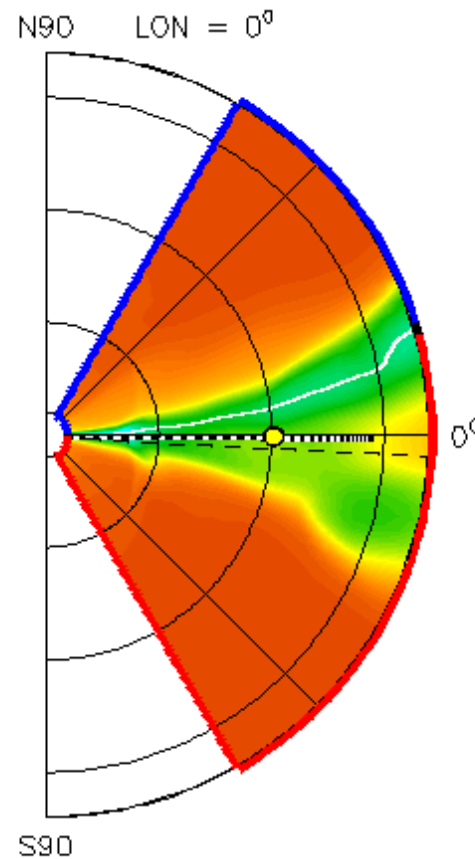
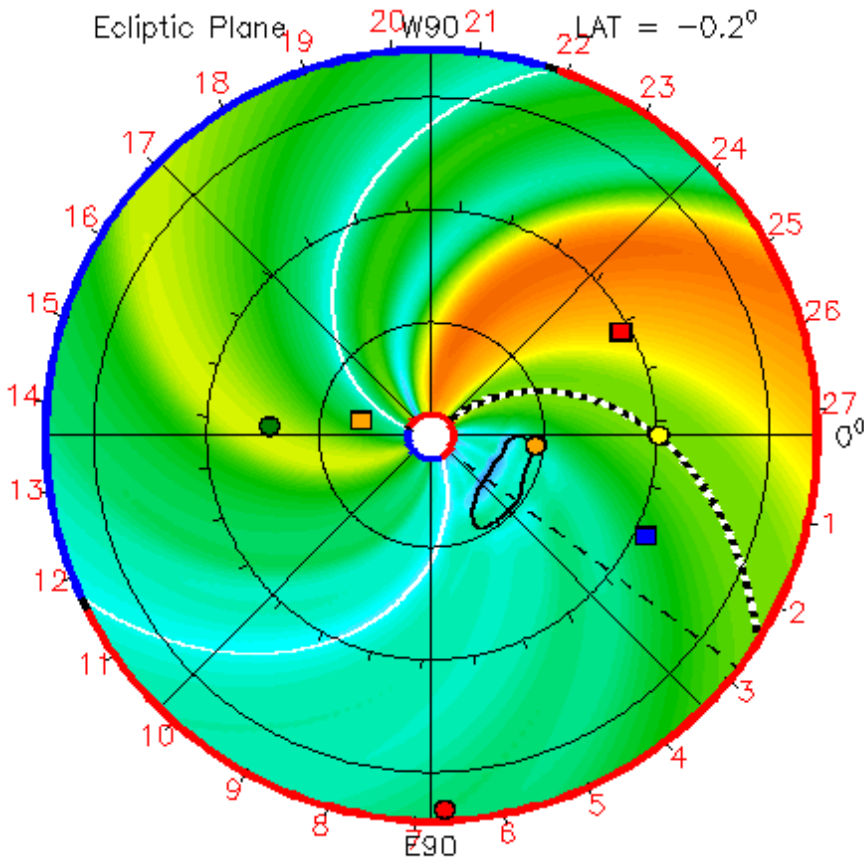


# 2008 June 2 CME – Cone Model

2008-06-04 08:00:11

2008-06-02 +2.33 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

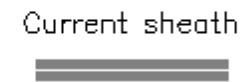
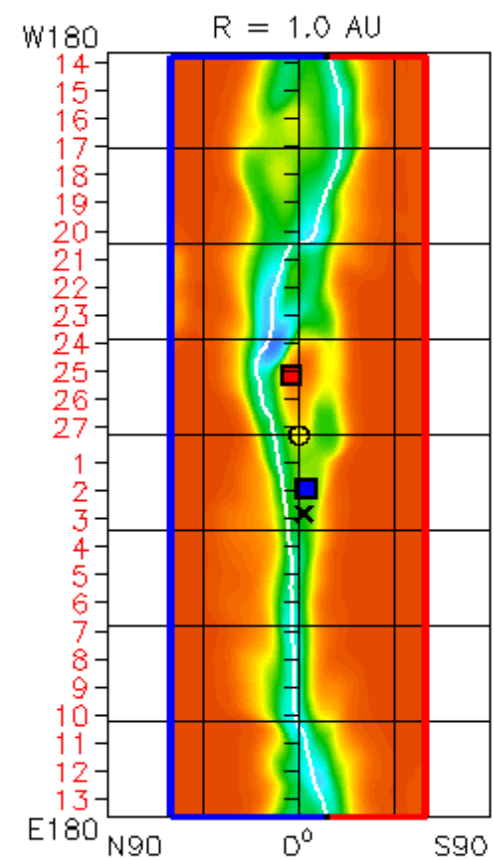
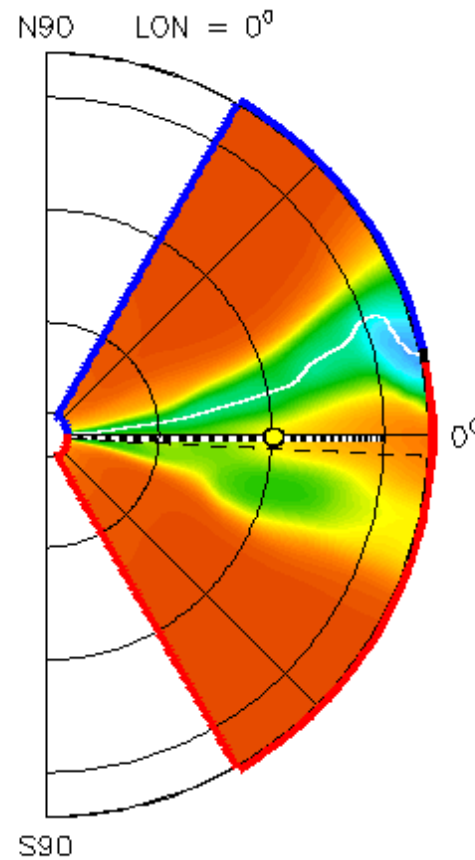
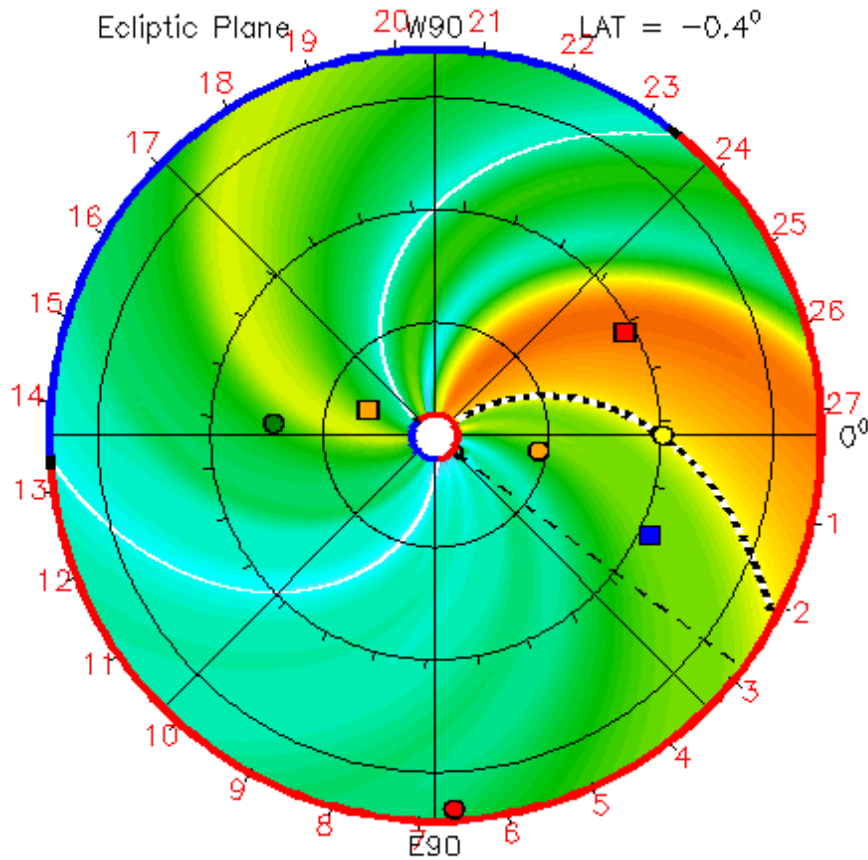


# 2008 June 2 CME – Rope Model

2008-06-02 18:00:24

2008-06-02 +0.75 days

● Mercury   
 ● Venus   
 ● Earth   
 ● Mars   
 ■ Messenger   
 ■ Stereo\_A   
 ■ Stereo\_B



# 2007 December 31 CME – Cone Model

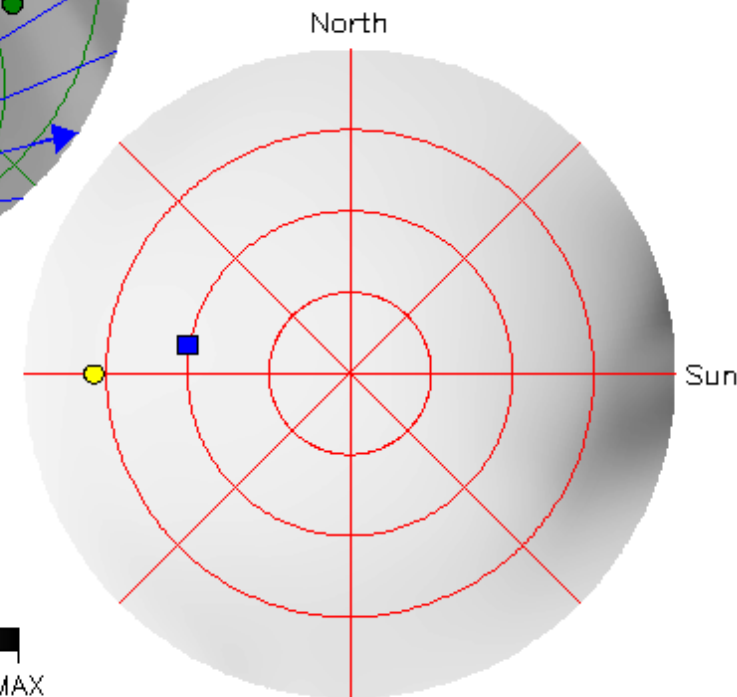
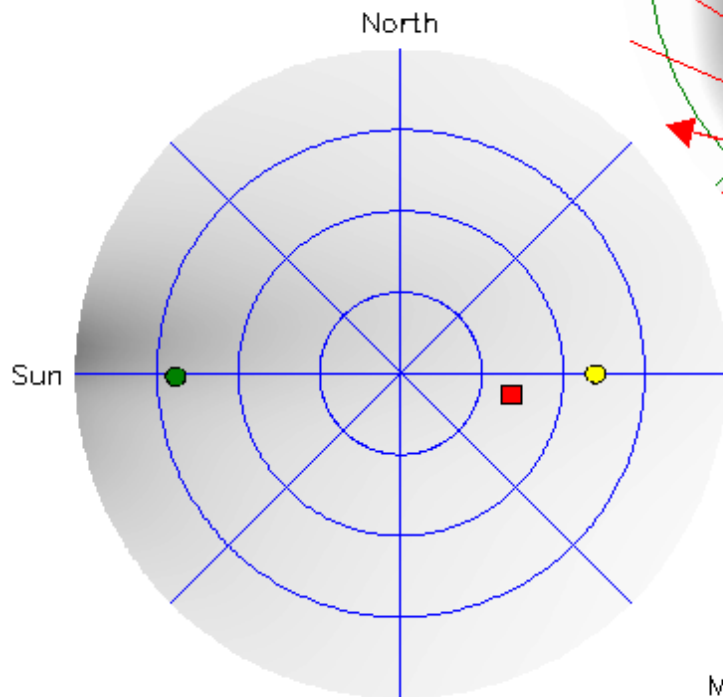
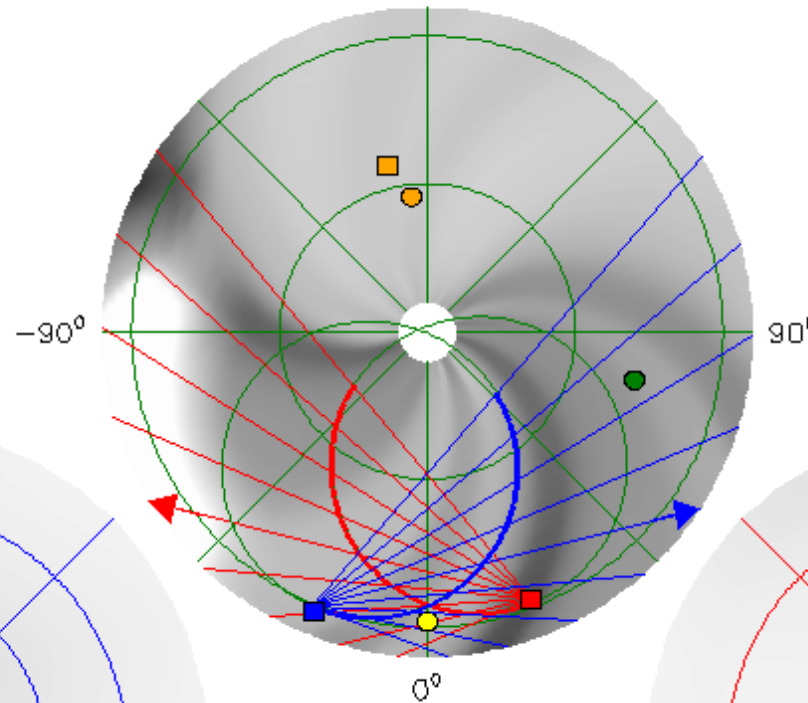
ENLIL-2.5 medres WSA-1.6 GONG

2008-01-03 14:00:39

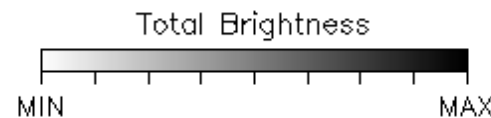
2007-12-31 +3.58 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N$  ( $\text{cm}^{-3}$ )



White-Light Images:  
Stereo\_A/HI2 →  
← Stereo\_B/HI2



# 2007 December 31 CME – Rope Model

ENLIL-2.5 medres WSA-1.6 GONG

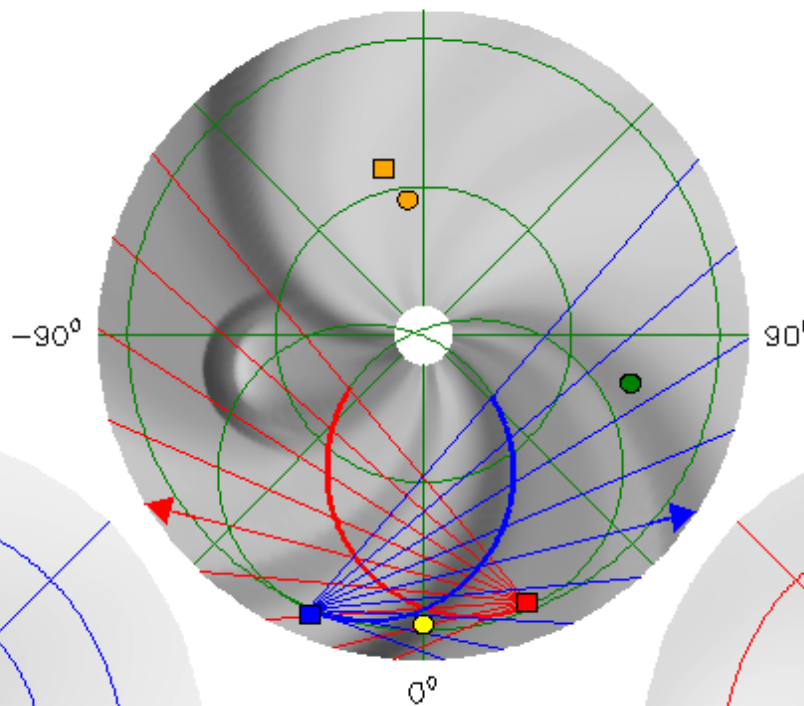
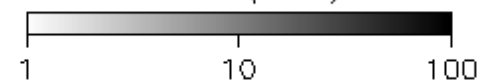
2008-01-02 00:01:23

2007-12-31 +2.00 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane

$R^2 * N$  ( $\text{cm}^{-3}$ )



North

North

Sun

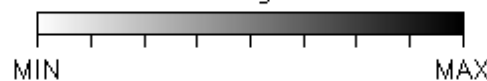
Sun

White-Light Images:

Stereo\_A/HI2 →

← Stereo\_B/HI2

Total Brightness



# 2008 January 2 CME – Cone Model

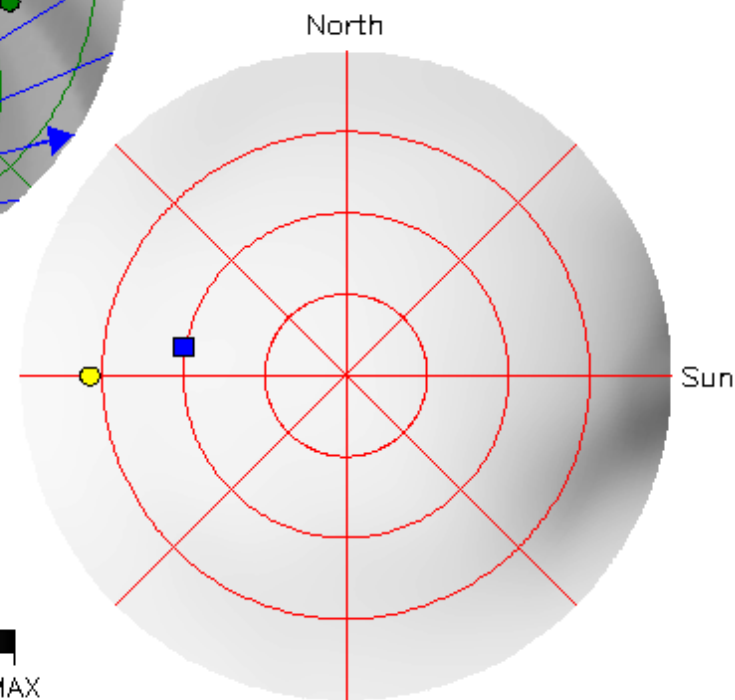
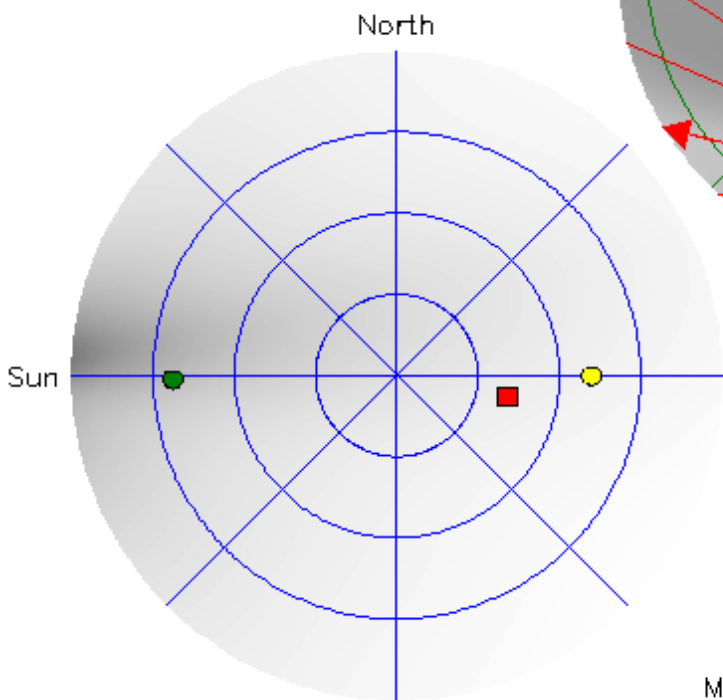
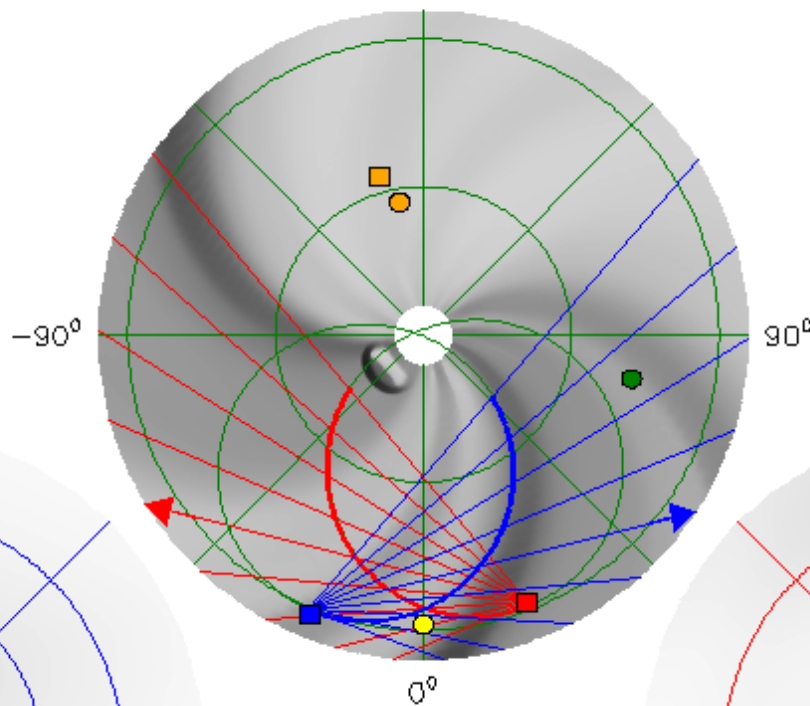
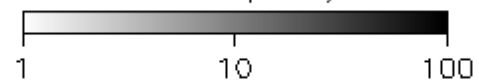
ENLIL-2.5 medres WSA-1.6 GONG

2008-01-03 00:02:42

2008-01-02 +1.00 days

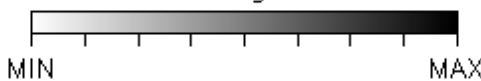
- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N$  ( $\text{cm}^{-3}$ )



White-Light Images:  
Stereo\_A/HI2 →  
← Stereo\_B/HI2

Total Brightness



# 2008 January 2 CME – Rope Model

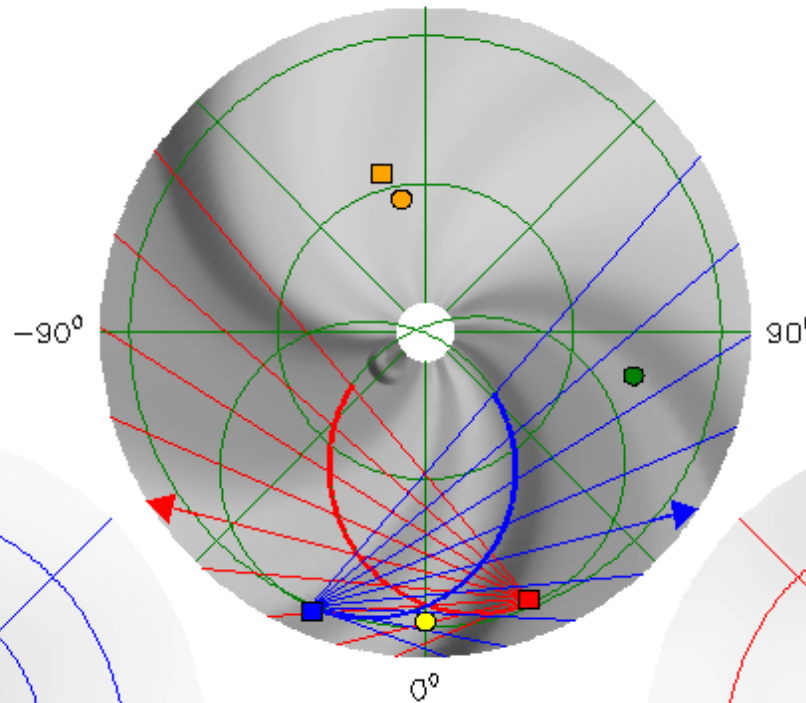
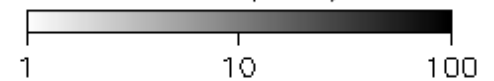
ENLIL-2.5 medres WSA-1.6 GONG

2008-01-03 00:01:27

2008-01-02 +1.00 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N$  ( $\text{cm}^{-3}$ )



North

North

Sun

Sun

White-Light Images:  
Stereo\_A/HI2 →  
← Stereo\_B/HI2

Total Brightness



# 2008 February 4 CME – Cone Model

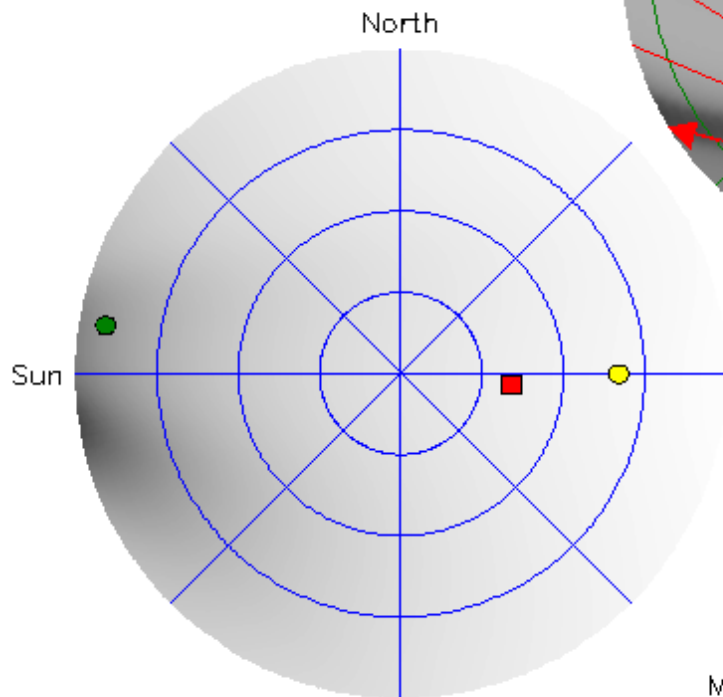
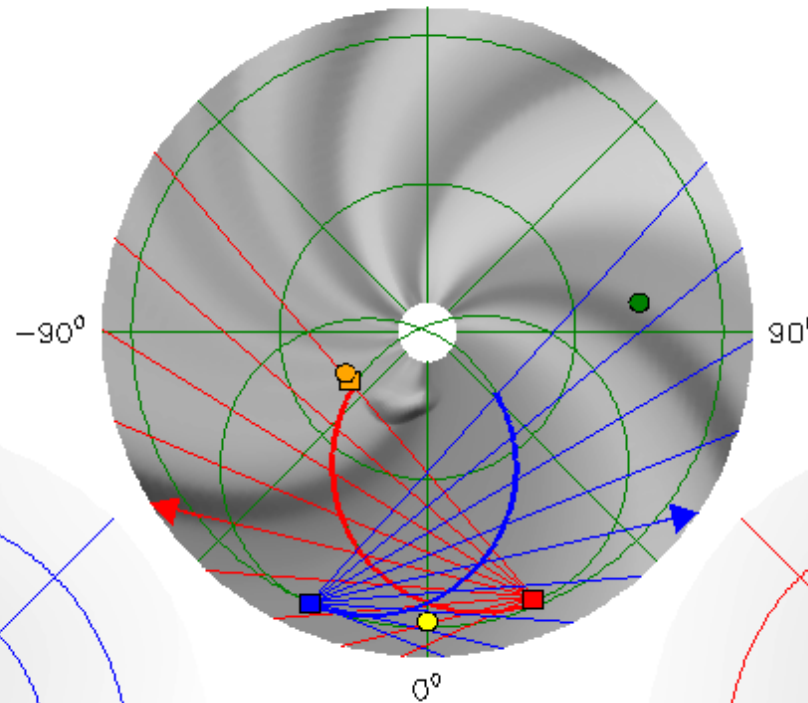
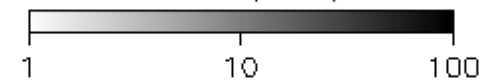
ENLIL-2.5 medres WSA-1.6 GONG

2008-02-05 06:01:31

2008-02-04 +1.25 days

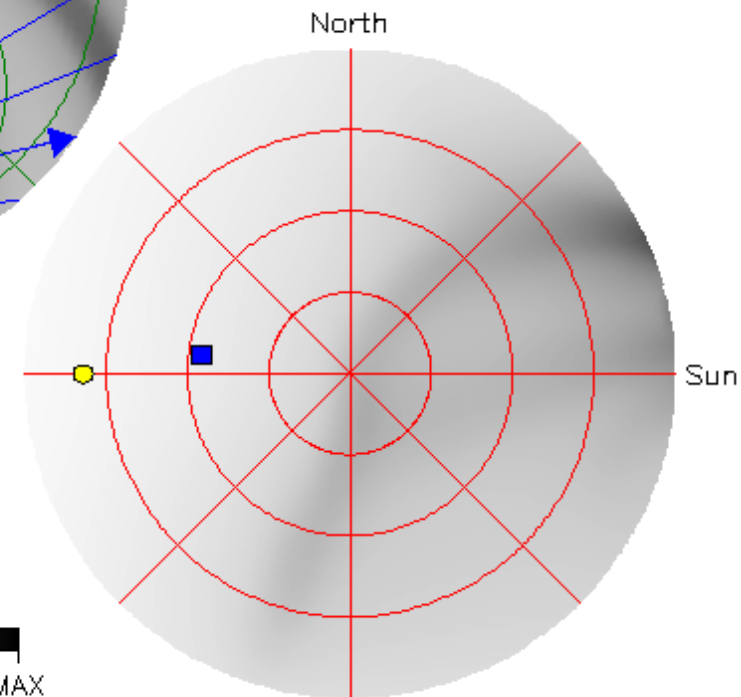
- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N \text{ (cm}^{-3}\text{)}$



White-Light Images:  
Stereo\_A/HI2 →  
← Stereo\_B/HI2

Total Brightness



# 2008 February 4 CME – Rope Model

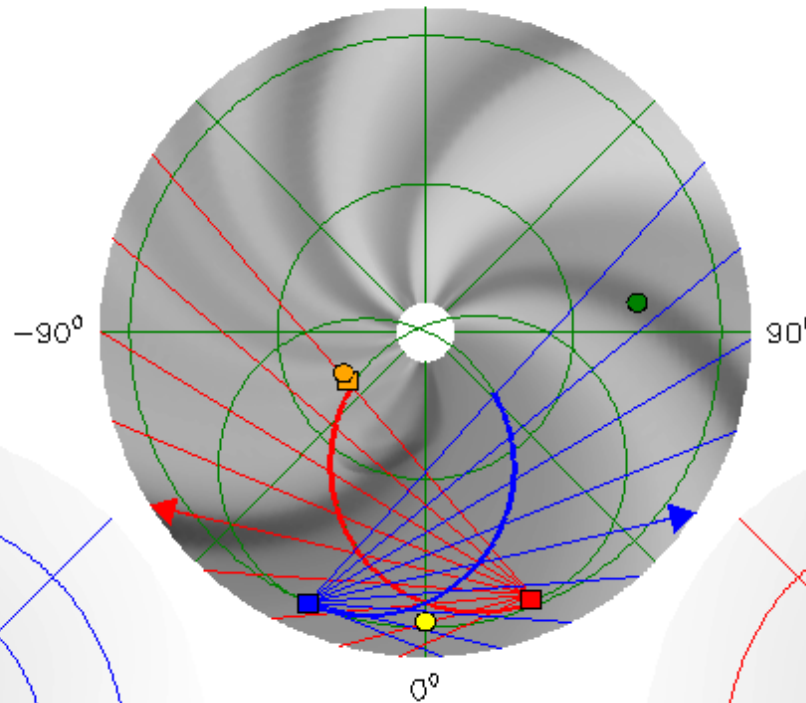
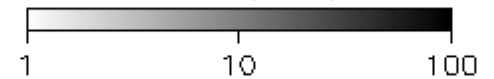
ENLIL-2.5 medres WSA-1.6 GONG

2008-02-05 20:02:29

2008-02-04 +1.83 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N$  ( $\text{cm}^{-3}$ )



North

North

Sun

Sun

White-Light Images:

Stereo\_A/HI2 →

← Stereo\_B/HI2

Total Brightness





# 2008 April 26 CME – Cone Model

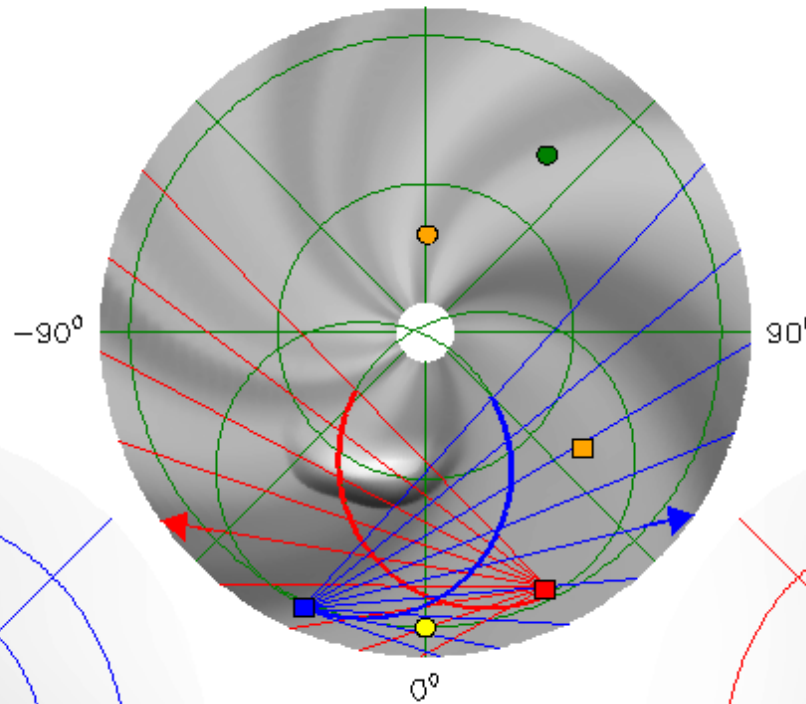
ENLIL-2.5 medres WSA-1.6 GONG

2008-04-28 04:00:25

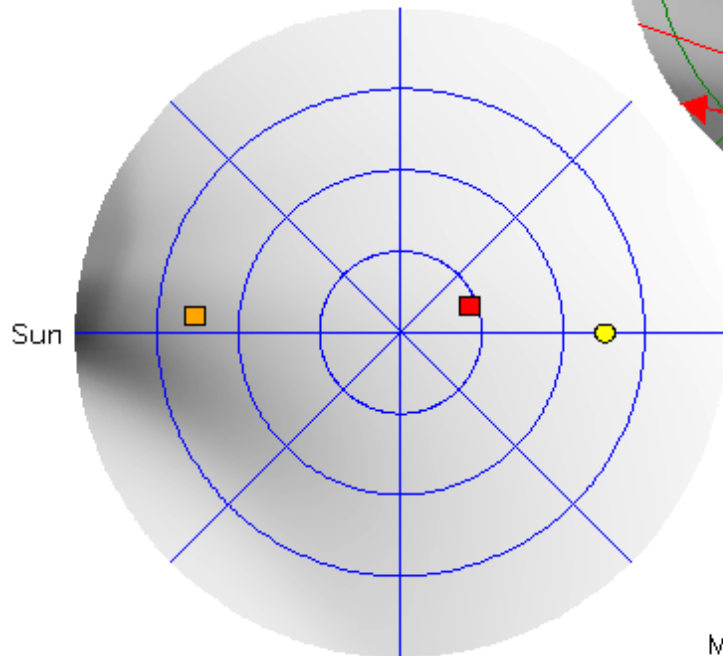
2008-04-26 +2.16 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

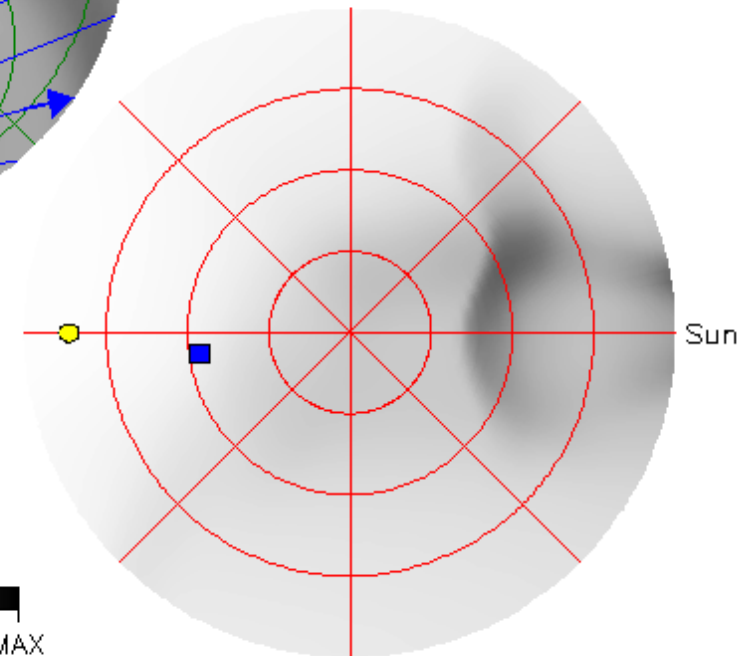
Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N \text{ (cm}^{-3}\text{)}$



North



North



White-Light Images:

Stereo\_A/HI2 →

← Stereo\_B/HI2

Total Brightness



# 2008 April 26 CME – Rope Model

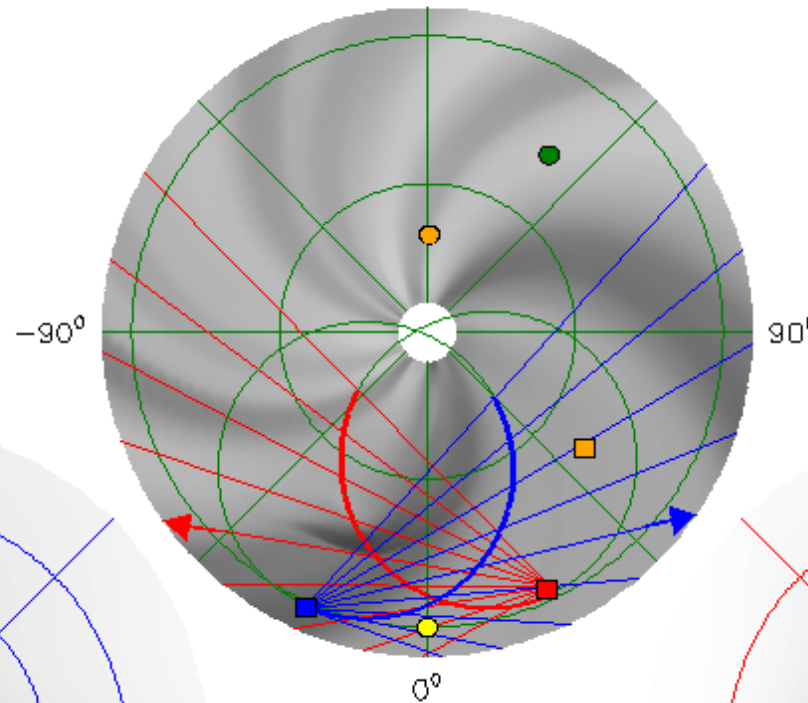
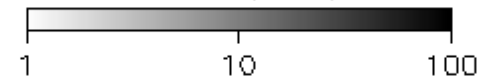
ENLIL-2.5 medres WSA-1.6 GONG

2008-04-28 22:02:54

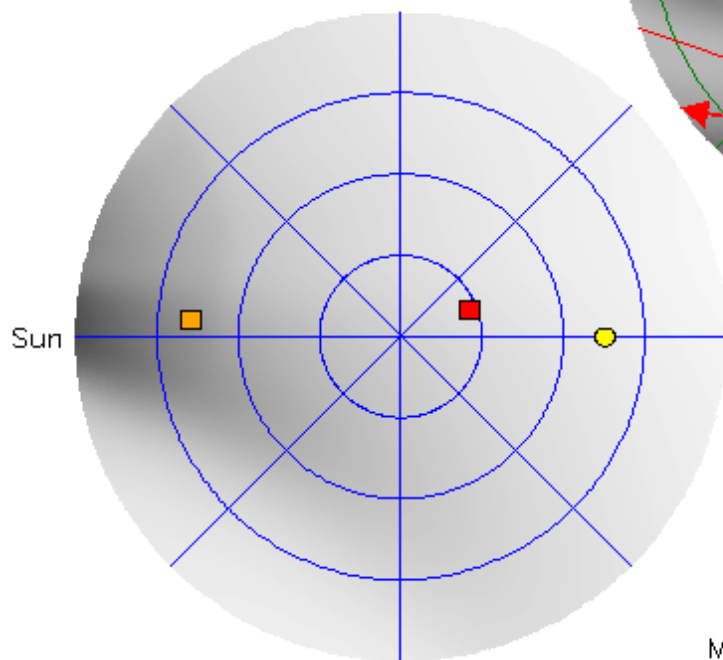
2008-04-26 +2.91 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

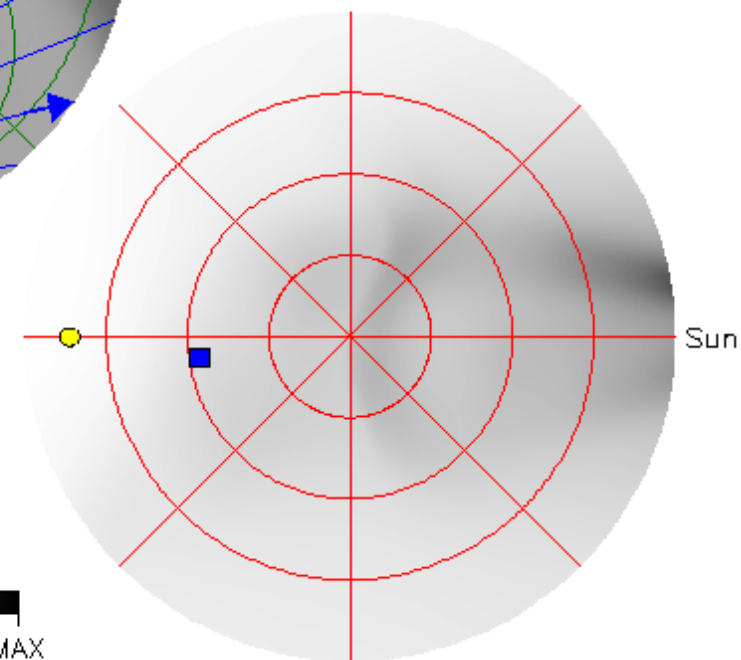
Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N \text{ (cm}^{-3}\text{)}$



North



North



White-Light Images:

Stereo\_A/HI2 →

← Stereo\_B/HI2

Total Brightness



# 2008 May 17 CME – Cone Model

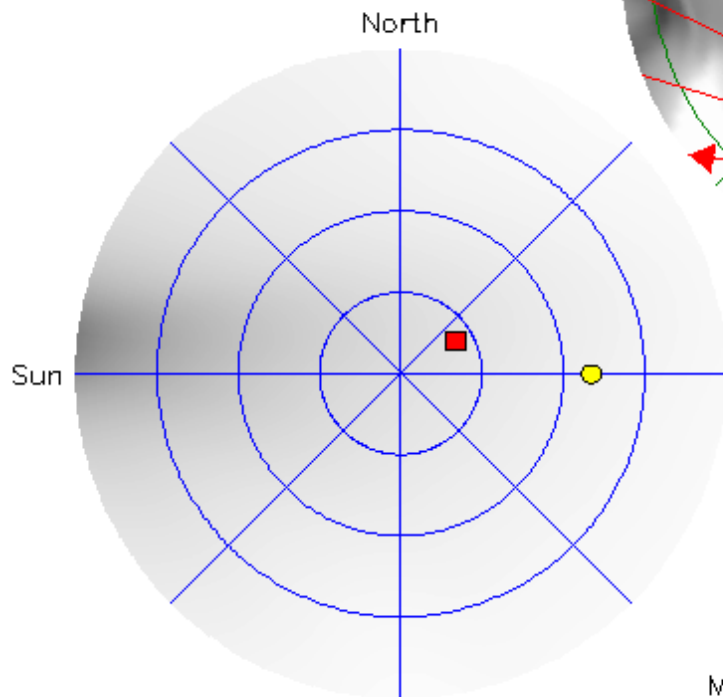
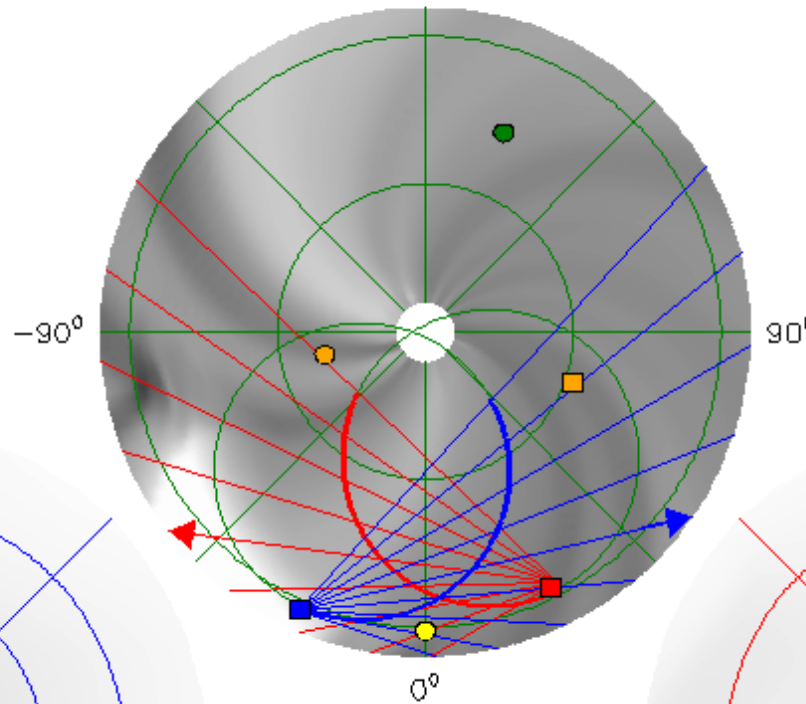
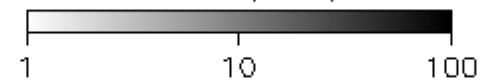
ENLIL-2.5 medres WSA-1.6 GONG

2008-05-20 16:00:53

2008-05-17 +3.66 days

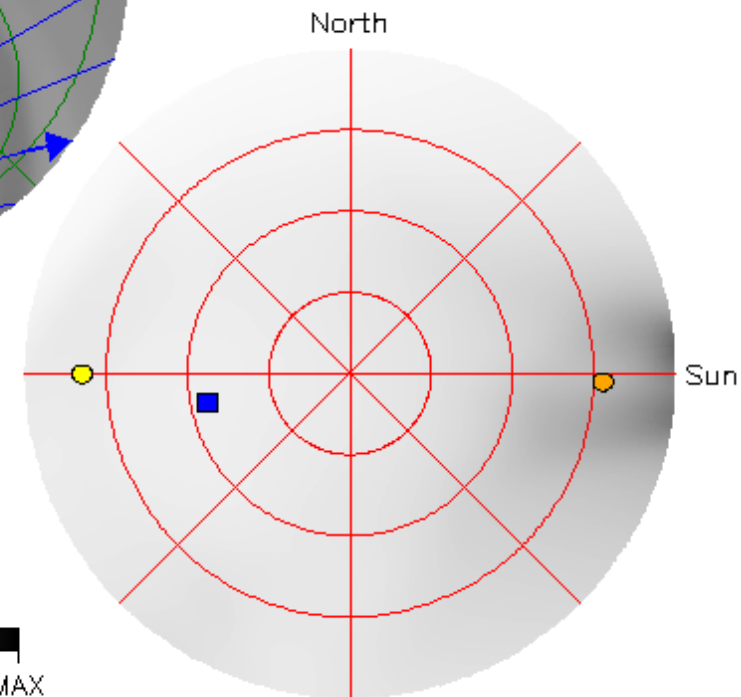
- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N \text{ (cm}^{-3}\text{)}$



White-Light Images:  
Stereo\_A/Hi2 →  
← Stereo\_B/Hi2

Total Brightness



# 2008 May 17 CME – Rope Model

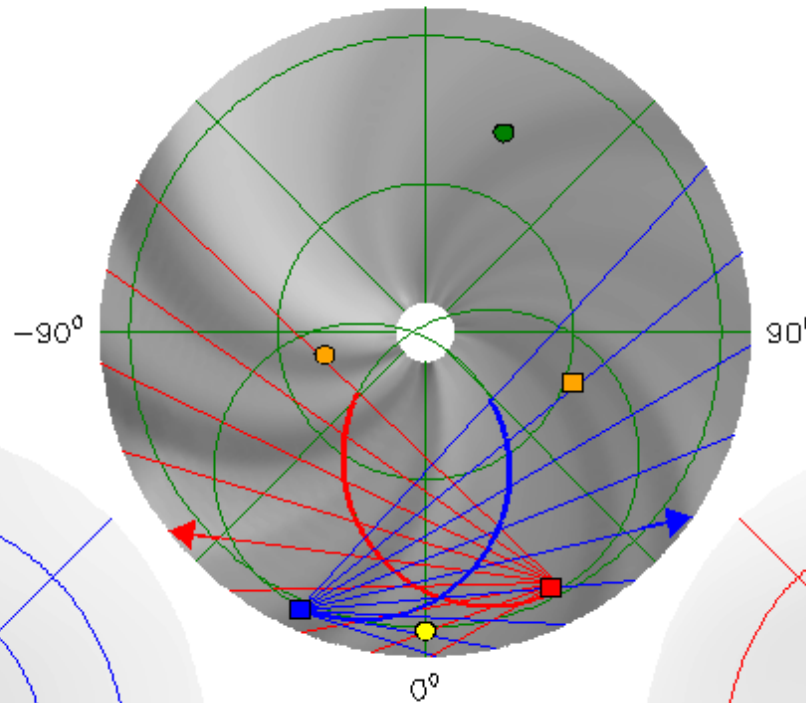
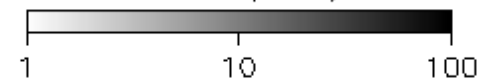
ENLIL-2.5 medres WSA-1.6 GONG

2008-05-21 10:01:00

2008-05-17 +4.41 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N \text{ (cm}^{-3}\text{)}$



North

North

Sun

Sun

White-Light Images:

Stereo\_A/HI2 →

← Stereo\_B/HI2

Total Brightness



# 2008 June 2 CME – Cone Model

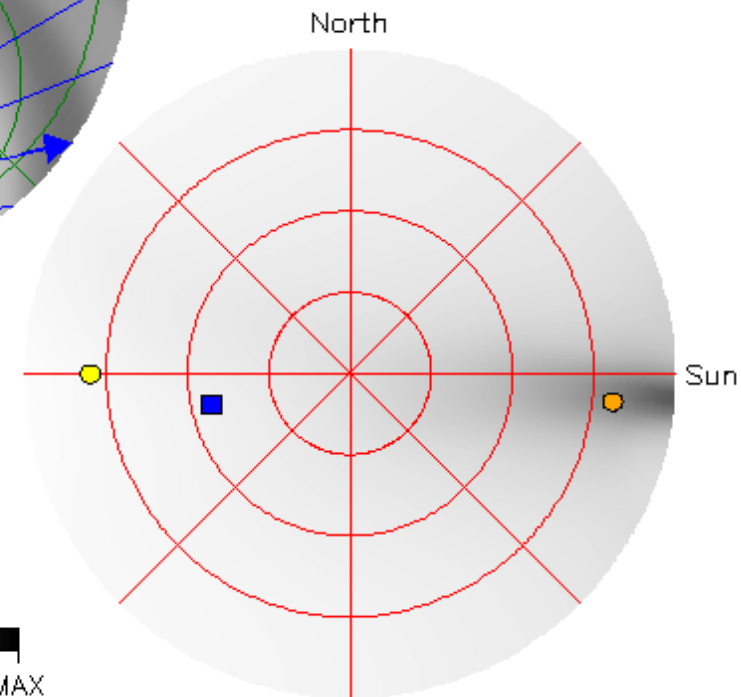
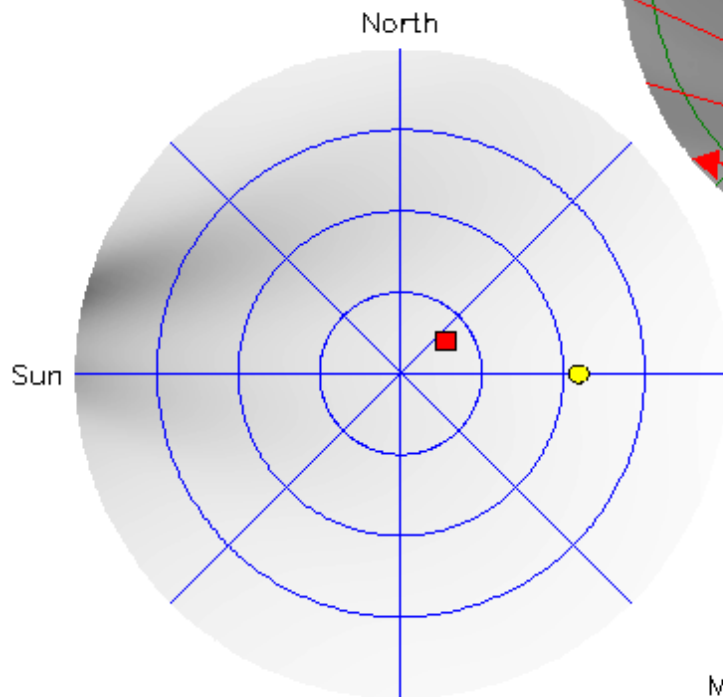
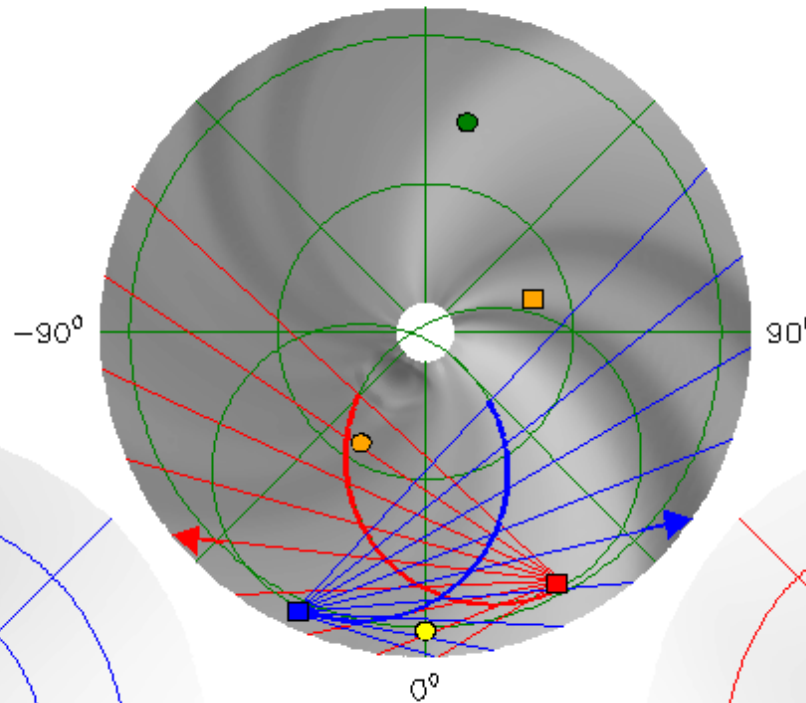
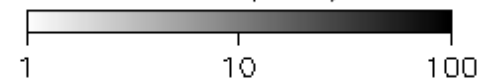
ENLIL-2.5 medres WSA-1.6 GONG

2008-06-03 08:00:51

2008-06-02 +1.33 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N \text{ (cm}^{-3}\text{)}$



White-Light Images:  
Stereo\_A/Hi2 →  
← Stereo\_B/Hi2

Total Brightness



# 2008 June 2 CME – Rope Model

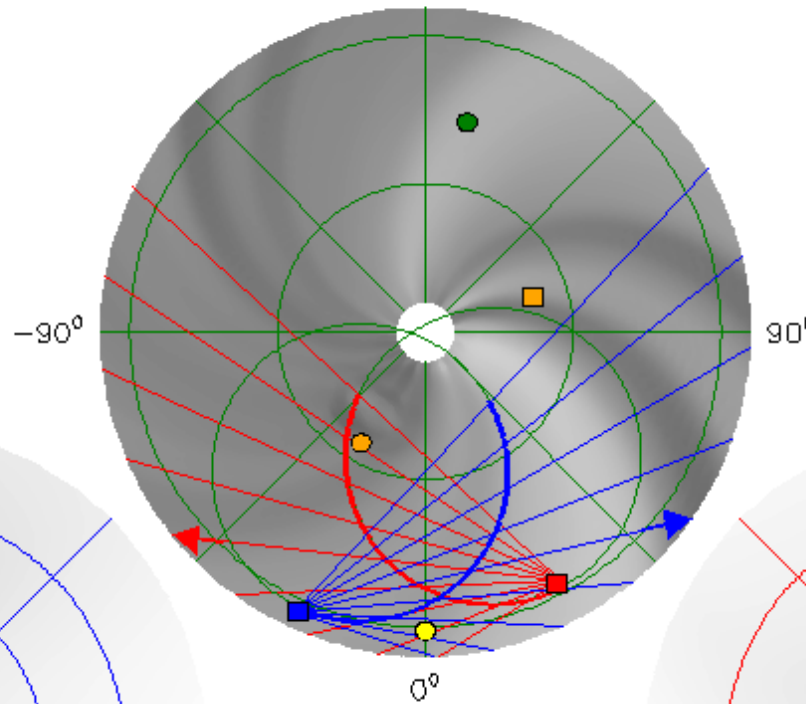
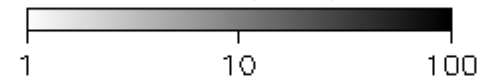
ENLIL-2.5 medres WSA-1.6 GONG

2008-06-03 16:00:59

2008-06-02 +1.66 days

- Mercury
- Venus
- Earth
- Messenger
- Stereo\_A
- Stereo\_B

Solar Wind Density:  
← Equatorial Plane  
 $R^2 * N \text{ (cm}^{-3}\text{)}$



North

North

Sun

Sun

White-Light Images:

Stereo\_A/HI2 →

← Stereo\_B/HI2

Total Brightness



# In-Situ Observations and Predictions

( work in progress )

CME	STEREO-B			ACE			STEREO-A		
event	obs	cone	rope	obs	cone	rope	obs	cone	rope
2007-12-31	0	0	0	0	0	0	0	0	0
2008-01-02	0	S+e	0	0	0	0	0	0	0
2008-02-04	?	S+E	S+e	0	S	0	0	0	0
2008-04-26	S+E	S+E	S+E	0	S+e	0	0	0	0
2008-05-17	0	S+E	S	0	s	0	?	0	0
2008-06-02	S+E	E	E	0	e	0	0	0	0

## Disk space requirements:

- 15 GBytes/event – 6-day period, 2-hour cadence
- 8 Mbytes/event – animations & temporal profiles

# Conclusions

- Interpretation of multi-spacecraft heliospheric observations and 3D reconstruction of structures observed by STEREO heliospheric imagers is challenging:
  - the same white-light intensity can be produced by different CME parts;
  - the same CME parts can be observed with different white-light intensities.
- Numerical simulations can provide:
  - provide global context and hints what can and cannot be observed;
  - missing quantities to interpret observations;
  - predict arrival of disturbances to different locations.
- We have developed a hybrid modeling system for simulation of co-rotating and transient heliospheric disturbances. This system can serve as a practical and efficient solution until better near-Sun observations and more sophisticated CME models become available. The main advantage of our approach is robust, fast, event-by-event simulation.
- Results from ICMEs simulated so far suggest that the rope model provides much better match with remote and in-situ observations than the cone model does with a circular cross section.



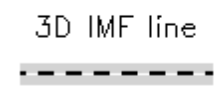
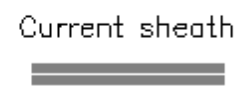
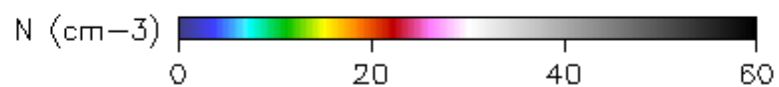
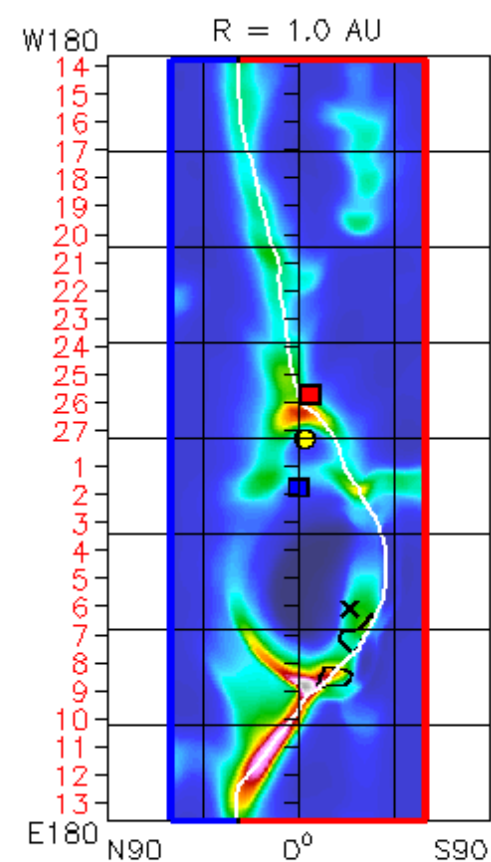
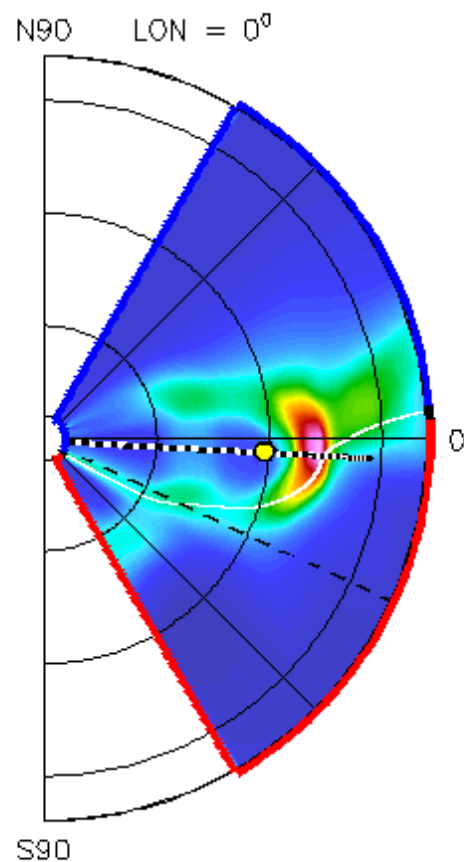
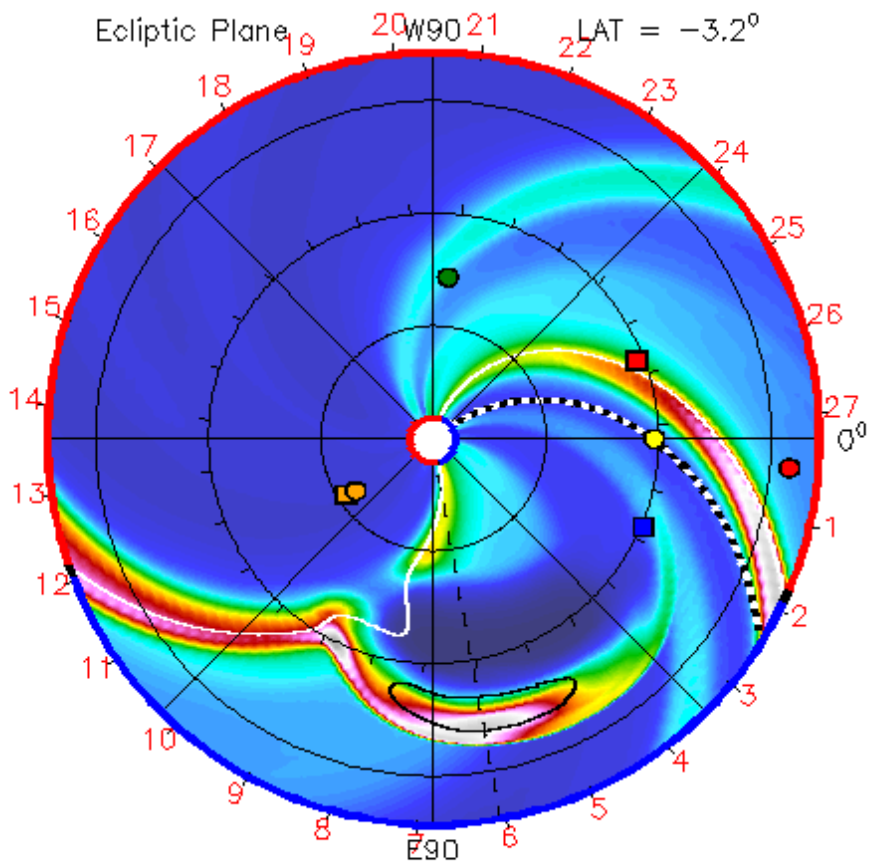
BACKUP

# 2007 December 31 CME – Cone Model

2008-01-03 04:01:46

2007-12-31 +3.16 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

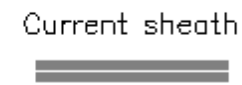
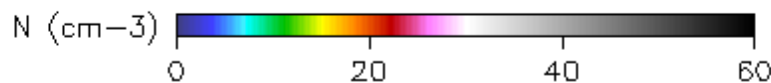
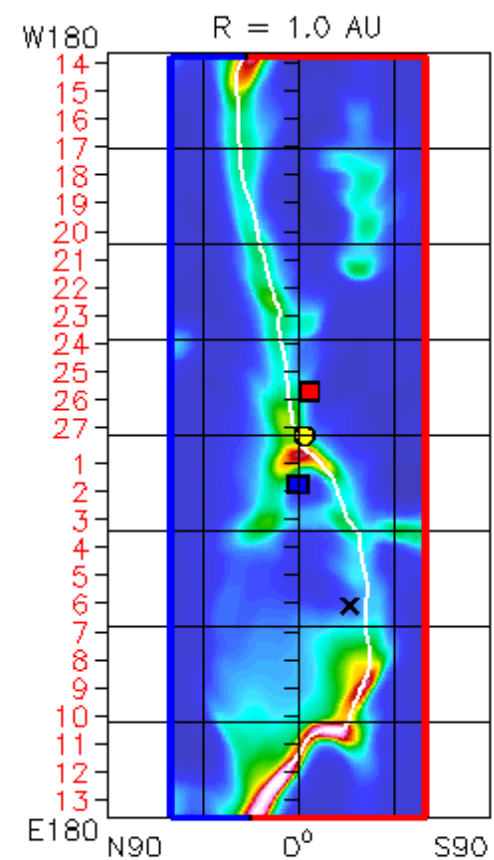
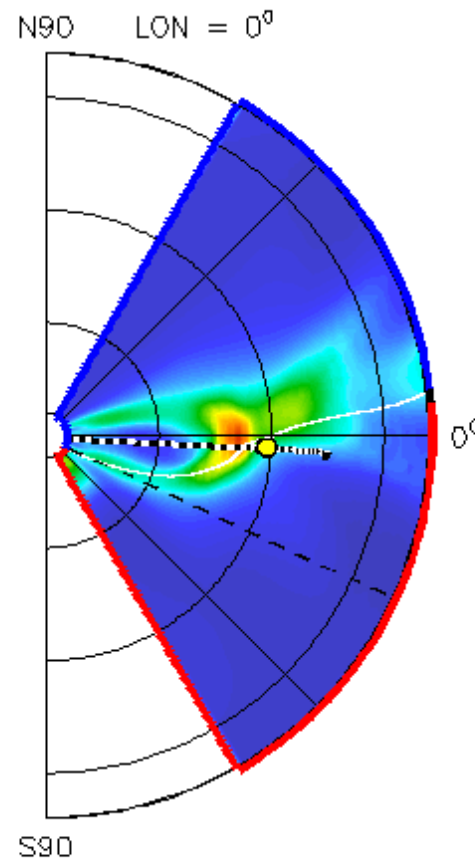
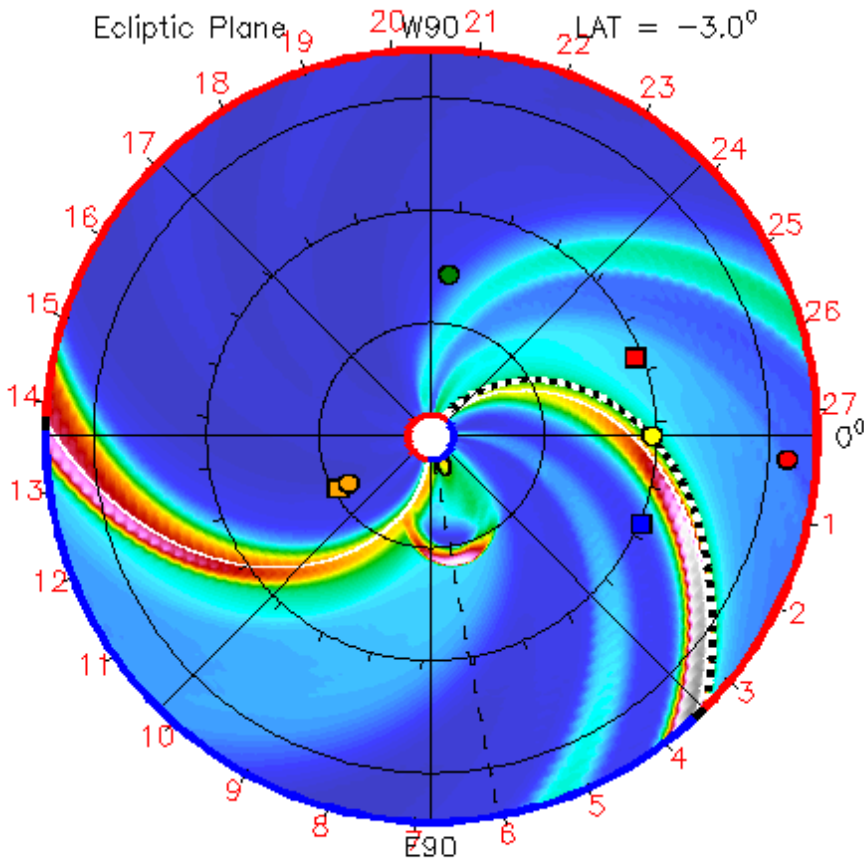


# 2007 December 31 CME – Rope Model

2008-01-01 12:00:00

2007-12-31 +1.50 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

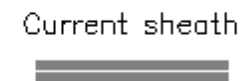
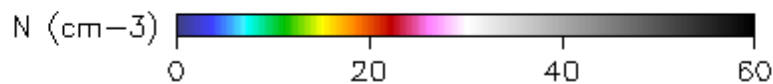
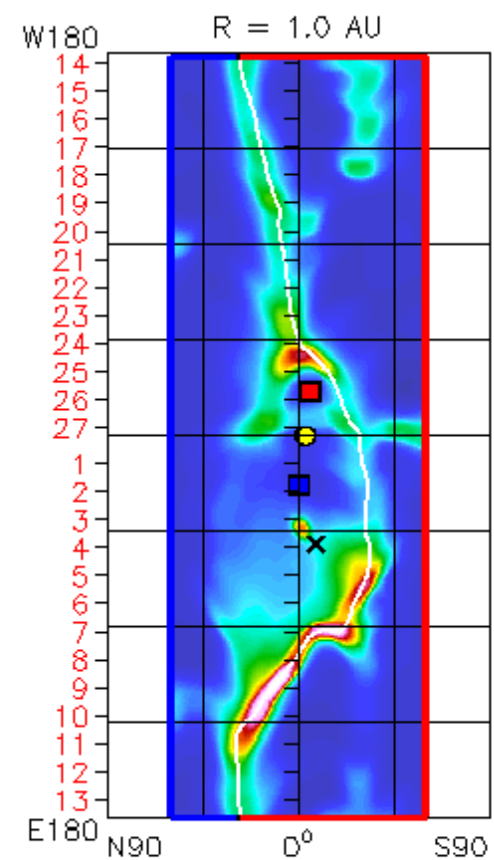
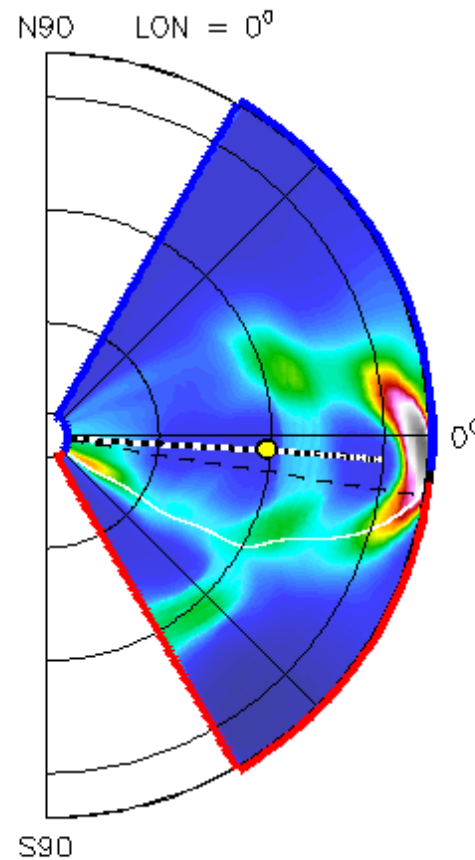
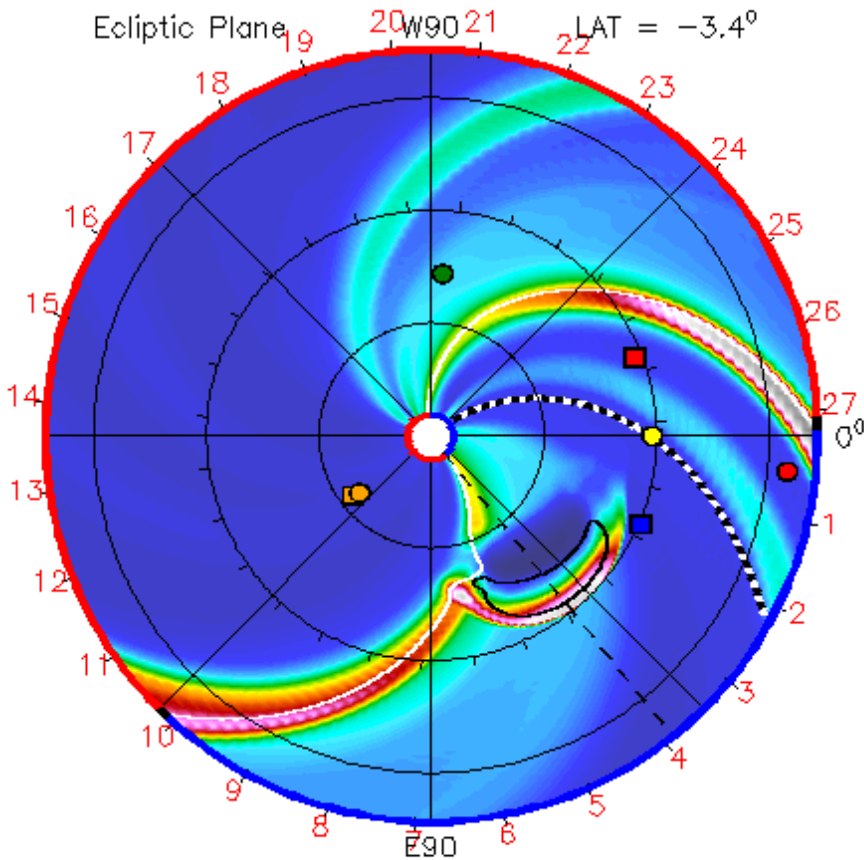


# 2008 January 2 CME – Cone Model

2008-01-05 02:00:33

2008-01-02 +3.08 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

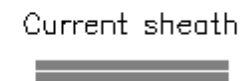
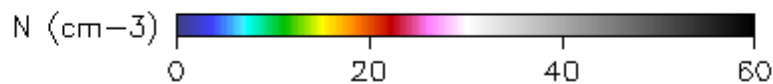
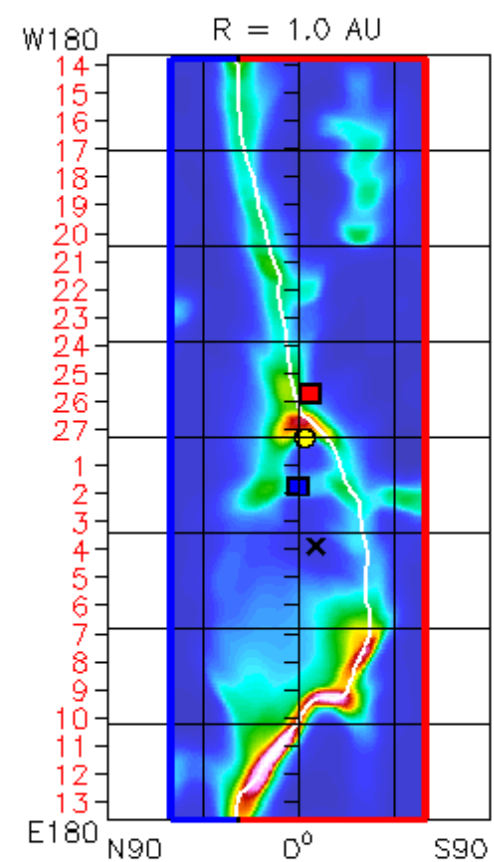
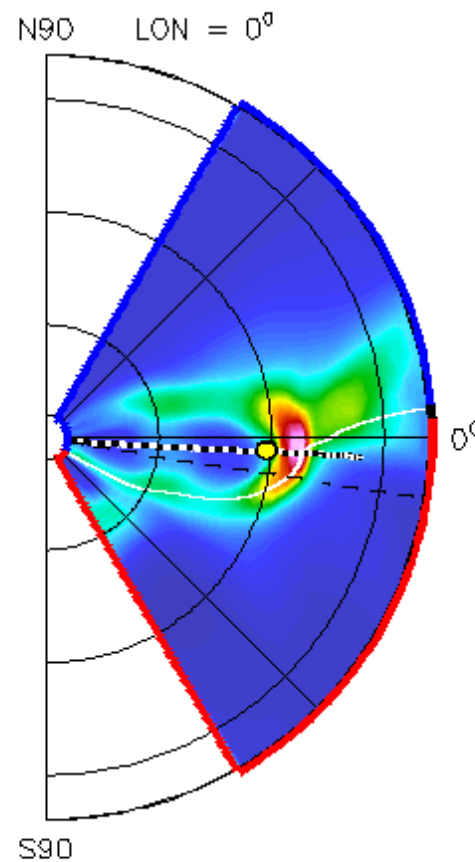
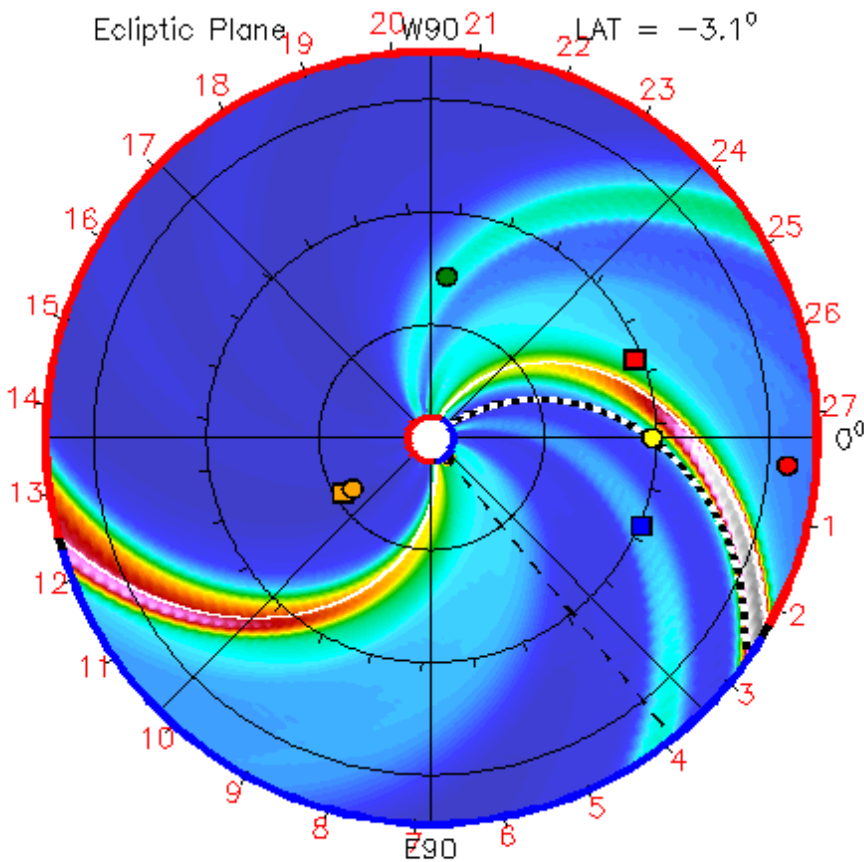


# 2008 January 2 CME – Rope Model

2008-01-02 18:00:00

2008-01-02 +0.75 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

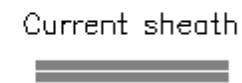
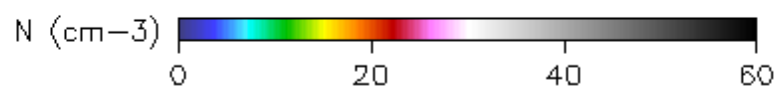
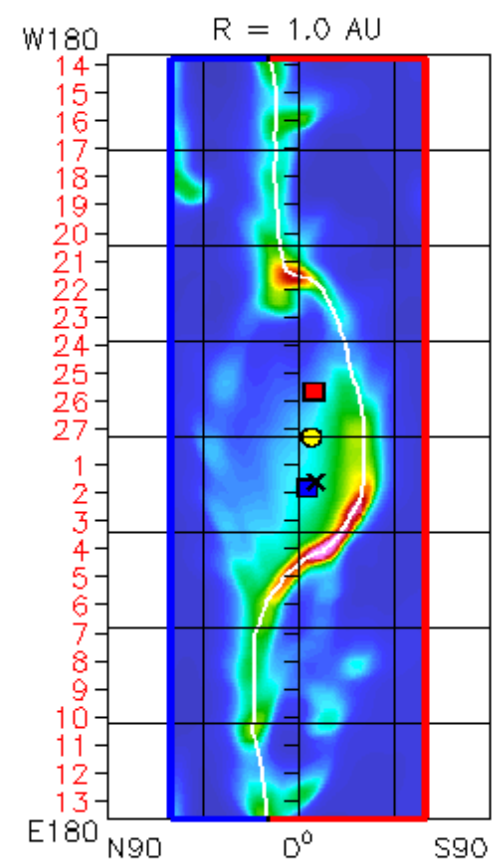
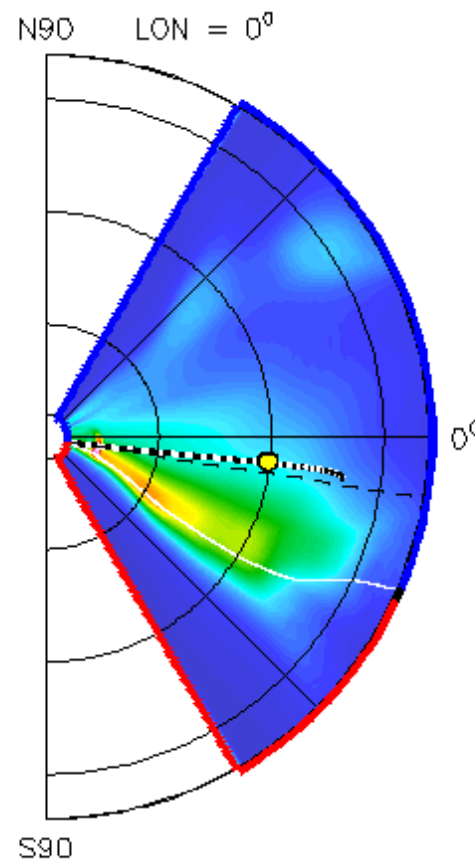
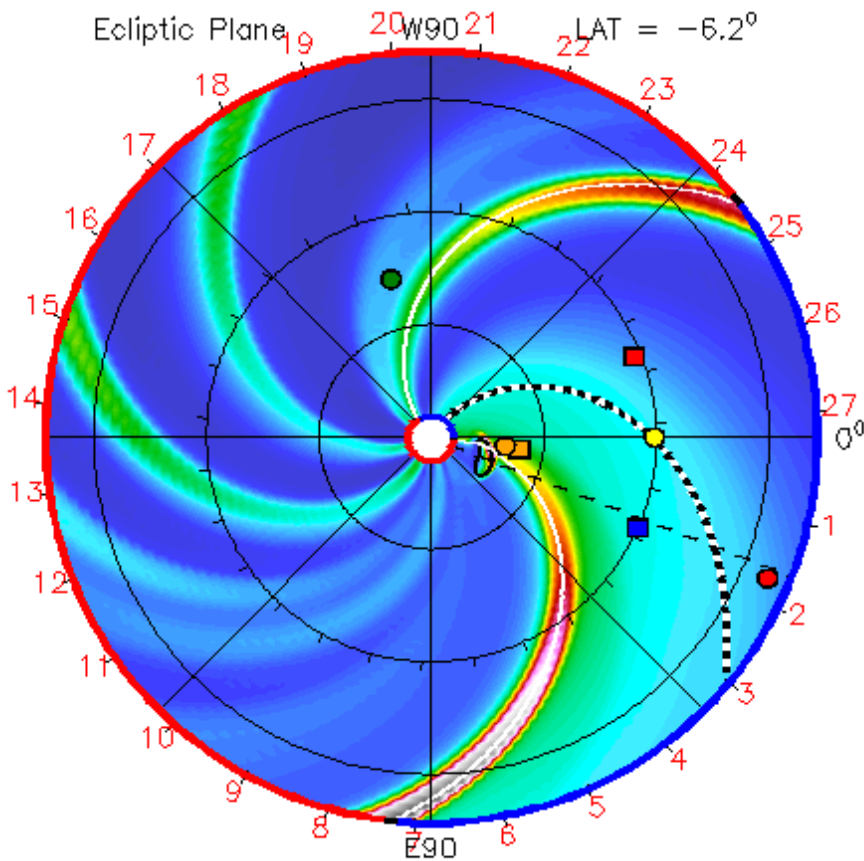


# 2008 February 4 CME – Cone Model

2008-02-05 04:03:00

2008-02-04 +1.16 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

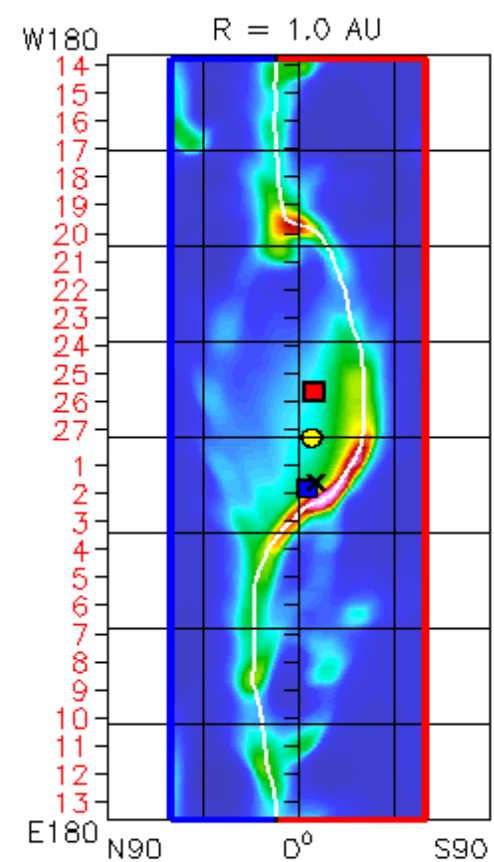
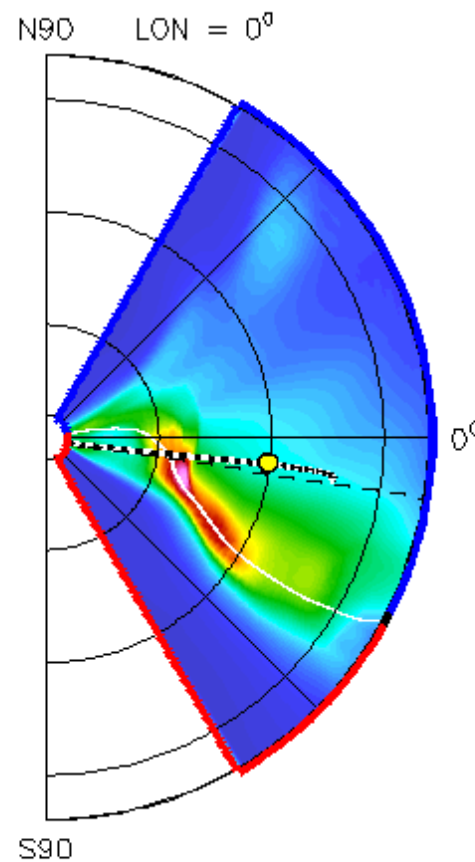
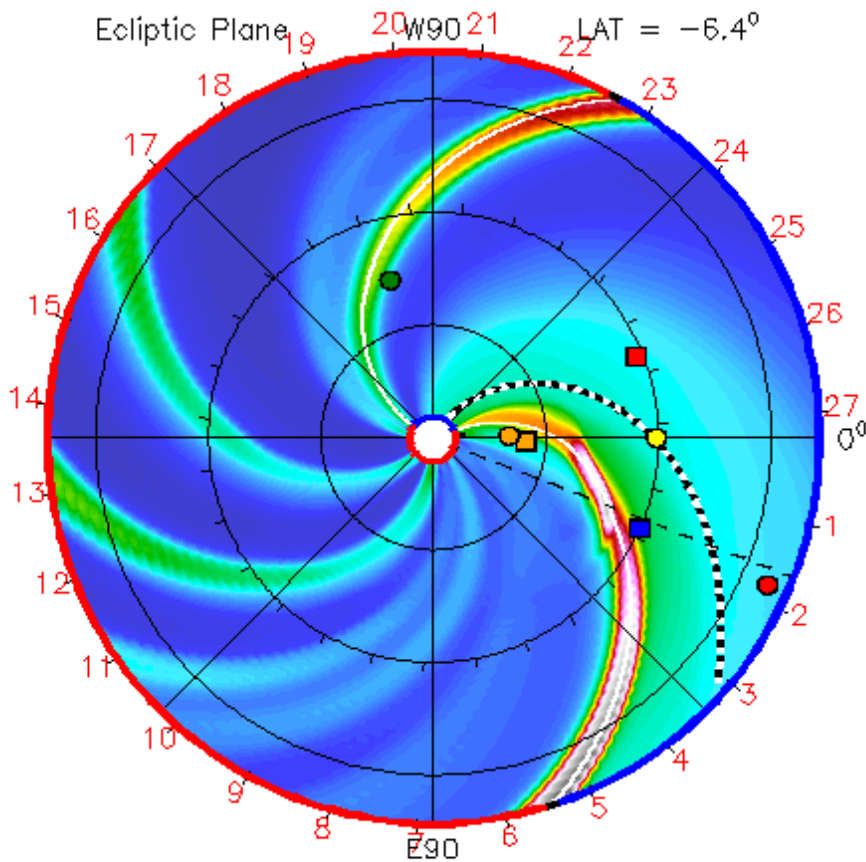


# 2008 February 4 CME – Rope Model

2008-02-07 00:00:00

2008-02-04 +3.00 days

● Mercury   
 ● Venus   
 ● Earth   
 ● Mars   
 ■ Messenger   
 ■ Stereo\_A   
 ■ Stereo\_B



N ( $\text{cm}^{-3}$ )

0 20 40 60

IMF polarity

- ■ ■ +

Current sheath

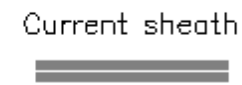
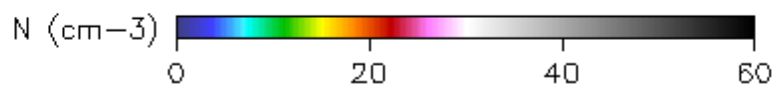
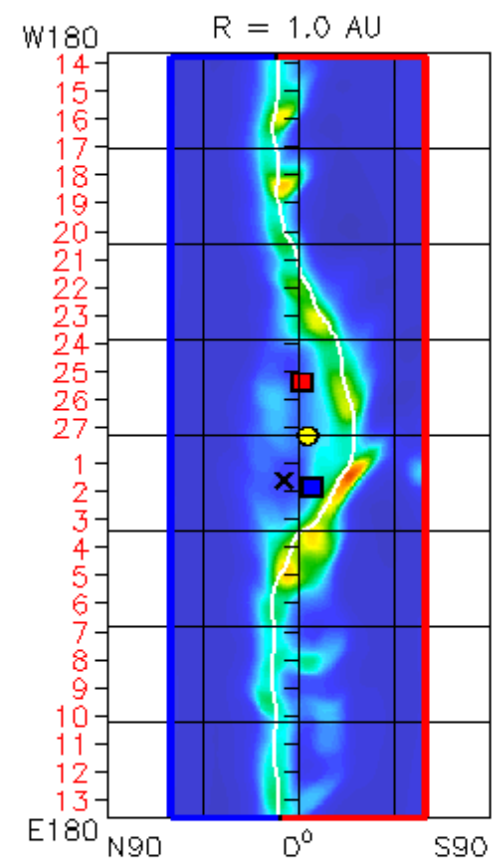
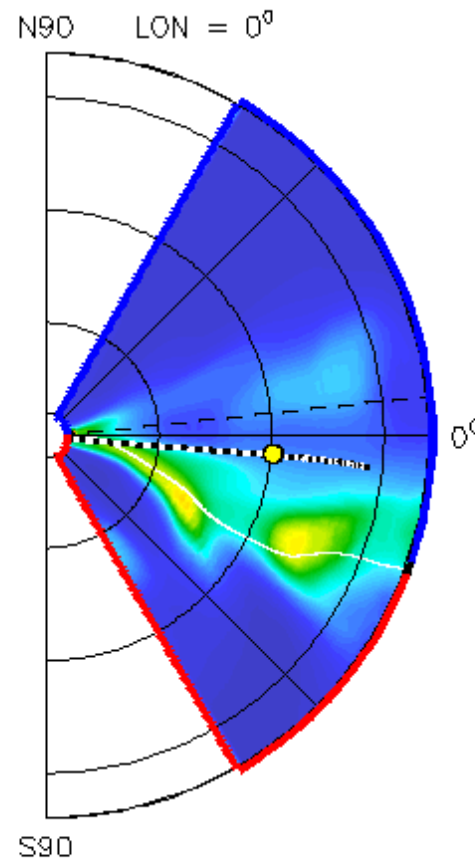
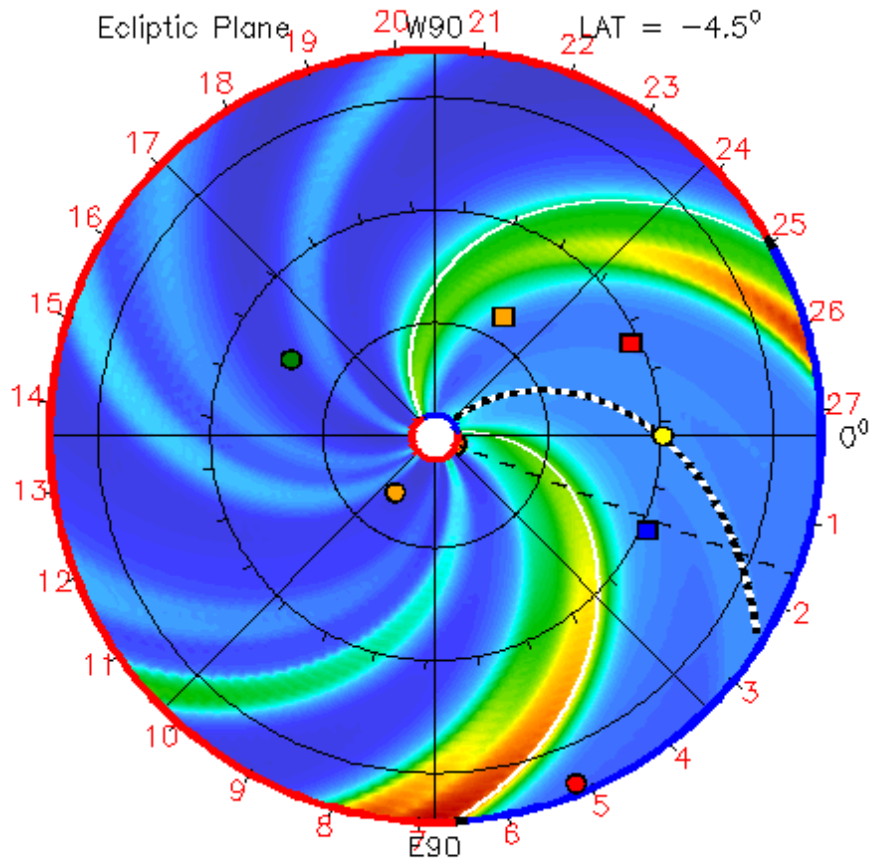
3D IMF line

# 2008 April 26 CME – Cone Model

2008-04-26 22:01:05

2008-04-26 +0.91 days

● Mercury   
 ● Venus   
 ● Earth   
 ● Mars   
 ■ Messenger   
 ■ Stereo\_A   
 ■ Stereo\_B



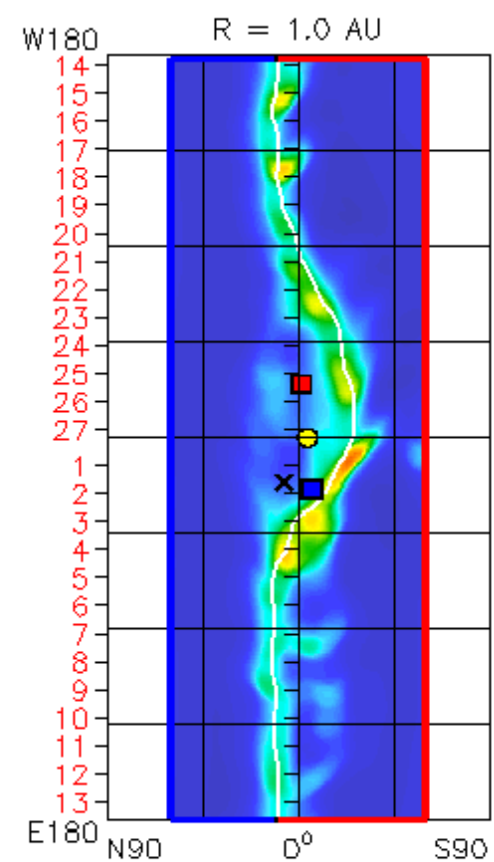
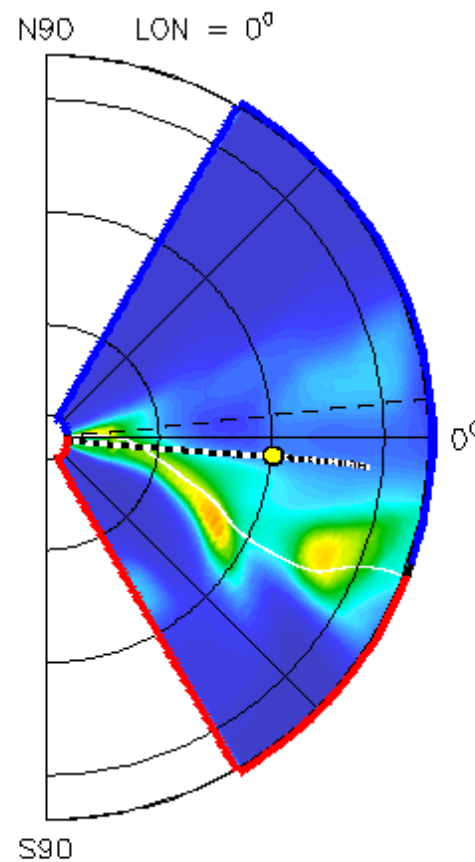
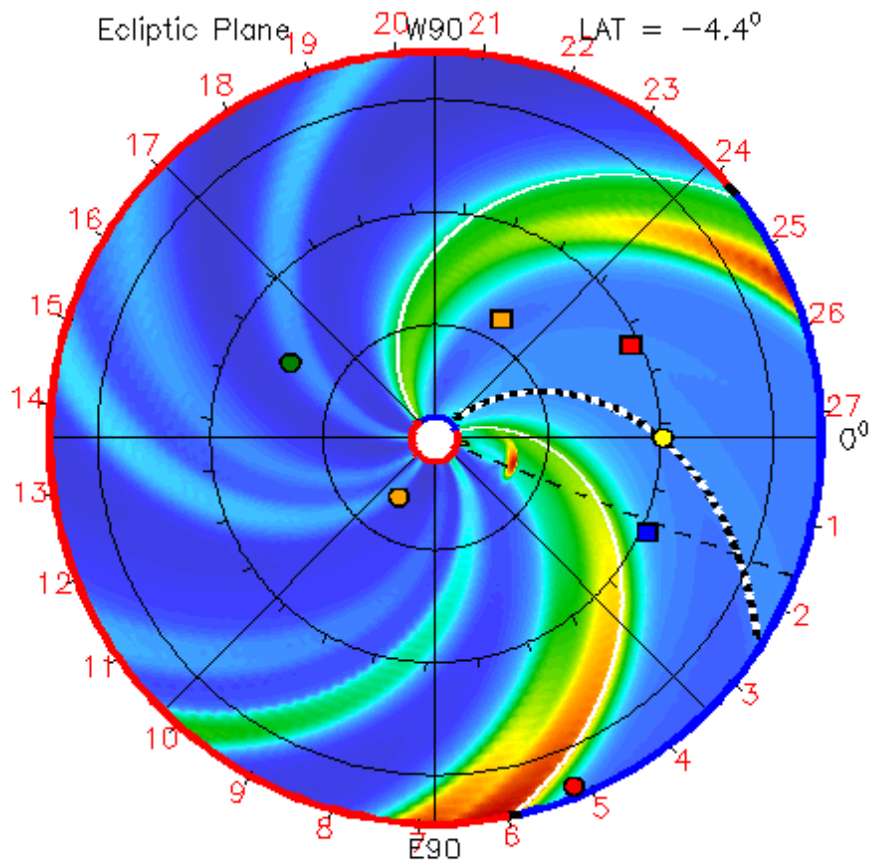


# 2008 April 26 CME – Rope Model

2008-04-27 14:00:57

2008-04-26 +1.58 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B



$N$  ( $\text{cm}^{-3}$ )

0 20 40 60

IMF polarity

- +

Current sheath

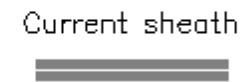
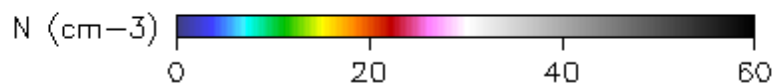
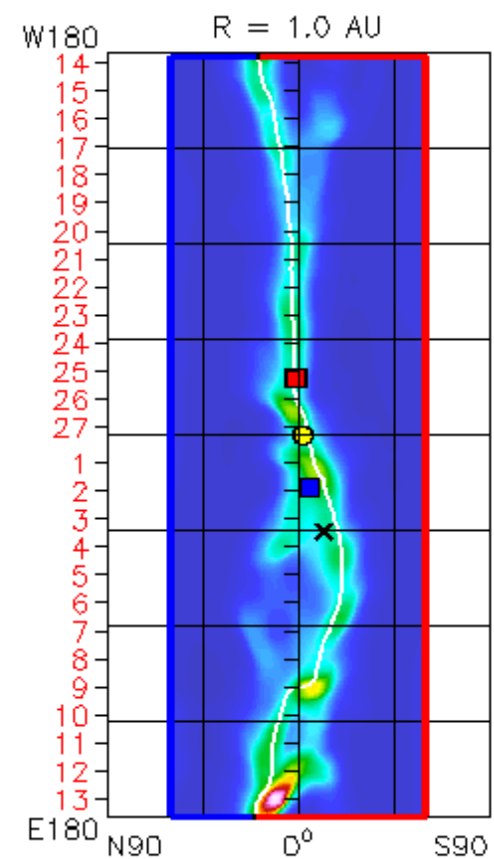
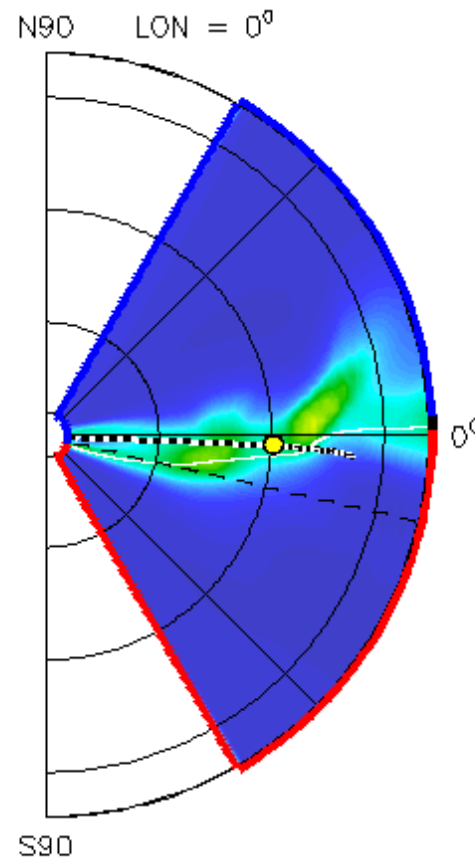
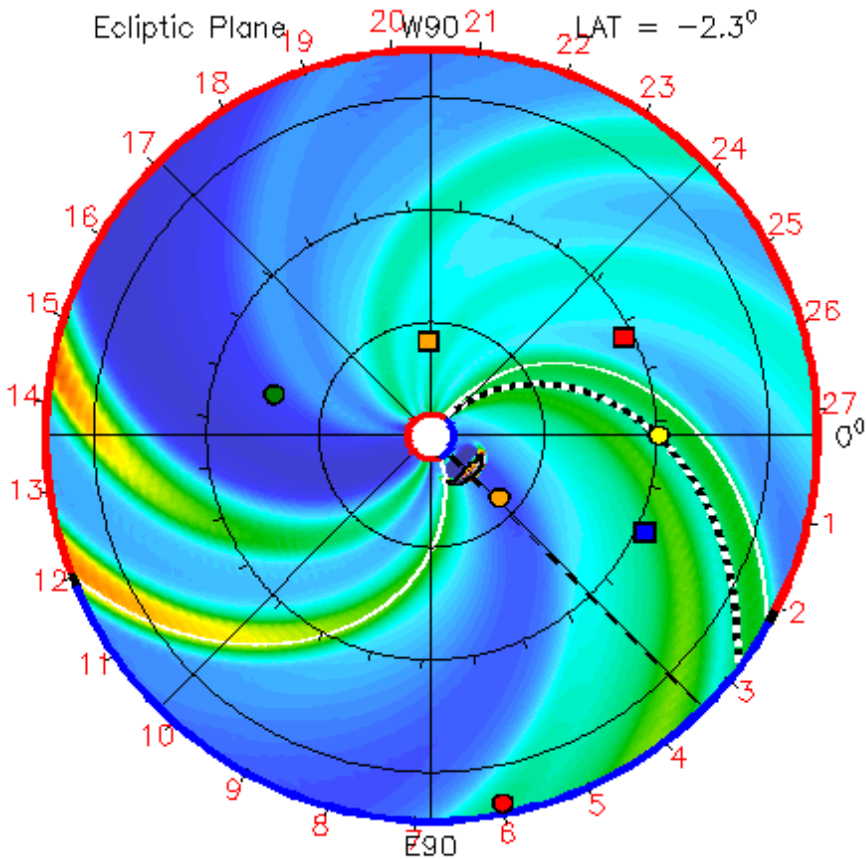
3D IMF line

# 2008 May 17 CME – Cone Model

2008-05-17 22:01:54

2008-05-17 +0.91 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

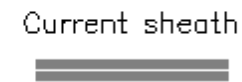
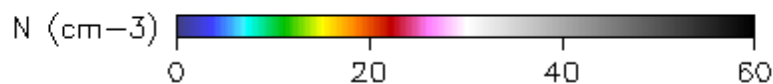
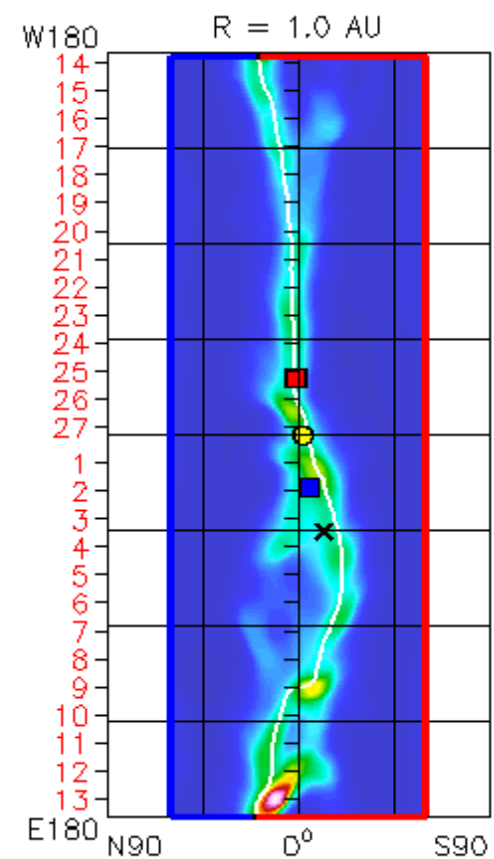
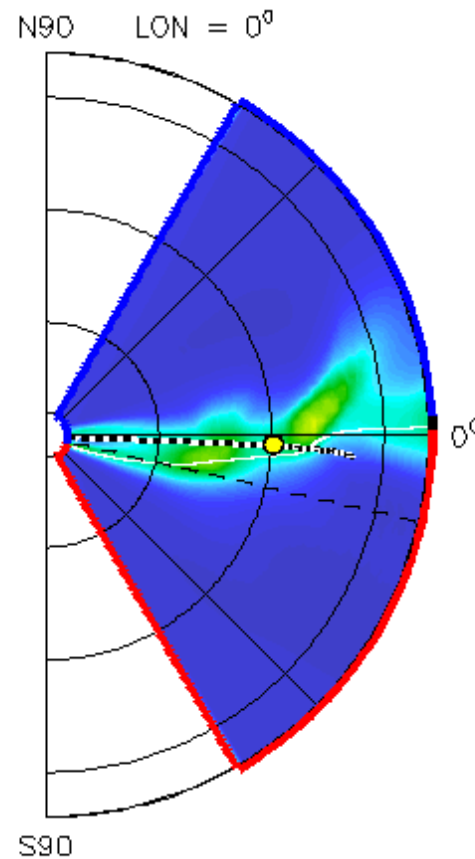
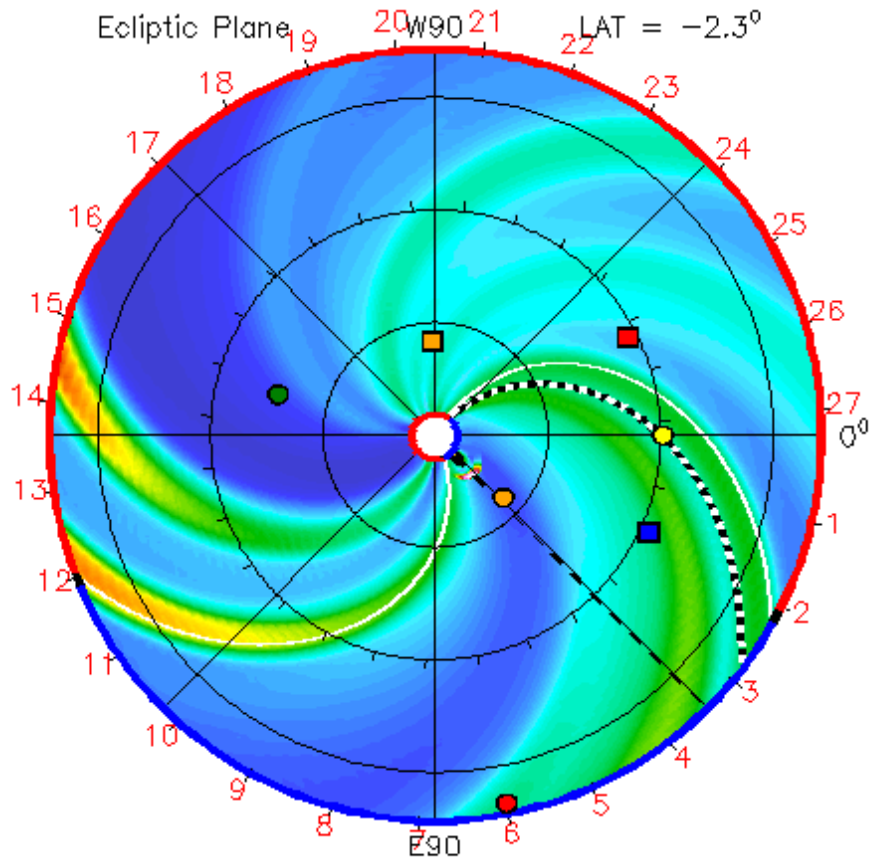


# 2008 May 17 CME – Rope Model

2008-05-17 22:00:04

2008-05-17 +0.91 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B

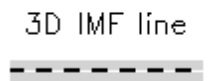
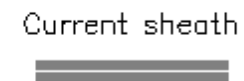
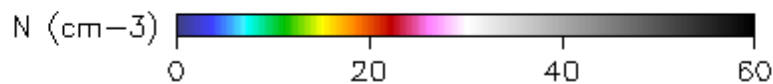
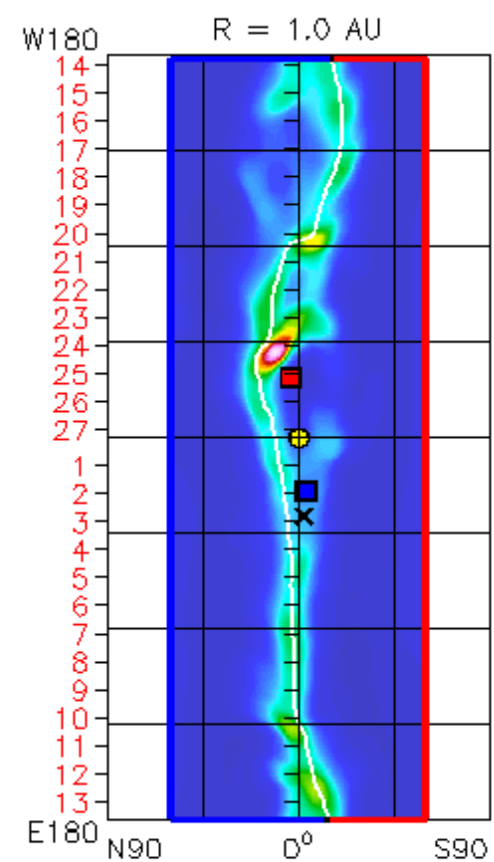
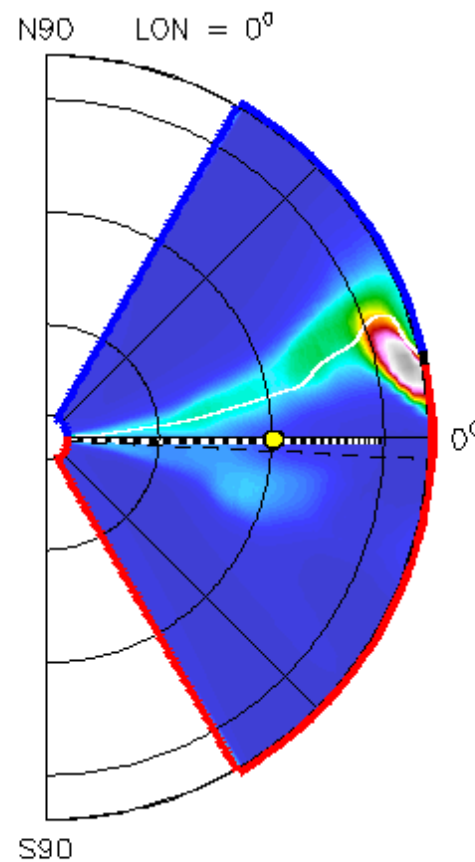
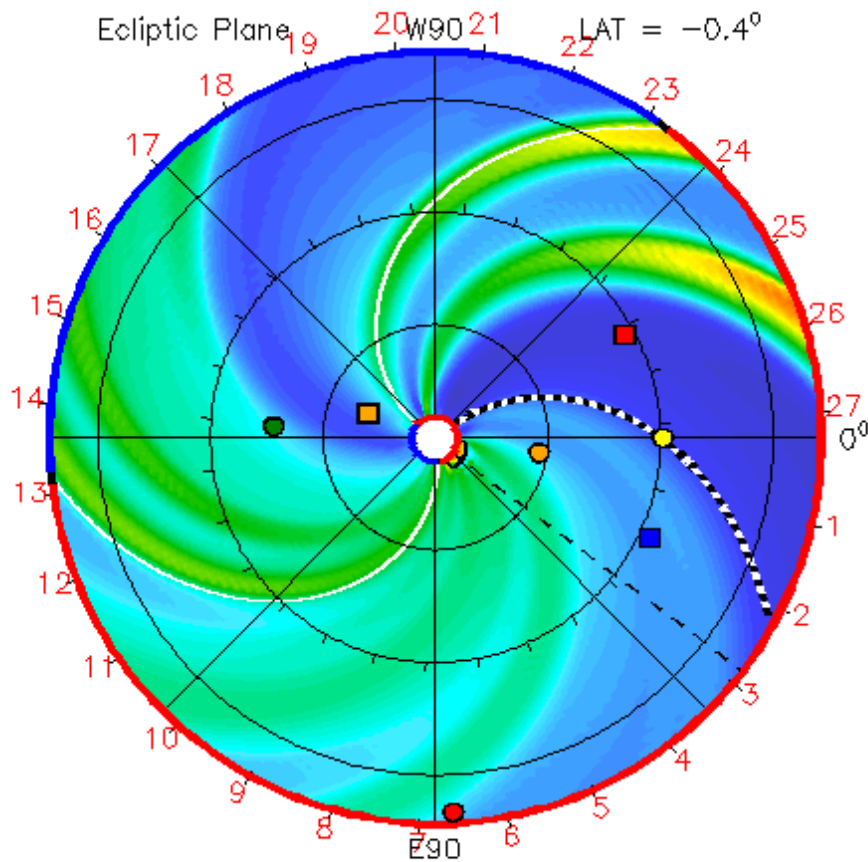


# 2008 June 2 CME – Cone Model

2008-06-02 22:01:53

2008-06-02 +0.91 days

● Mercury ● Venus ● Earth ● Mars ■ Messenger ■ Stereo\_A ■ Stereo\_B



# 2008 June 2 CME – Rope Model

2008-06-03 04:02:41

2008-06-02 +1.16 days

● Mercury   
 ● Venus   
 ● Earth   
 ● Mars   
 ■ Messenger   
 ■ Stereo\_A   
 ■ Stereo\_B

