RT Modelling of CMEs Using WSA-ENLIL Cone Model

K. Muglach

(original presentation by A. Taktakishvili)

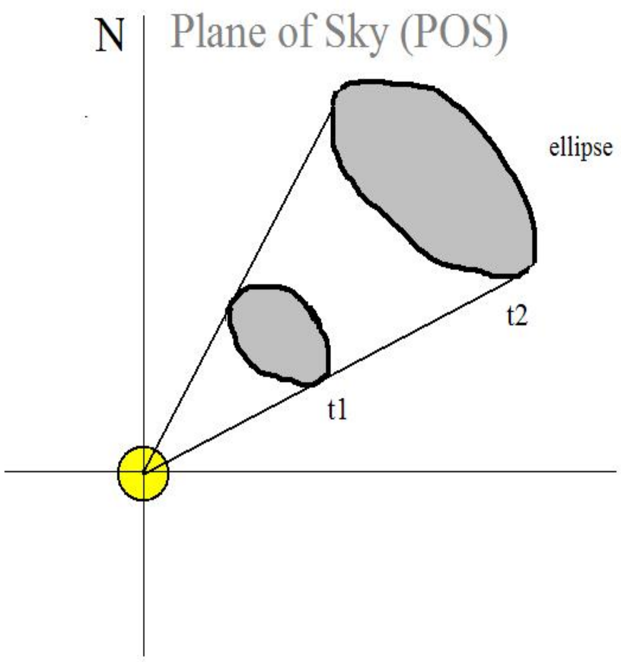
Space Weather Training at KSC

Feb.2015

Outline

- Basic Principles behind cone modeling of CMEs.
- Brief description of the models
- Analyzing CME propagation and impact
- Operations

Cone Model for CMEs



The projection of the cone on the POS is an ellipse

Zhao et al, 2002, Cone Model:

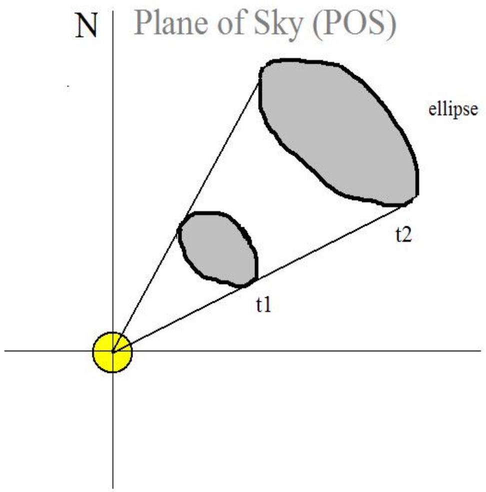
The CME cone model is based on observational evidence that CME has more or less constant angular diameter in corona, being confined by the external magnetic field, so that CME does not expand in latitude in the lower corona, but expands in interplanetary space because of the weaker external field

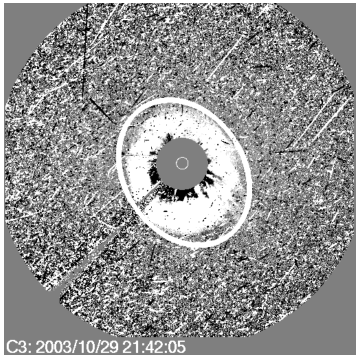
- CME propagates with nearly constant angular width in a radial direction
- CME bulk velocity is radial and the expansion is isotropic

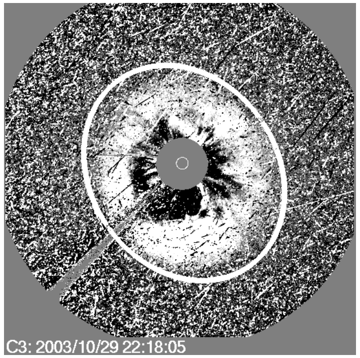
Overly simplistic approximation to describe halo CME

Cone Modelling for Halo CMEs

SOHO LASCO C3 difference images







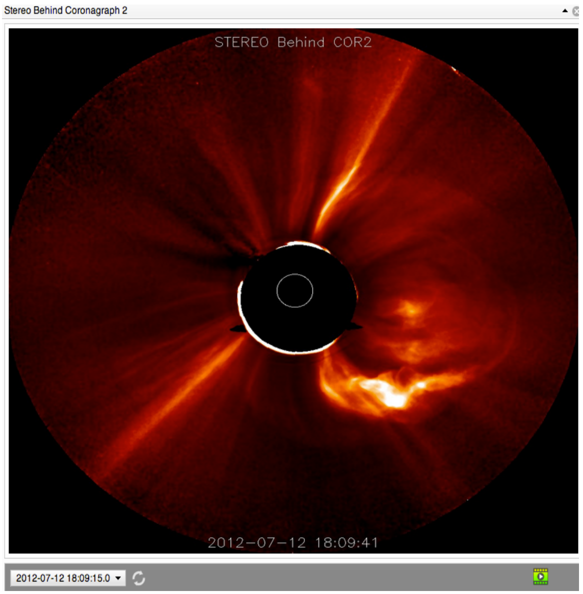
Xie et al, 2004, Cone Model for Halo CMEs – analytical method

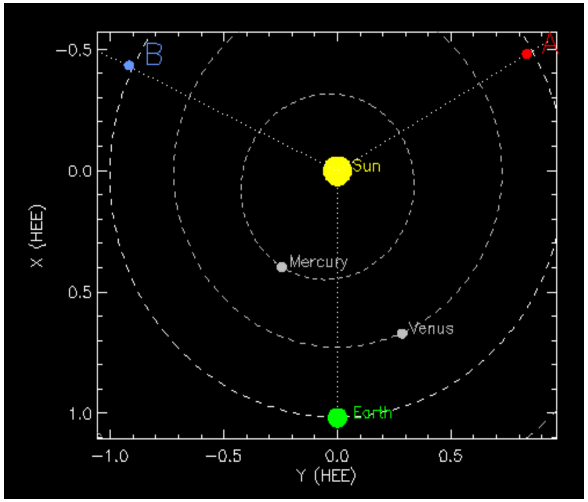
A. Pulkkinen, 2010, Cone Model for Halo CMEs – automatic method

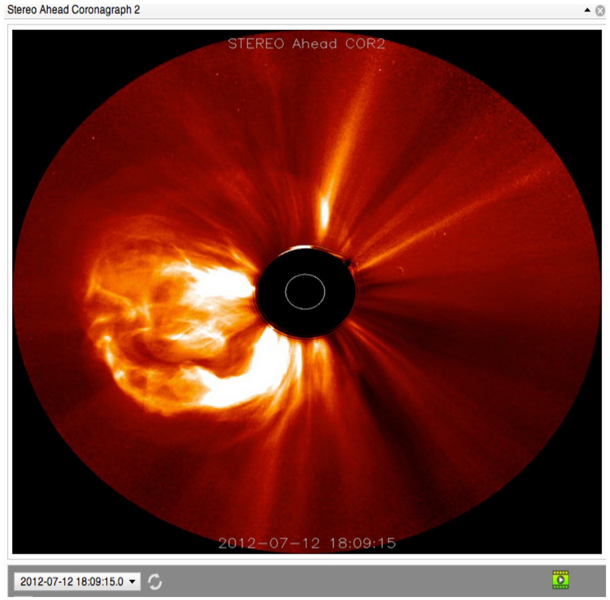
CME V and orientation

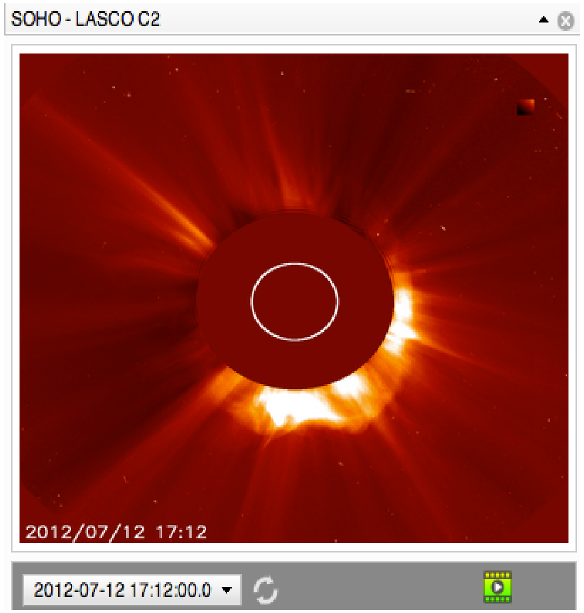
Input to WSA-ENLIL

July 12, 2012CME Viewed by Coronagraph Imagers



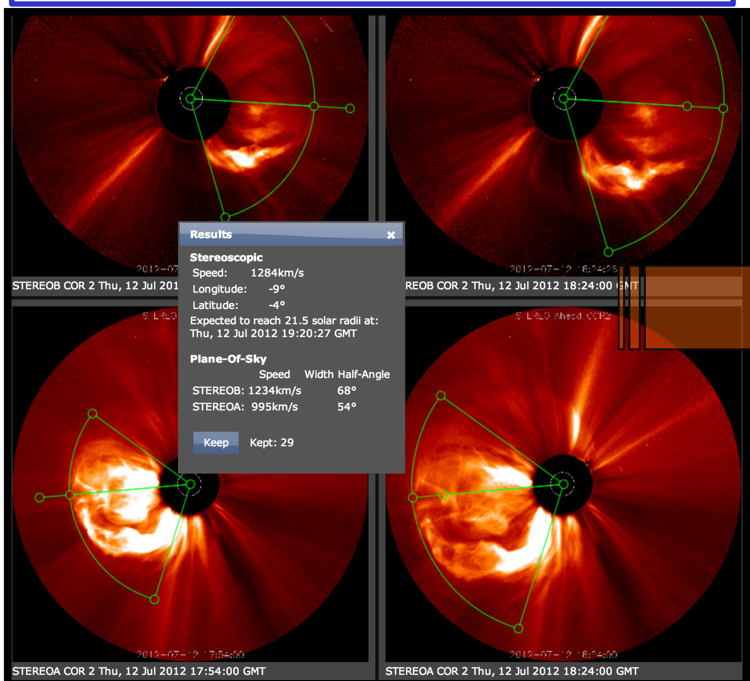




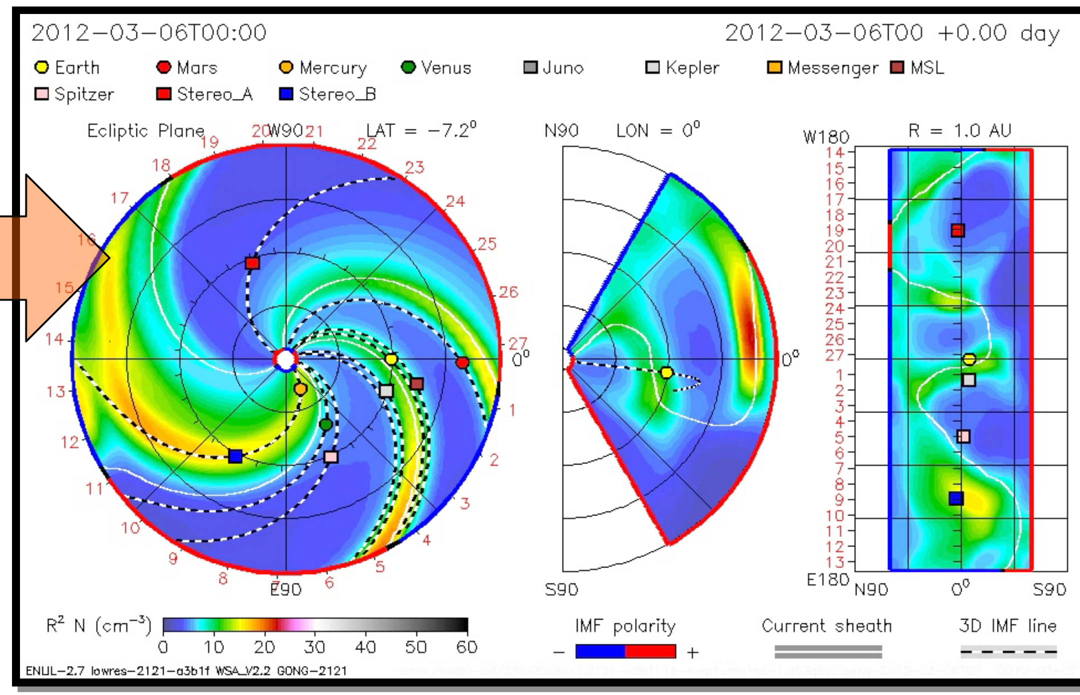


WSA-ENLIL Cone Model

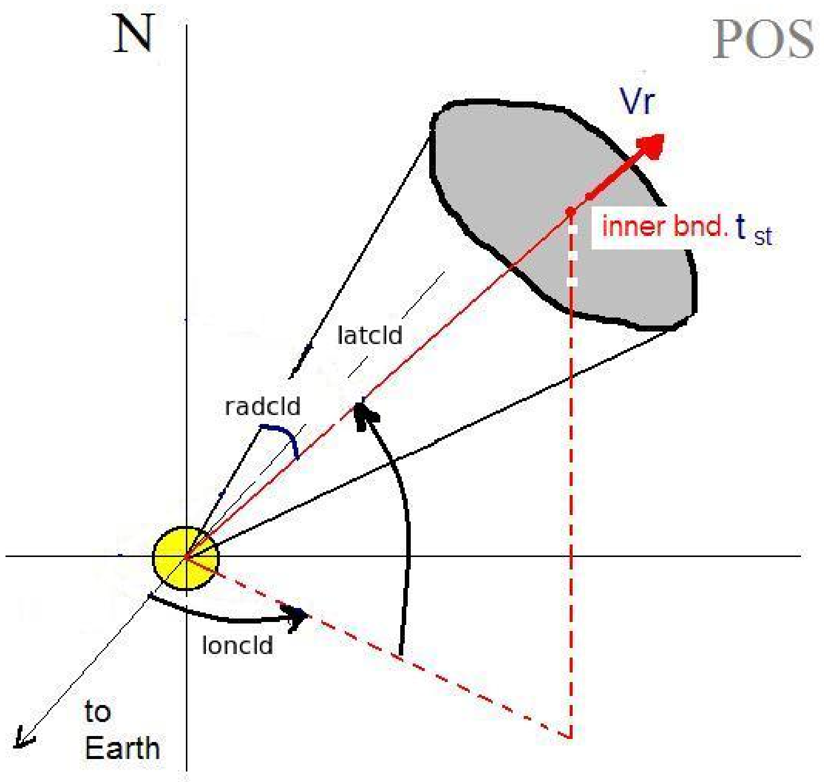
Parameters Defined with CCMC CME Triangulation Tool



CME Parameters: Input To WSA-ENLIL Cone Model



Cone model parameters

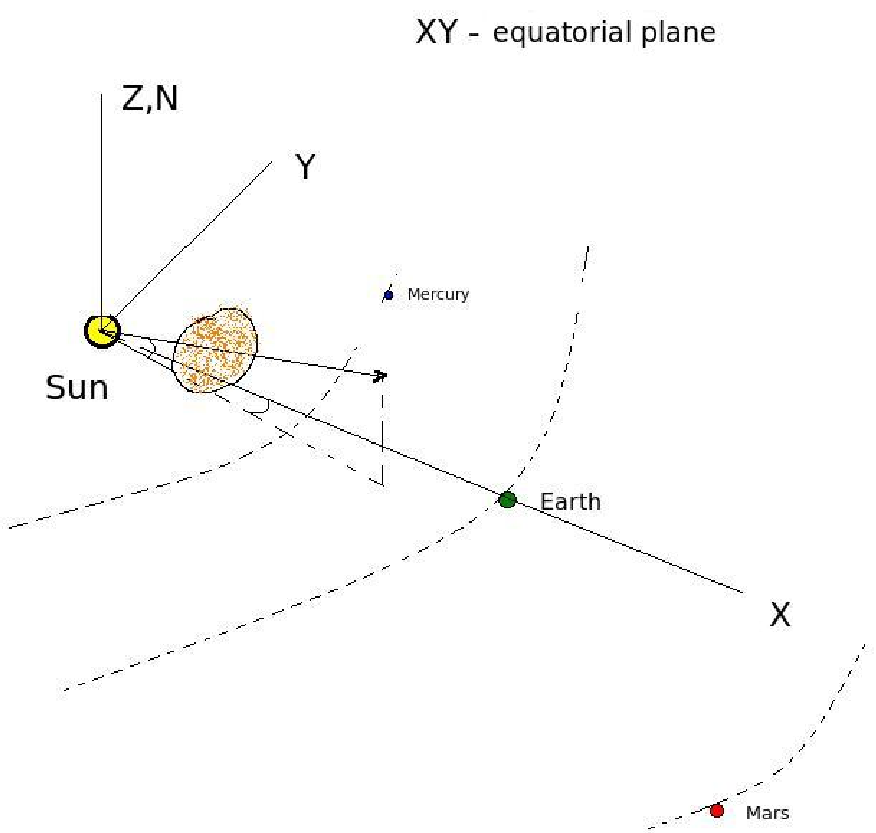


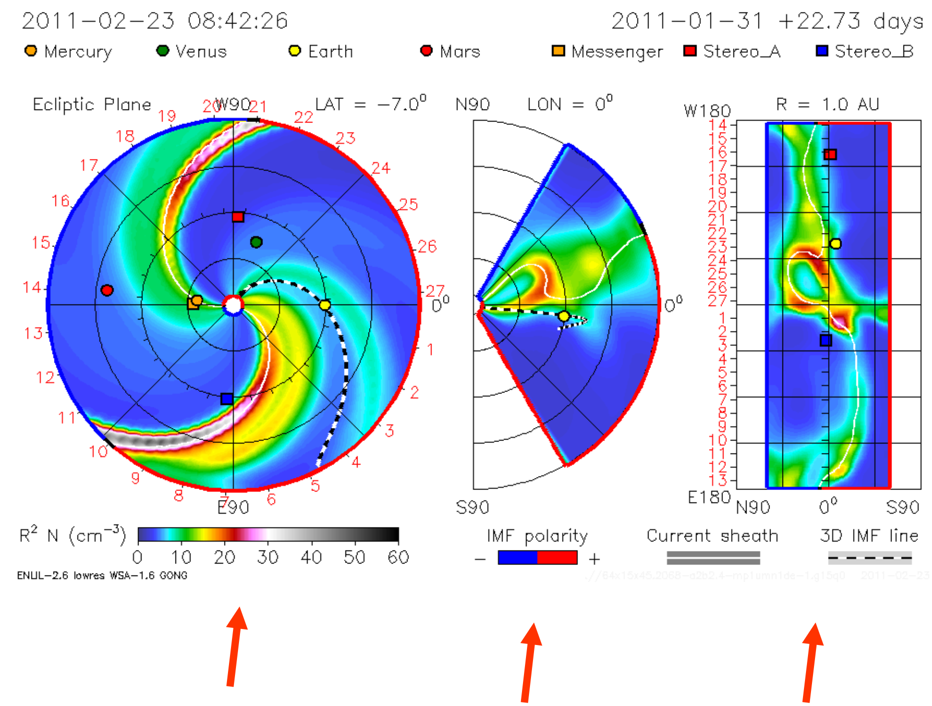
- tstart - when cloud at 21.5Rs
- Latitude
- Longitude
- Radius (angular width)
- Vr - radial velocity

Input to ENLIL cone model run

Sun, Planets, CME

Heliocentric Earth Equatorial Coordinates - Heliographic





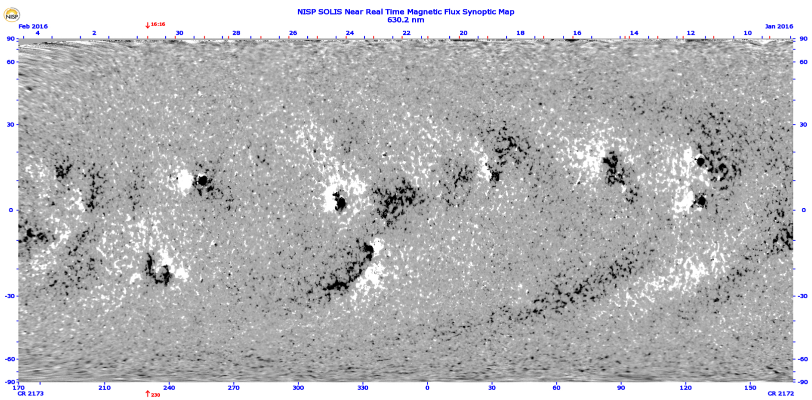
Constant Latitude Plane passing through Earth (polar view)

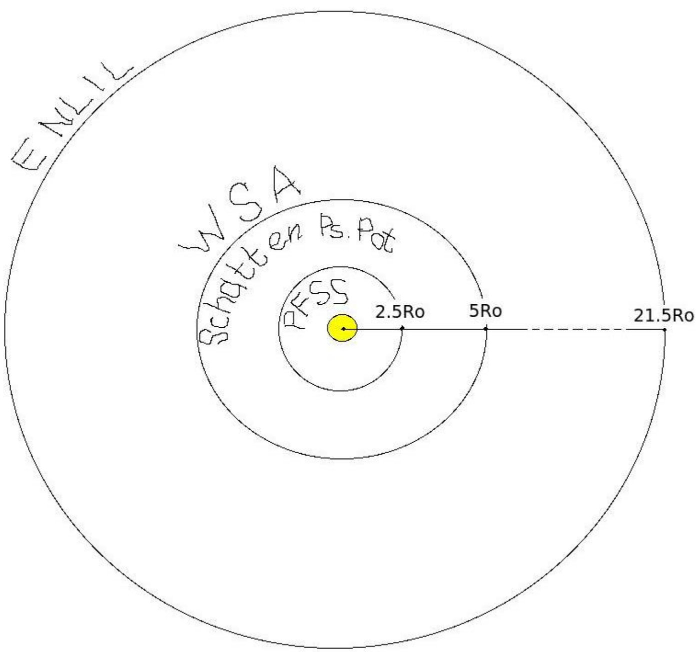
Meridional Plane ('side' view)

1AU quasi-sphere

WSA- Input to ENLIL

WSA (Wang-Sheeley-Arge, AFRL):



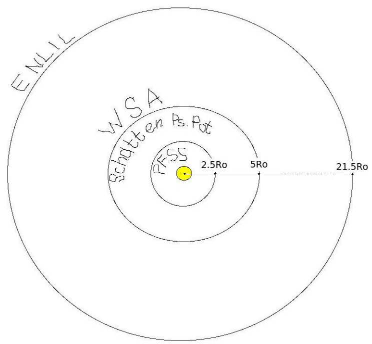


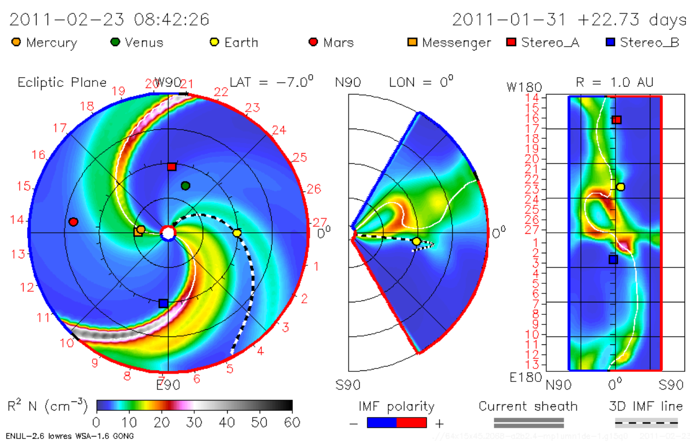
- **PFSS** (Potential Field Source Surface)**.**
  Input: synoptic map photospheric magnetogram.
  Force free (even current free) solution with radial field at 2.5 Ro.
- **Schatten Current Sheet**.
  Input: PFSS.
  Modifies the sign of radial field to positive to prevent reconnection, creates potential solution with radial boundary conditions, restores the sign in the new solution at 5 Ro.
- **WSA.**
  Input: Schatten CS.
  Assuming radial constant speed flow at 5 Ro uses empirical formula for speed, determined by the rate of divergence of the magnetic field at 5 Ro and proximity of the given field line to the coronal hole boundary.

ENLIL - Schematic Description

ENLIL – *Sumerian God of Winds and Storms*

Dusan Odstrcil, GMU & GSFC



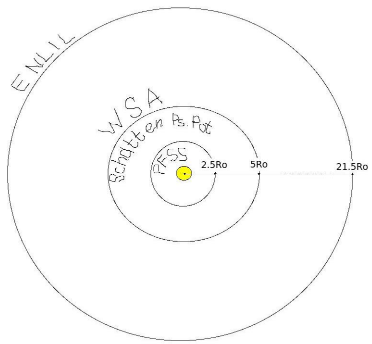


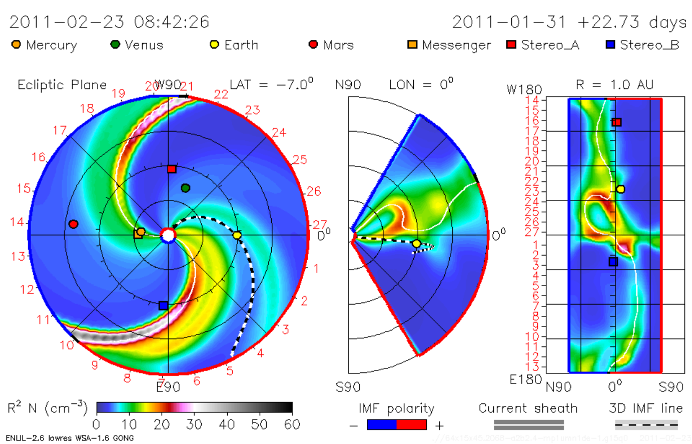
Input: WSA (coronal maps of Br and Vr updated 4 times a day). For toroidal components at the inner boundary- Parker spiral.

ENLIL's inner radial boundary is located beyond the sonic point: the solar wind flow is supersonic in ENLIL.

Computes a time evolution of the global solar wind for the inner heliosphere, driven by co-rotating background structure and transient disturbances (CMEs) at it's inner radial boundary at 21.5 Ro. Solves ideal fully ionized plasma MHD equations in 3D with two additional continuity equations: for density of transient and polarity of the radial component of B.

ENLIL Schematic Description (cont.)





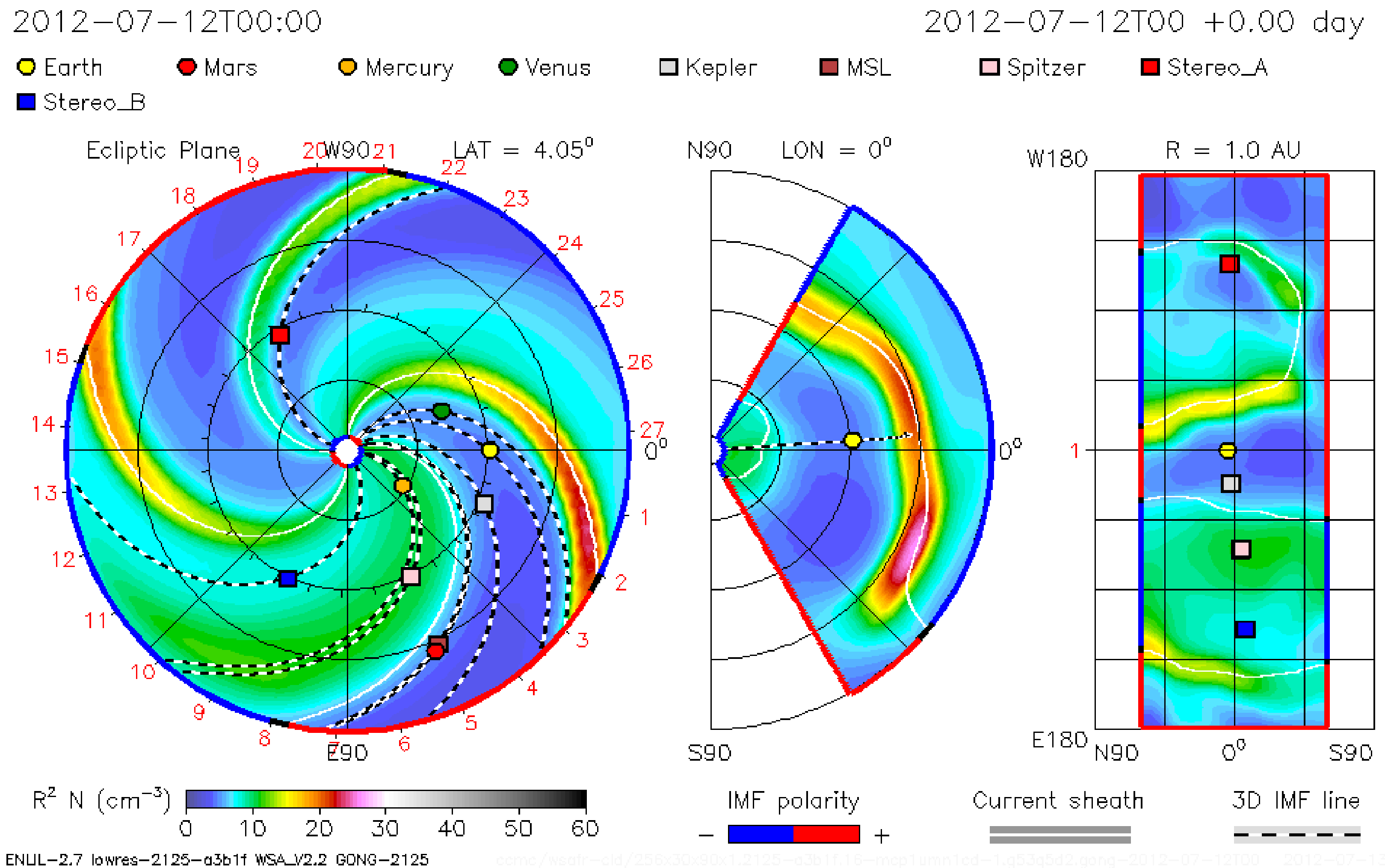
ENLIL model does not take into account the realistic complex magnetic field structure of the CME magnetic cloud and the CME as a plasma cloud has a uniform velocity.

It is assumed that the CME density is 4 times larger than the ambient fast solar wind density, the temperature is the same. Thus, the CME has about four times larger pressure than the ambient fast wind. Launching of an over pressured plasma cloud at 21.5 **Rs,** roughly represents CME eruption scenario

Output:

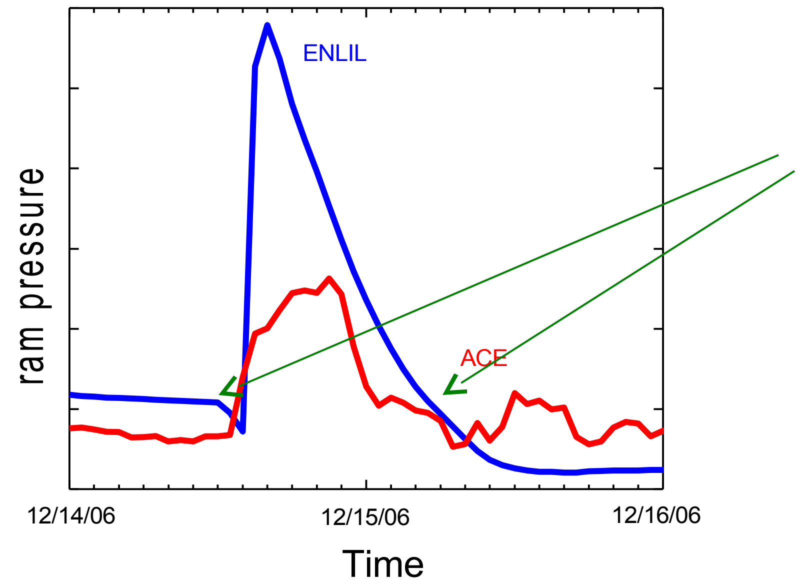
3D distribution of the solar wind parameters at spacecrafts and planets and topology of the interplanetary magnetic field.

CME modeling



CME Impact – arrival, duration, MP standoff distance, Kp index

CME shock arrival – a sharp jump in the dynamic pressure



Duration of the disturbance – duration of the dynamic pressure hump

Empirical equations for:

- Magnetopause standoff distance

- Kp Index (measure for the strength of the geomagnetic storm)

e-mail with CME impact estimate at Earth

Arrival time(year/month/day, hr:min UT) =2012-07-31T15:02Z
(confidence level +-7 hours)

Duration of the disturbance (hr) = 10.3
(confidence level +-8 hours)

Minimum magnetopause standoff distance: Rmin(Re)=5.6
(under quiet conditions: Rmin(Re)=10;
R_geosynchr(Re)=6.6)

Kp index for three possible IMF clock angles
(angle 180 gives the maximum possible estimated Kp):
(Kp)_90=4
(Kp)_135=6
(Kp)_180=7

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Here are the links to the movies of the modeled event

http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-vel.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-pdyn.gif

Inner Planets
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel.gif
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http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel-Stereo_B.gif

Timelines
http://iswa2.ccmc.gsfc.nasa.gov/downloads/20120729_014700_ENLIL_CONE_timeline.gif
http://iswa2.ccmc.gsfc.nasa.gov/downloads/20120729_014700_ENLIL_CONE_Kp_timeline.gif

e-mail for NASA missions

Mars
****

CME did not hit the Mars.
or
CME impact is very weak.

****

Stereo A
****

CME did not hit the StereoA.
or
CME impact is very weak.

****

Stereo B
****
CME did not hit the StereoB.
or
CME impact is very weak.

****

Spitzer
****

Arrival time(year/month/day, hr:min UT) =2015-05-11T20:49Z

Inner Planets
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-vel.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-den-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-vel-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-den-Stereo_B.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-vel-Stereo_B.gif

Inner Planet Timelines
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_Mars_timeline.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_STA_timeline.gif
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http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_Venus_timeline.gif

RT Modelling of CMEs Using WSA-ENLIL Cone Model

K. Muglach

(original presentation by A. Taktakishvili)

Space Weather Training at KSC

Feb.2015

1

In this presentation we will make an introduction to the
WSA-ENLIL Cone model, used at SWRC to model propagation
of coronal mass ejections (CMEs) in the heliosphere.

Outline

- Basic Principles behind cone modeling of CMEs.
- Brief description of the models
- Analyzing CME propagation and impact
- Operations

2

First, I will say few words about basic principles behind cone modeling of CMEs.
Then, I will make a brief description of the WSA and ENLIL models.
After that I will describe how we analyze CME propagation and it's impact
Finally, I will demonstrate an example of forecasting in operations:
A collaboration with Air Force Weather Agency (AFWA)

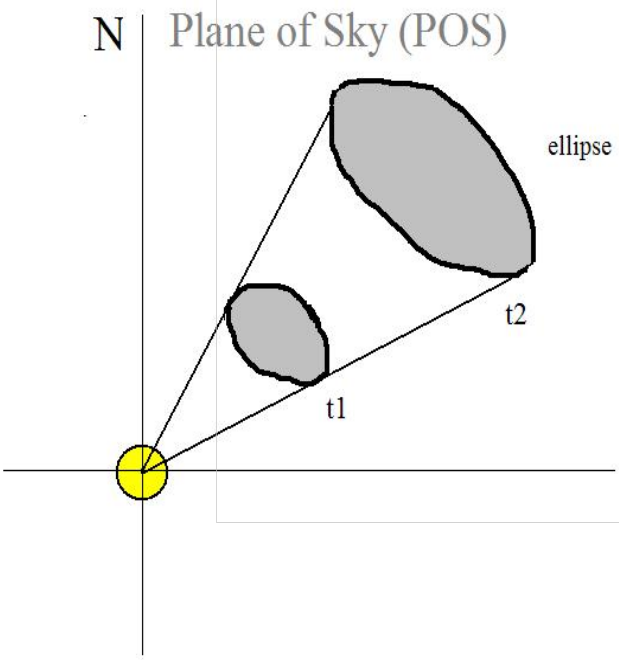
Cone Model for CMEs

l, 2002, Cone Model:

ıdel is based on observational
Ξ has more or less constant angular
ı, being confined by the external
that CME does not expand in
ır corona, but expands in
ɔe because of the weaker external

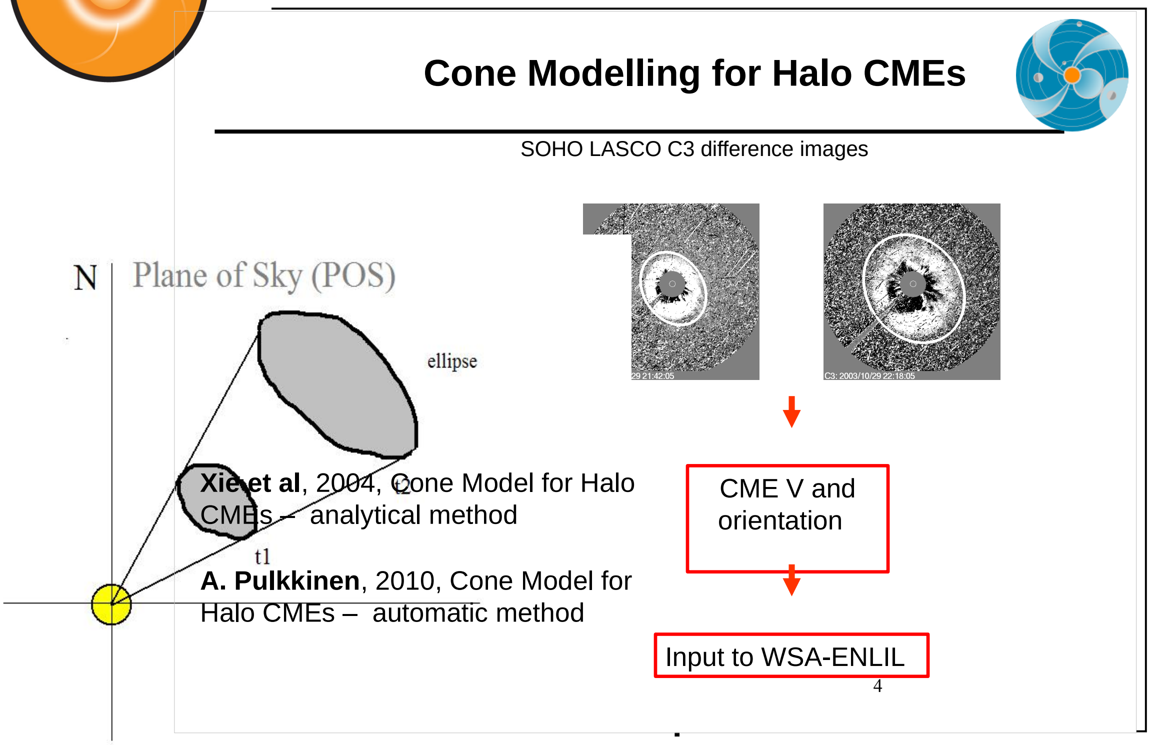
ɘs with nearly constant angular width
ion
ity is radial and the expansion is

ɔribe halo CME



Zhao was the first to come up with the Cone model of CME. The CME cone model is based on observational evidence that CME has more or less constant angular diameter in corona, being confined by the external magnetic field, so that CME does not expand in latitude in the lower corona, but expands in interplanetary space because of the weaker external field. The assumptions are the following:

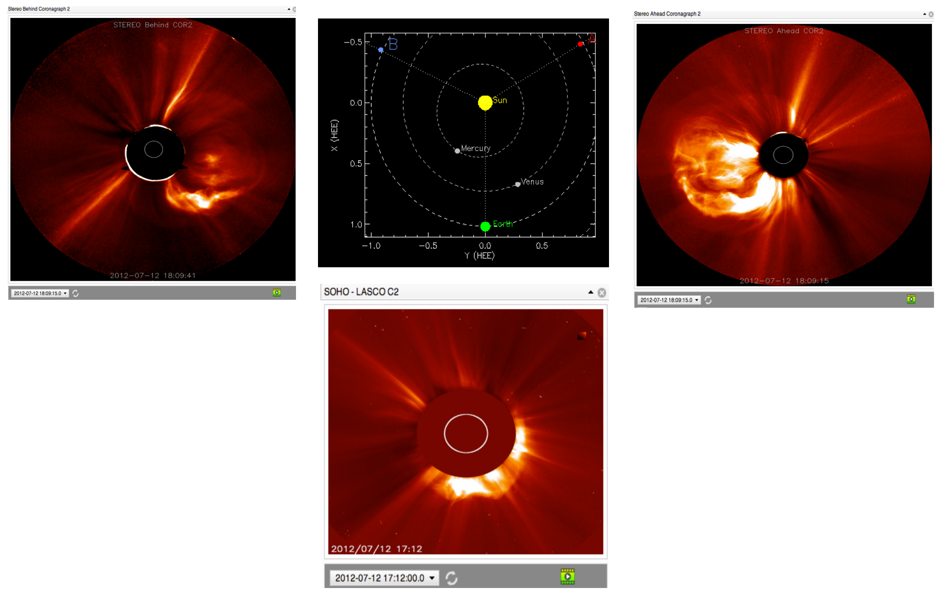
- CME propagates with nearly constant angular width in a radial direction
- CME bulk velocity is radial and the expansion is isotropic



artificial eclipse of the Sun. Eclipses allow corona to be better viewed. But natural eclipses do not happen often. Occulting disk blocks the bright sun so we can observe coronal features. Shown in this slide are difference images.

Xie et al, 2004, developed analytical method of defining Cone Model CME parameters for Halo CMEs based on series of coronograph image. A. Pulkkinen , 20010 developed automatic method

July 12, 2012CME Viewed by Coronagraph Imagers

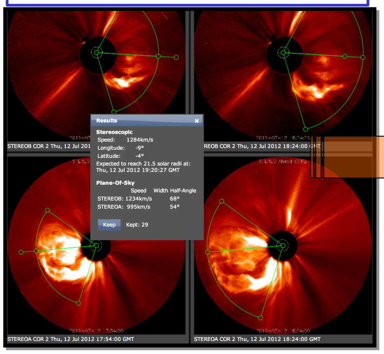


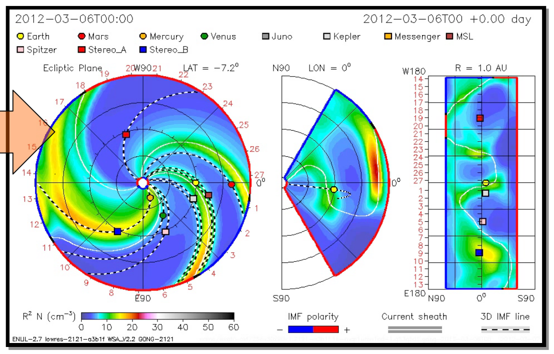
Another method to derive Cone model parameters is triangulation method.
This slide shows the a CME seen in 3 coronographs located on three different satellites.
The schematic in the upper center shows the location of STEREO B,
SOHO and STEREO A satellites in the ecliptic plane at the time when the CME occurred.
The CME was moving sort of towards the Earth, so STB sees it moving to
the right in its plane of sky, for STA it moves to the left and it’s a halo
image for SOHO that is located on a sun-earth line.

WSA-ENLIL Cone Model

Parameters Defined with CCMC CME Triangulation Tool

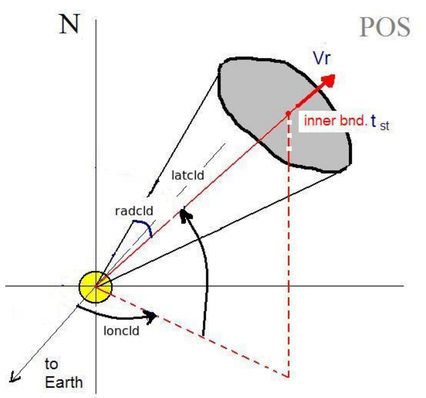
CME Parameters: Input To WSA-ENLIL Cone Model





Parameters defined with CCMC CME
Triangulation Tool
(CAT) or other tools are used as input
CMEpParameters
to WSA-ENLIL Cone Model.

Cone model parameters



- tstart - when cloud at 21.5Rs
- Latitude
- Longitude
- Radius (angular width)
- Vr - radial velocity

Input to ENLIL cone model run

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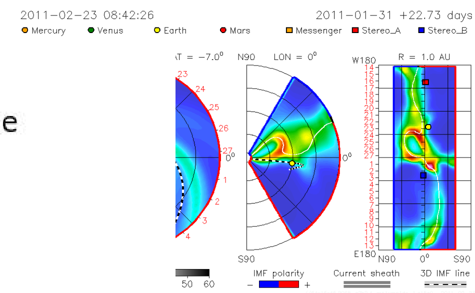
Parameters defined with CCMC CME Triangulation or other Tools yield CME Parameters: Input To WSA-ENLIL Cone Model. These parameters are:

1- start time of CME at 21.5 Rs (inner boundary of the ENLIL model)
2- Cone axis latitude
3- Cone axis longitude
5- Cone Radius – half angle of the cone angular width
6- Radial Velocity

Sun, Planets, CME

Heliocentric Earth Equatorial Coordinates - Heliographic

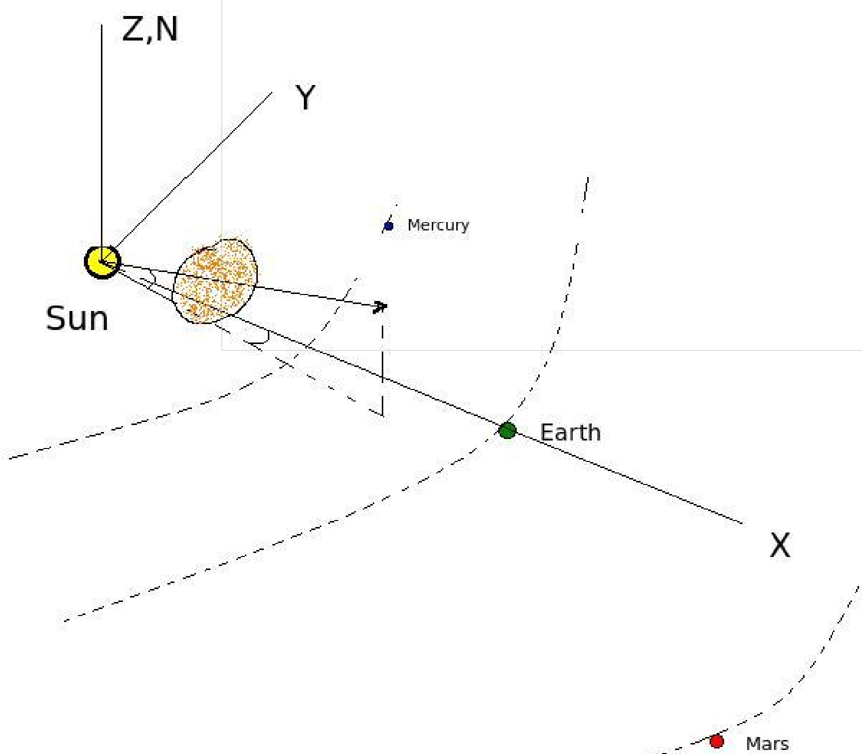
XY - equatorial plane



Meridional Plane ('side' view)

1AU quasi-sphere

8



e of the Sun

ocated in the

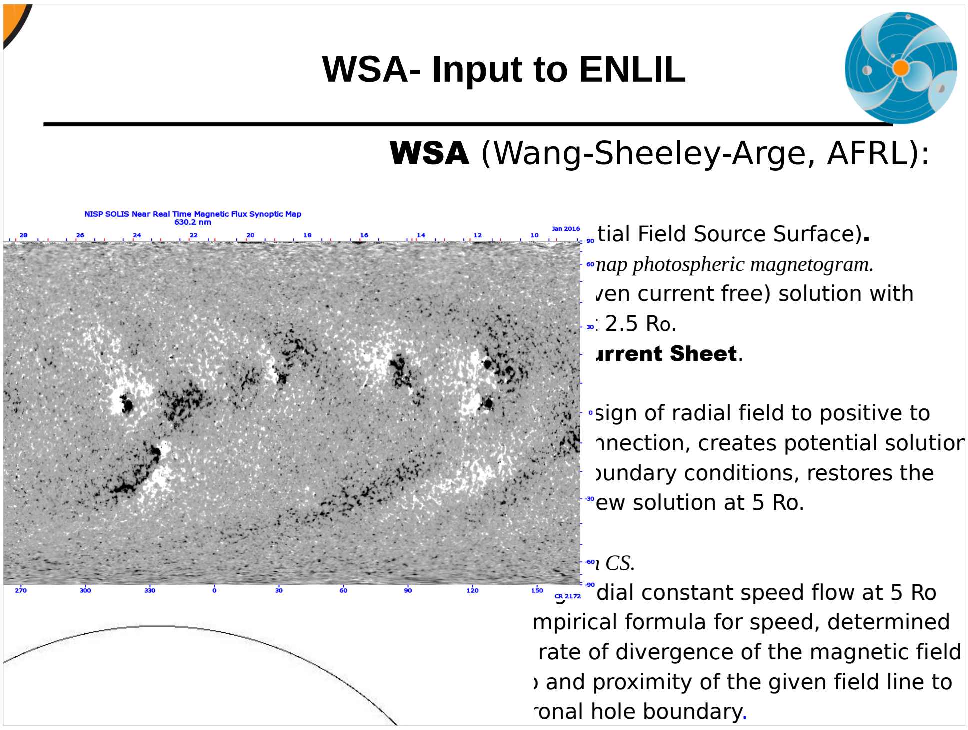
uatorial plane

(changes from -7.5 deg to 7.5 deg).

The first panel in WSA-ENLIL plot shows a plane passing through the Earth and is parallel to equatorial plane. The second panel is a meridianal cut passing through the Earth. The latitude goes from -60 to 60 degrees.

The third panel shows Longitude-Latitude map of a quasi sphere at 1 AU and with

The cut off for Latitude > |60 deg|



Wang-Sheeley-Arge model WSA (Wang-Sheeley-Arge, AFRL) is the input model to the ENLIL at it's inner boundary of 21.5Rs. The input to the WSA is daily magnetograms of the solar surface, that describe the magnetic field of the photosphere.

WSA model itself consists of different models

- **PFSS** (Potential Field Source Surface).

  Input: synoptic map photospheric magnetogram.

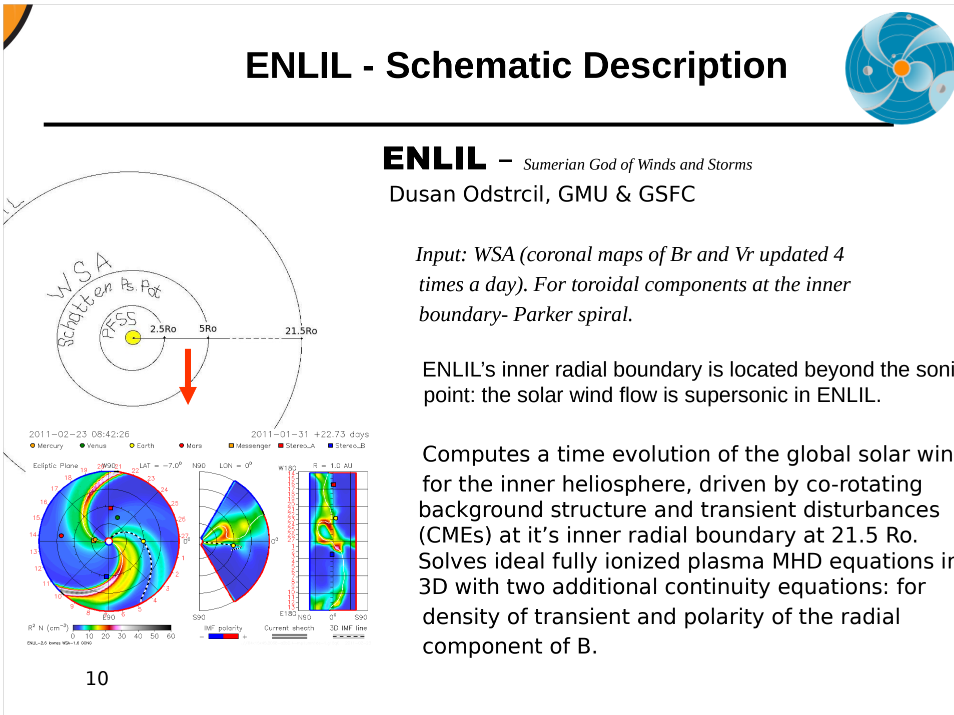
  Force free (even current free) solution with radial field at 2.5 Ro.
- **Schatten Current Sheet**.

  Input: PFSS.

  Modifies the sign of radial field to positive to prevent reconnection, creates potential solution with radial boundary conditions, restores the sign in the new solution at 5 Ro.
- **WSA.**

  Input: Schatten CS.

  Assuming radial constant speed flow at 5 Ro uses empirical formula for speed, determined by the rate of divergence of the magnetic field at 5 Ro and proximity of the given field line to the coronal hole boundary.



ENLIL – Sumerian God of Winds and Storms
Dusan Odstrcil, GMU & GSFC

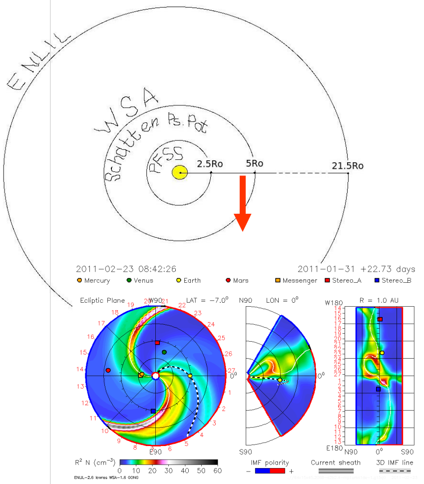
Input: WSA (coronal maps of Br and Vr updated 4 times a day). For toroidal components at the inner boundary- Parker spiral.

ENLIL's inner radial boundary is located beyond the sonic point: the solar wind flow is supersonic in ENLIL.

Computes a time evolution of the global solar wind for the inner heliosphere, driven by corotating background structure and transient disturbances (CMEs) at it's inner radial boundary at 21.5 Ro.

Solves ideal fully ionized plasma MHD equations in 3D with two additional continuity equations: for density of transient and polarity of the radial component of B.

ENLIL Schematic Description (cont.)



ENLIL model does not take into account the realistic complex magnetic field structure of the CME magnetic cloud and the CME as a plasma cloud has a uniform velocity.

It is assumed that the CME density is 4 times larger than the ambient fast solar wind density, the temperature is the same. Thus, the CME has about four times larger pressure than the ambient fast wind. Launching of an over pressured plasma cloud at 21.5 **Rs,** roughly represents CME eruption scenario

Output:
3D distribution of the solar wind parameters at spacecrafts and planets and topology of the interplanetary magnetic field.

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Limitation of the ENLIL model:

It does not take into account the realistic complex magnetic field structure

of the CME magnetic cloud and the CME as a plasma cloud has a uniform velocity.

It is assumed that the CME density is 4 times larger than the ambient fast solar wind

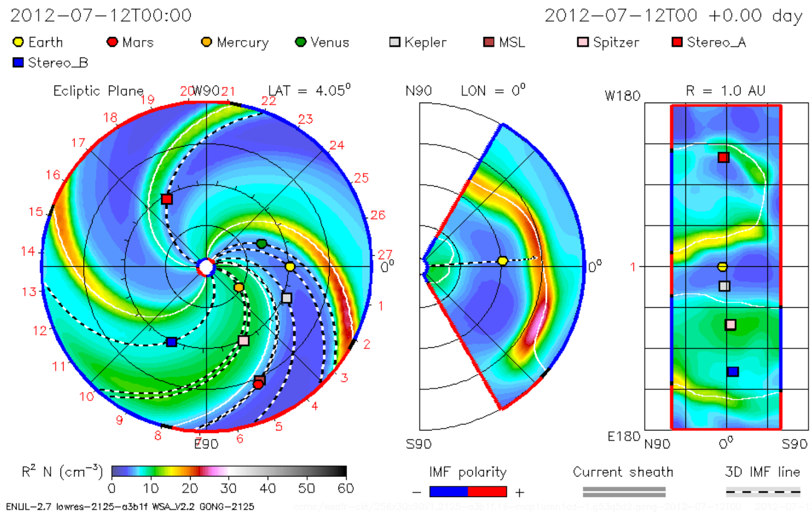
density, the temperature is the same. Thus, the CME has about four times larger

pressure than the ambient fast wind. Launching of an over pressured plasma cloud

at 21.5 **Rs,** roughly represents CME eruption scenario

Output:
3D distribution of the SW parameters at spacecrafts and planets and topology of IMF.

CME modeling



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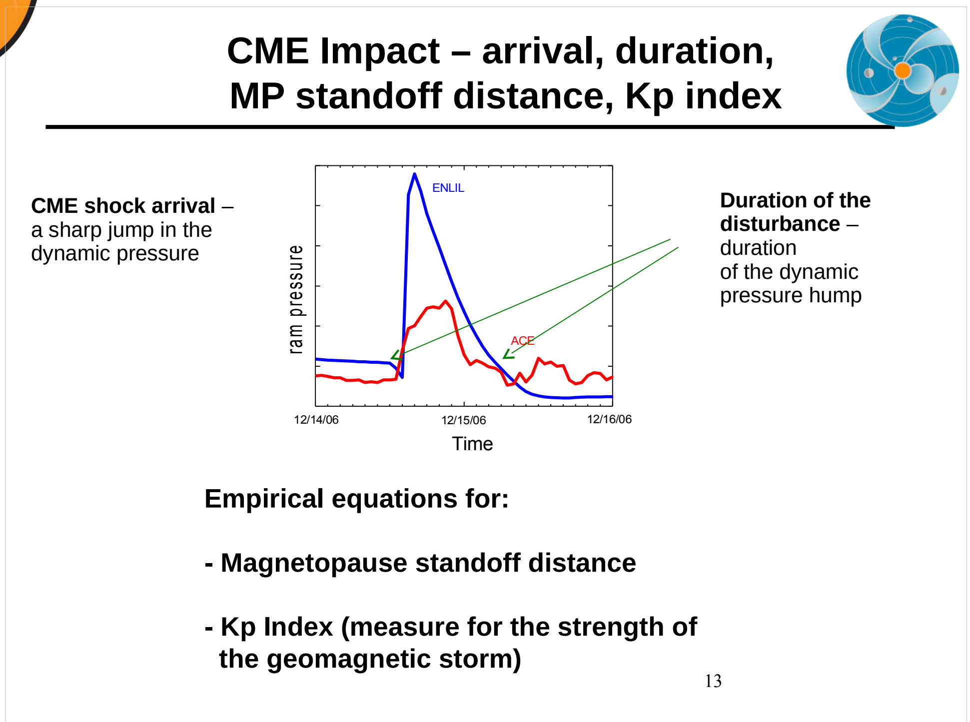
After we define the CME parameters we run the WSA-ENLIL cone model.



After the run is done, we estimate the CME impact on planets, satellites.

1. CME shock arrival – a sharp jump in the dynamic pressure.
2. Duration of the disturbance – duration of the dynamic pressure hump.
3. In case of the Earth we estimate also the degree of compressing of the magnetosphere: when the CME mass reaches the magnetosphere it pushes it inward and the magnetic field of the Earth is stressed like a spring to stop the CME motion.

e-mail with CME impact estimate at Earth

Arrival time(year/month/day, hr:min UT) =2012-07-31T15:02Z
(confidence level +-7 hours)

Duration of the disturbance (hr) = 10.3
(confidence level +-8 hours)

Minimum magnetopause standoff distance: Rmin(Re)=5.6
(under quiet conditions: Rmin(Re)=10;
R_geosynchr(Re)=6.6)

Kp index for three possible IMF clock angles
(angle 180 gives the maximum possible estimated Kp):
(Kp)_90=4
(Kp)_135=6
(Kp)_180=7

****

Here are the links to the movies of the modeled event

http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-vel.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_afwa_anim.tim-pdyn.gif

Inner Planets
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-den-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-den-Stereo_B.gif
http://iswa.gsfc.nasa.gov/downloads/20120729_014700_anim.tim-vel-Stereo_B.gif

Timelines
http://iswa2.ccmc.gsfc.nasa.gov/downloads/20120729_014700_ENLIL_CONE_timeline.gif
http://iswa2.ccmc.gsfc.nasa.gov/downloads/20120729_014700_ENLIL_CONE_Kp_timeline.gif

And here is our response e-mail the them in details.
It contains the CME impact estimate for the Earth
(arrival time, magnetopause standoff distance,
Kp estimate for three possible clock angles of the IMF),
and links to the modeling animation and timelines.

e-mail for NASA missions

Mars
****

CME did not hit the Mars.
or
CME impact is very weak.

****

Stereo A
****

CME did not hit the StereoA.
or
CME impact is very weak.

****

Stereo B
****
CME did not hit the StereoB.
or
CME impact is very weak.

****

Spitzer
****

Arrival time(year/month/day, hr:min UT) =2015-05-11T20:49Z

Inner Planets
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-den.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-vel.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-den-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-vel-Stereo_A.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-den-Stereo_B.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_anim.tim-vel-Stereo_B.gif

Inner Planet Timelines
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_Mars_timeline.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_STA_timeline.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_STB_timeline.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_Spitz_timeline.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_Merc_timeline.gif
http://iswa.gsfc.nasa.gov/downloads/20150509_071500_2.0_ENLIL_CONE_Venus_timeline.gif

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But we are not monitoring only Earth impact. Being responsible for providing space weather assessment to NASA robotic mission operators, we are monitoring possible impact of the CME on NASA missions.

So we send out another e-mail, that shows this estimate.