A Comparison of Models That Predict Magnetopause Location Changes

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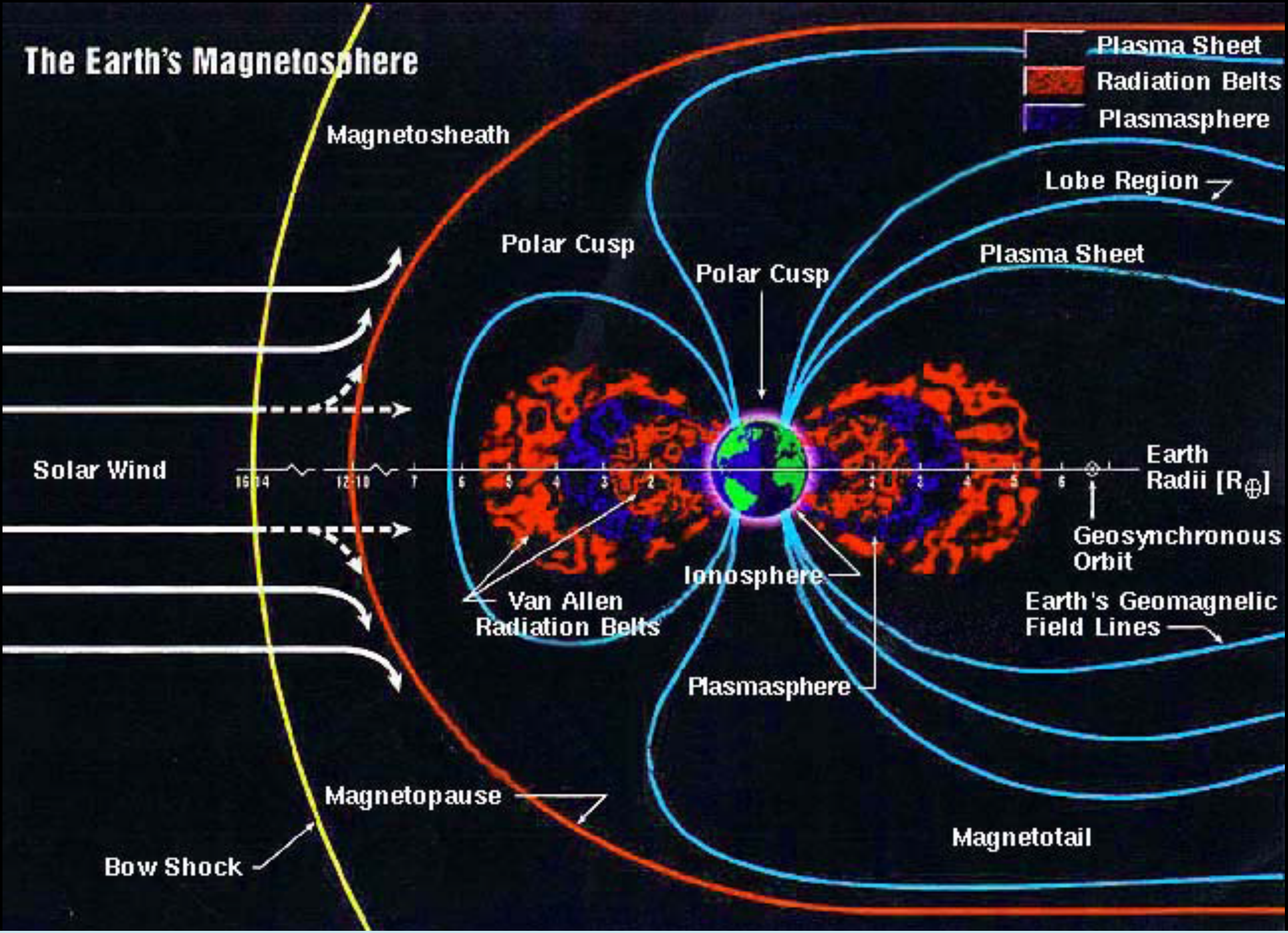
What is the Magnetopause?

- **Magnetopause** is the last boundary that separates the Earth's magnetosphere from the solar wind environment
  - typical subsolar distance of 9-11 Earth Radii (R_E)
- A shock wave (***Bow Shock***) is formed in front of the nose of the magnetopause by the encounter of the supersonic solar wind with the "obstacle" to its flow presented by the Earth's magnetic field
- ***Magnetosheath*** is the shocked/compressed solar wind plasma behind the Bow Shock
- Most of the solar wind particles are heated and slowed at the Bow Shock and detour around the Earth
- Solar wind drags out the night-side magnetosphere to more than 1000 R_E. This extension of the magnetosphere is known as the ***magnetotail.***



The Earth's Magnetosphere. *Source: NASA*

Magnetopause Crossing of Geosynchronous Orbit

- When a solar storm reaches Earth’s magnetosphere, the magnetopause can get pushed inwards at it’s nose and flanks
  - The high solar wind dynamic pressure act to compress the dayside of Earth’s magnetosphere
  - Large negative Interplanetary Magnetic Field (IMF) Bz also contributes to the erosion of the dayside
  - During periods of extreme space weather, the solar storm may compress the dayside of the Earth’s magnetosphere past the geosynchronous orbit of 6.6 R_E

Why Track the Magnetopause Boundary?

- Gauges the level of space weather activity as substantial compression/ erosion of the magnetosphere. This is often an indicator of the arrival of a solar storm at Earth
- Because of Magnetopause Crossing (MC) of Geosynchronous Orbit, the geosynchronous satellites may find themselves in the magnetosheath or outside the magnetosphere
  - This change in environment can damage satellites
- Therefore, the magnetopause location provides an important context to satellite operators and helps them decide what to do to protect their spacecraft from extreme space weather

Predicting MCs of Geosynchronous Orbit

- Several studies and models to predict the magnetopause location and shape have been put forth
- Some simulation models available at the Community Coordinated Modeling Center (CCMC) at NASA/Goddard Space Flight Center (GSFC):
  - **BATS-R-US** (Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme), aka Space Weather Modeling Framework (SWMF)
  - **Open GGCM** (Open Geospace General Circulation Model)
  - **GUMICS** (Grand Unified Magnetosphere–Ionosphere Coupling Simulation)
  - **LFM** (Lyon Fedder Mobarry global MHD model)

See CCMC website for references: https://ccmc.gsfc.nasa.gov/models/models_at_glance.php

Hypothesis

- **Testable question:**

  Which of the following four models can most accurately predict Magnetopause Locations or Magnetopause Crossings of Geocynchronous orbit during extreme solar wind conditions: BATS-R-US, OpenGGCM, GUMICS, and LFM?

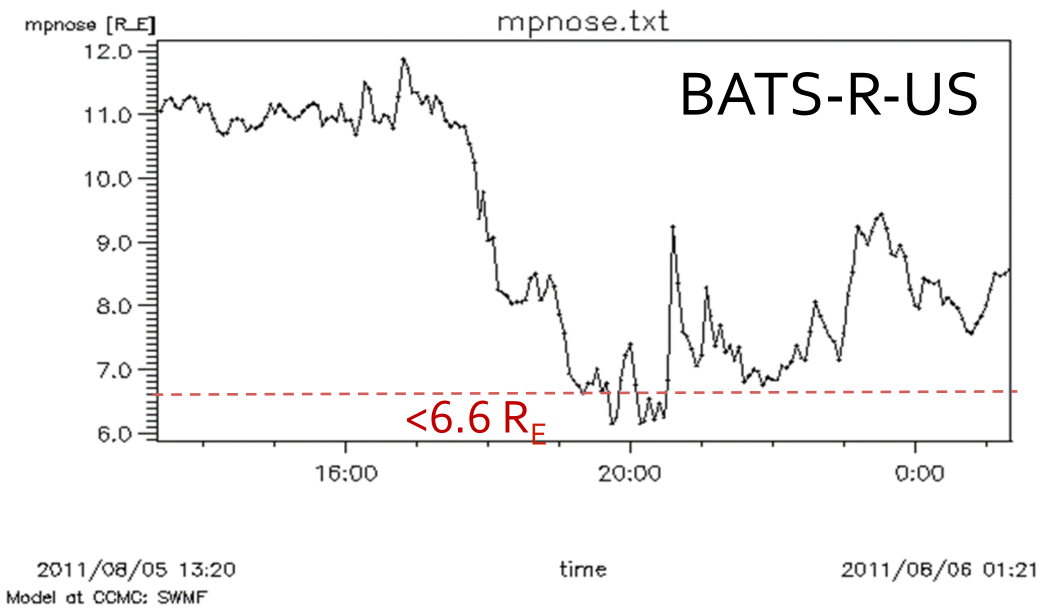
- **Hypothesis:**

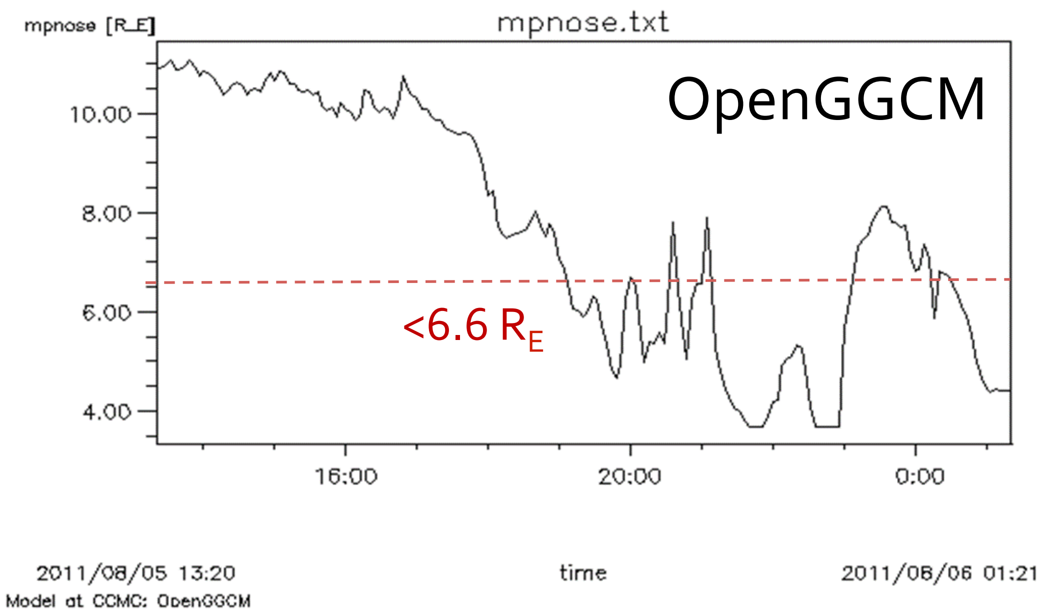
  My hypothesis was that all these four models will be equally efficient in accurately predicting the Magnetopause Locations during extreme solar wind conditions

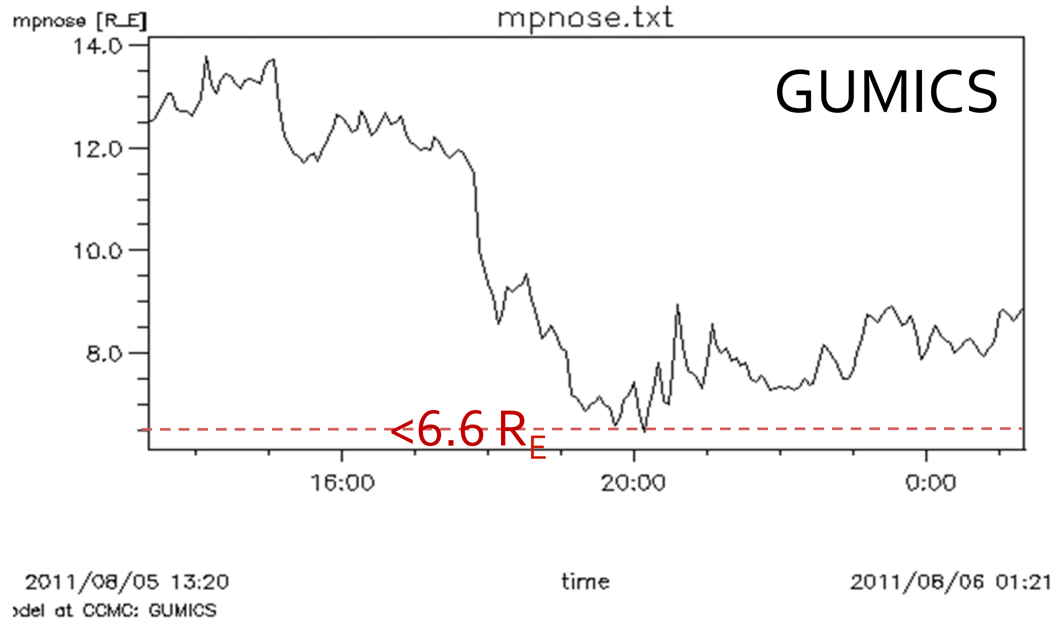
Materials & Methods

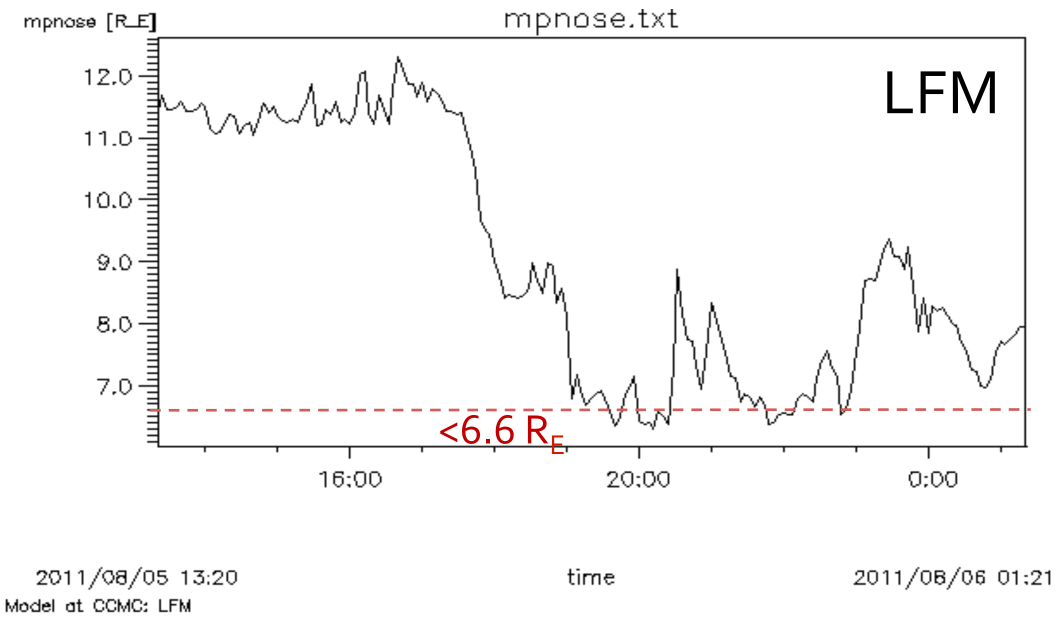
1. The dates and times for Magnetopause Crossings from 2010 to 2016 were identified using the SW-DONKI database (https://kauai.ccmc.gsfc.nasa.gov/DONKI/)
2. Magnetopause locations predicted by the four different models (BATS-R-US, OpenGGCM, GUMICS, and LFM) on the dates and times identified were requested from the CCMC database
3. The Magnetopause Crossing start times and the total Magnetopause Crossing durations (i.e. the time below 6.6 R_E) predicted by each of these models were recorded
4. Thereafter, real-time location of the GOES satellite during the Magnetopause Crossings was recorded as day-side or not using the Orbit plotting tool available from: https://sscweb.gsfc.nasa.gov/

Comparison of the magnetopause positions predicted by the different models for the August 5, 2011 event







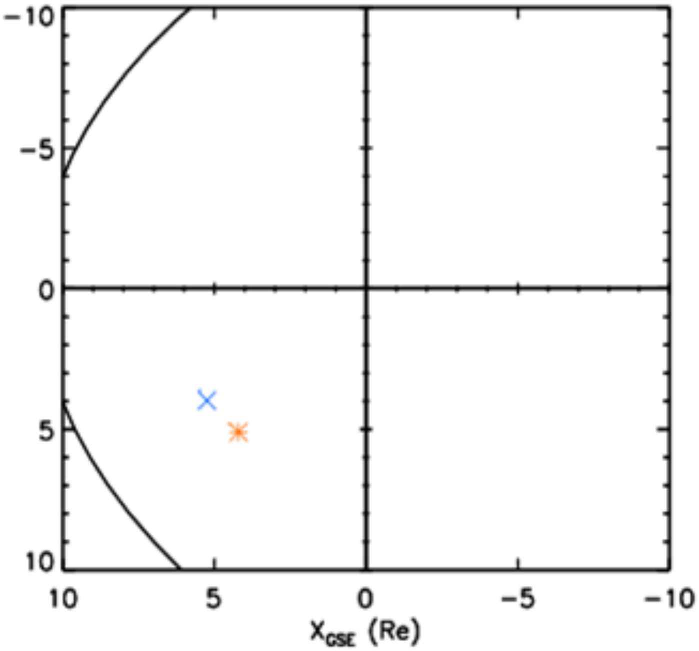


Real-time Location of the GOES 13/15 satellites

DAY SIDE

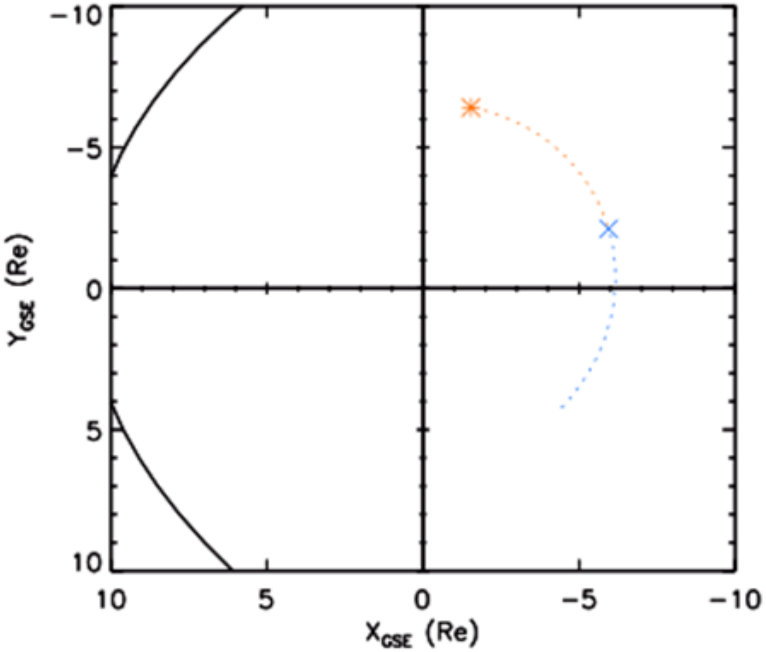
August 5, 2011

20:00 UT to 20:18 UT



July 15, 2012

6:12 UT to 10:12 UT

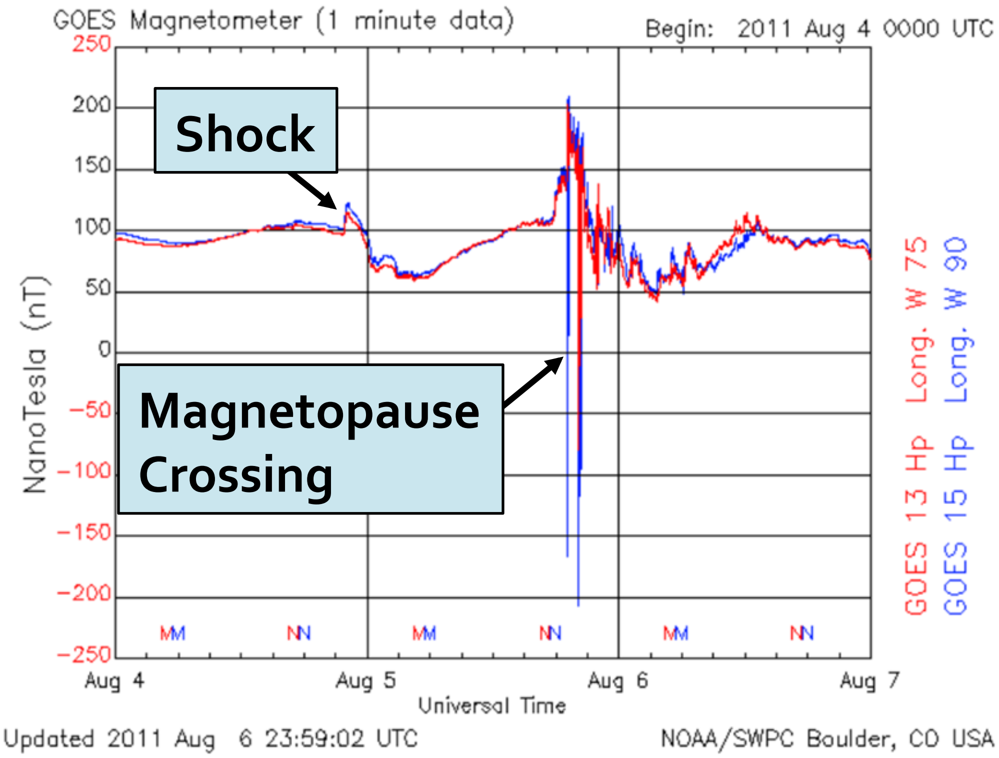


NIGHT SIDE

— GOES 13 — GOES 15

GOES 13 and 15 magnetic field Hp component at the onset of the geomagnetic storms

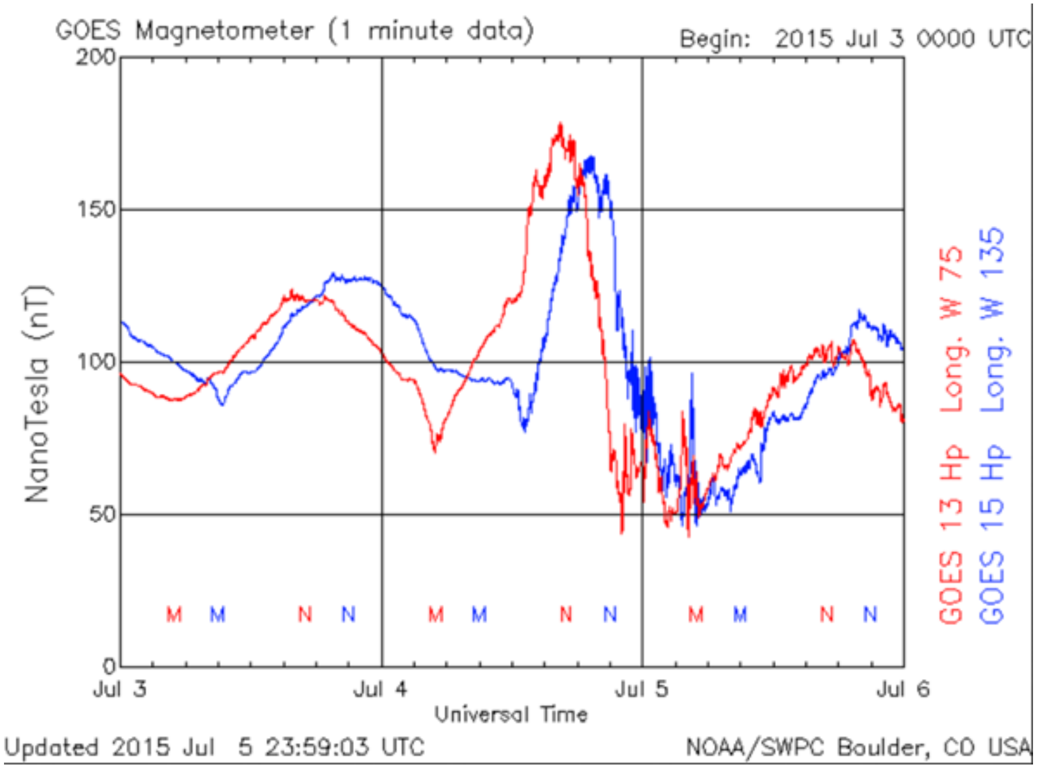
August 5, 2011
GOES observed
Magnetopause Crossing



Shock

Magnetopause Crossing

July 4, 2015
GOES observed
No Magnetopause Crossing



Materials & Methods (continued)

5. The Magnetopause Crossing start time and total duration predicted by the above four models were compared with the observed magnetometer readings on the GOES satellites using the Dynamic Plots of the GOES data available at: https://spitfire.estec.esa.int/ODI/dplot_goesM.html
6. Difference in crossing start times (and crossing duration) predicted by models and observed by GOES satellites were calculated and the root-mean-square errors (RMSE) was calculated using the equation:

$$\textbf{RMSE =} \surd\sum i=1\uparrow n \text{▒} (xobs\ i - xmod\ i)2\ /n$$

where $x_{obs\ i}$ is the Magnetopause Crossing start time (or crossing duration) observed by the GOES satellites for the *ith* observation and $x_{mod\ i}$ is the Magnetopause Crossing start time (or crossing duration) predicted by the different models

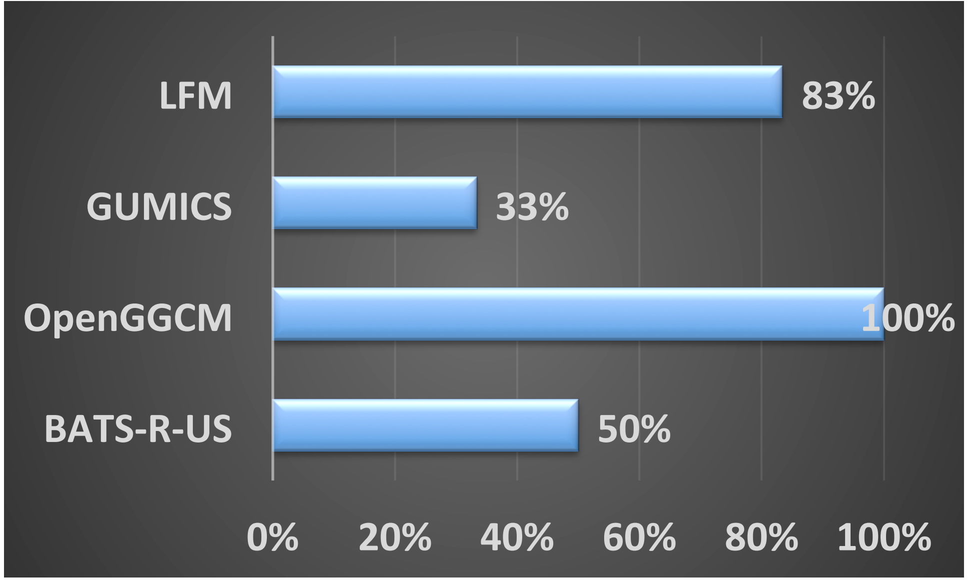
Results

Magnetopause Crossings between 2010 to 2016

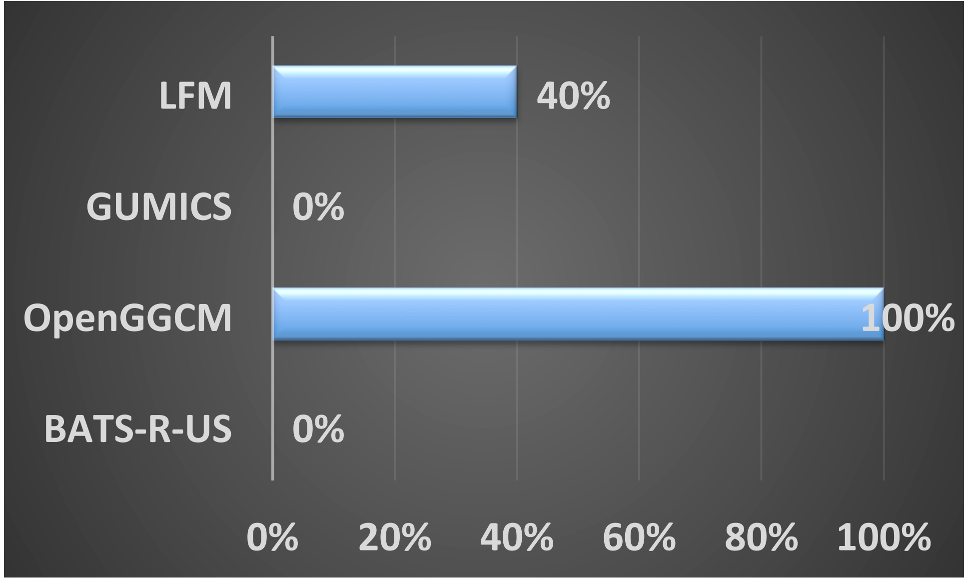
- 31 Magnetopause Crossings are reported on the SW DONKI website
- 16 of the 31 (51%) Magnetopause Crossings were analyzed
- For 11 of these 16 storms, GOES was located on the Day-Side during the Magnetopause Crossing

Comparison of Magnetopause Crossings predicted by the different models

Model predictions for storms with crossings observed by GOES



Model predictions for storms with no crossings observed by GOES



Differences in observed and predicted MC start times for the 6 MCs observed by GOES 13/15 satellites

Date	Xobs-Xmod (Time Difference in Crossing Start time, in decimal hours)			
	BATS-R-US	**OpenGGCM**	**GUMICS**	**LFM**
3/6/2016	x	2.68	x	-1.32
6/22/2015	-0.03	4.42	-0.18	x
10/8/2013	x	0.00	x	-1.02
6/16/2012	0.95	6.40	0.98	1.07
9/26/2011	x	3.87	x	3.82
8/5/2011	0.37	0.93	x	0.50
Average (in h)	**0.43**	**3.05**	**0.40**	**0.61**
RMSE (in h)	**0.59**	**3.73**	**0.71**	**1.94**

Positive values indicate early predictions, negative values indicate late predictions, and “x” indicates no crossings were predicted by models for these MCs observed by GOES satellites.

Comparison of the MC durations predicted by the different models with that observed by the GOES

		X_{obs}	X_{mod} Crossing duration (in hours)			
Date	**Crossing observed on GOES**	**GOES Crossing duration (in hours)**	**BATS-R-US**	**OpenGGCM**	**GUMICS**	**LFM**
3/6/2016	Yes	0.15	0	2.15	0	0.30
6/22/2015	Yes	1.75	5.27	10.25	3.42	0
10/8/2013	Yes	1.62	0	2.85	0	0.42
6/16/2012	Yes	0.17	2.02	1.92	3.07	0.83
9/26/2011	Yes	0.37	0	4.07	0	0.22
8/5/2011	Yes	0.08	0.57	4.58	0	1.17
6/5/2016	No	0	0	1.55	0	0
3/11/2016	No	0	0	0.37	0	0.97
12/31/2015	No	0	0	9.50	0	0
7/4/2015	No	0	0	9.38	0	0.25
12/28/2010	No	0	0	3.47	0	0
RMSE (in decimal hours)			**1.31**	**5.29**	**1.13**	**0.81**

Discussion & Analysis

1. The models give very different standoff positions of the dayside magnetopause for the same solar wind conditions
2. Often models (such as LFM and OpenGGCM) predicted Magnetopause Crossings while they were not observed by the GOES satellites
3. Most models couldn’t correctly predict all the GOES-observed MCs
4. All the models were primarily early in predicting Magnetopause Crossings

Discussion & Analysis (contd.)

4. Crossing durations predicted by OpenGGCM deviated the most from the GOES-observed crossing durations, and the crossing durations predicted by LFM deviated the least from the GOES-observed crossing durations.

5. Current models differ the most during extreme solar wind conditions

What next?

- Current model results are least valid during extreme solar wind conditions, when they are most needed. Therefore, there is a need for improved magnetopause models, the testing of these models under extreme conditions, and monitoring what actually occurs at the geosynchronous location at GOES.

References

- **BATS-R-US Model,** developed by Dr. Tamas Gombosi, et al., at Center for Space Environment Modeling, University of Michigan. Available at: https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=BATS-R-US
- **GUMICS,** a global solar wind-magnetosphere-ionosphere coupling model, developed by Pekka Janhunen et.al. at Finnish Meteorological Institut. Available at: https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=GUMICS
- **LFM model,** developed by John Lyon, Wenbin Wang, Slava Merkin, Mike Wiltberger, Pete Schmitt, and Ben Foster, at Dartmouth College/NCAR-HAO/JHU-APL/CISM. Available at: https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=CMIT/LFM-MIX
- **Open GGCM,** The Open Geospace General Circulation Model, developed by Joachim Raeder and Timothy Fuller-Rowell at Space Science Center, University of New Hampshire. Available at: https://ccmc.gsfc.nasa.gov/models/modelinfo.php?model=OpenGGCM
- Petrinec, S. M., Redmon, R. J., and Rastaetter, L. (2017), Nowcasting and forecasting of the magnetopause and bow shock—A status update, Space Weather, 15, 36–43, doi: 10.1002/2016SW001565.
- Singer, H.J., Matheson, L., Grubb, R., Newman, A. and Bouwer, S.D. Monitoring space weather with the GOES magnetometers. NOAA Space Environment Center. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.1029.7951&rep=rep1&type=pdf
- SW-DONKI database. Available at: https://kauai.ccmc.gsfc.nasa.gov/DONKI/

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CCMC

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