Heliophysics Summer School – Magnetosphere LAB

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The purpose of this lab is the acquaint you with the 3 Global MHD models available at the CCMC for runs on request, and compare some of their outputs to see how well they agree with each other and with some empirical or analytic estimates. These models are:

1. The Lyon-Fedder-Mobary (LFM) Global MHD code developed by John Lyon of Darmouth College and collaborators.
2. The Open Geospace General Circulation Model (called OPENGGCM, or GGCM) developed by Jimmy Raeder of the University of New Hampshire.
3. The Space Weather Modeling Framework (SWMF/BATSRUS) developed at the University of Michigan.

For this exercise multiple runs of these models have been made with idealized solar wind input conditions for 2 hours, using a solar wind speed of v_{sw}=(200, 400, 600) km/s a density ρ_{SW}=5 particles/cc. The IMF magnetic field has been fixed with only a z-component of (-5,0,5) nT. The ionospheric model is also highly idealized using a range of values of uniform Pederson conductance and zero Hall conductance.

In principle these models should agree at some level, since they are all solving the same set of equations (MHD) for the same set of conditions.

A. Comparing Magnetopause standoff distance from Global MHD codes

From the lecture notes, the analytic standoff distance is estimated to be:

$$r_{so} = \frac{11.43 R_E}{(\rho_{SW} v_{SW}^2)^{1/6}} \left(\frac{f}{1.16}\right)^{1/3} \left(\frac{0.885}{k}\right)^{1/6} \qquad (1)$$

For a nominal solar wind speed of v_{sw}=400 km/s and density ρ_{SW}=5 particles/cc, the standoff distance is 10.9 R_E. For the CCMC runs, the solar wind density has been set to 5 particles/cc and so the standoff then scales as the negative 1/3 power of velocity.

$$r_{so} = \frac{10.9 R_E}{(v_{SW}(km/s)/400)^{1/3}} \qquad (2)$$

Expected results based on equation 2 are shown in the table below:

v_{SW} (km/s)	200	400	600
Analytic standoff distance (r_{so}) in R_e	13.7	10.9	9.5

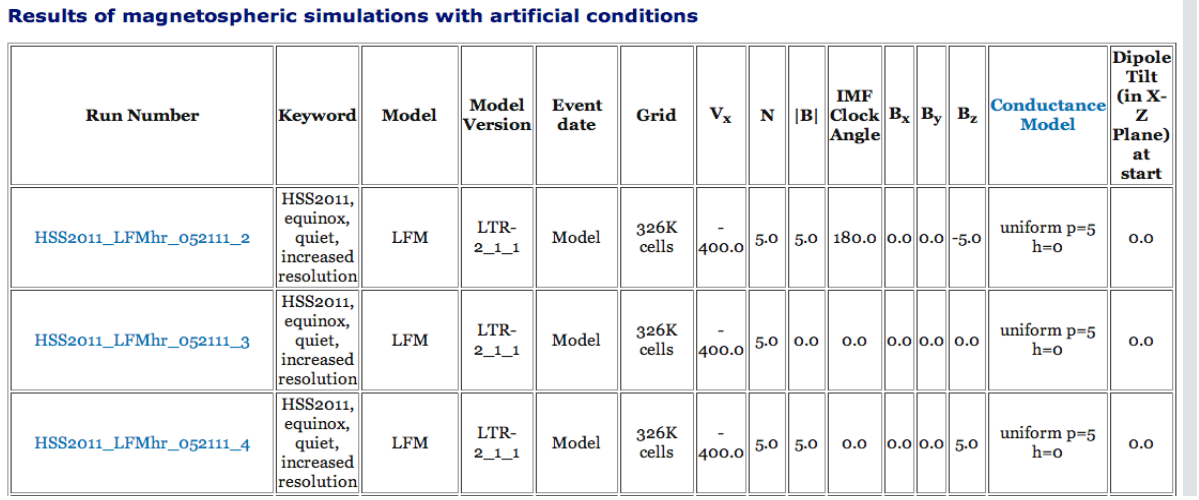
Table 1

This part of lab is then to plot and compare the actual MHD run results with the above table. The instructions are as follows:

1. Using your favorite browser, go to the HSS webpage: http://ccmc.gsfc.nasa.gov/support/HSS_2011.php
2. Under the magnetosphere subsection of the L1 to Geospace Section near the bottom of the page, select: Results of magnetospheric simulations with artificial conditions: http://ccmc.gsfc.nasa.gov/support/HSS_2011/results21.php
3. There you will find a rather large (and perhaps daunting) table listing a whole set of CCMC runs for the 3 models.
4. All of the runs are centered around what I call a default run, characterized by the following inputs

Solar Wind Speed v_x (km/s)	**Solar Wind density (particles/cc)**	**IMF Bz (nT)**	**Ionospheric Conductance (S)**	**Dipole tilt (degrees)**
400	5	5, 0 -5	5	0

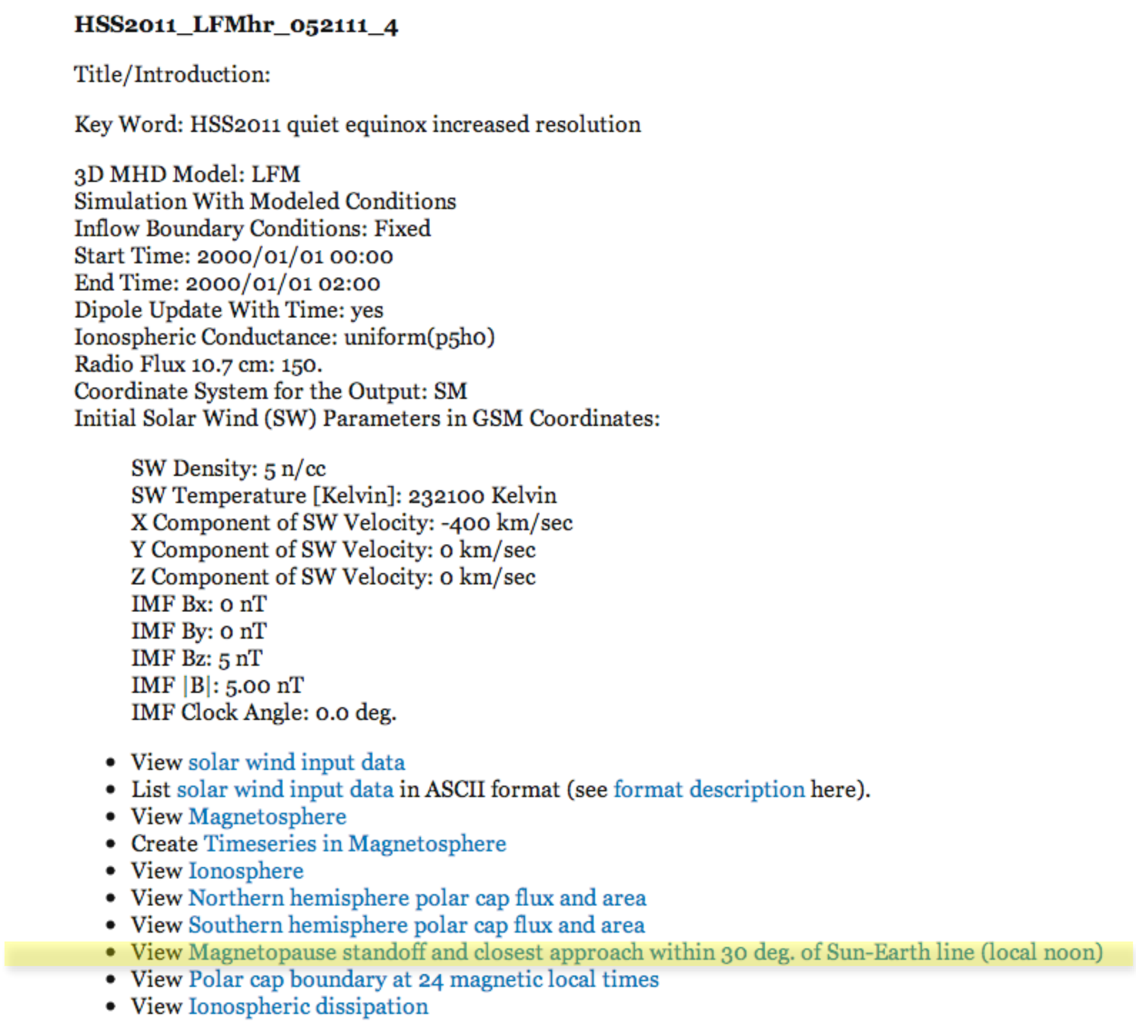
An example from the webpage for the LFM model is shown below



Results of magnetospheric simulations with artificial conditions

Run Number	Keyword	Model	Model Version	Event date	Grid	V_x	N	|B|	IMF Clock Angle	B_x	B_y	B_z	Conductance Model	Dipole Tilt (in X-Z Plane) at start
HSS2011_LFMhr_052111_2	HSS2011, equinox, quiet, increased resolution	LFM	LTR-2_1_1	Model	326K cells	-400.0	5.0	5.0	180.0	0.0	0.0	-5.0	uniform p=5 h=0	0.0
HSS2011_LFMhr_052111_3	HSS2011, equinox, quiet, increased resolution	LFM	LTR-2_1_1	Model	326K cells	-400.0	5.0	0.0	0.0	0.0	0.0	0.0	uniform p=5 h=0	0.0
HSS2011_LFMhr_052111_4	HSS2011, equinox, quiet, increased resolution	LFM	LTR-2_1_1	Model	326K cells	-400.0	5.0	5.0	0.0	0.0	0.0	5.0	uniform p=5 h=0	0.0

5. Now click on the third item HSS2011_LFMhr_052111_4 (http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_052111_4.php) which is the default run for +5 IMF Bz, you should get the following web page:



HSS2011_LFMhr_052111_4

Title/Introduction:

Key Word: HSS2011 quiet equinox increased resolution

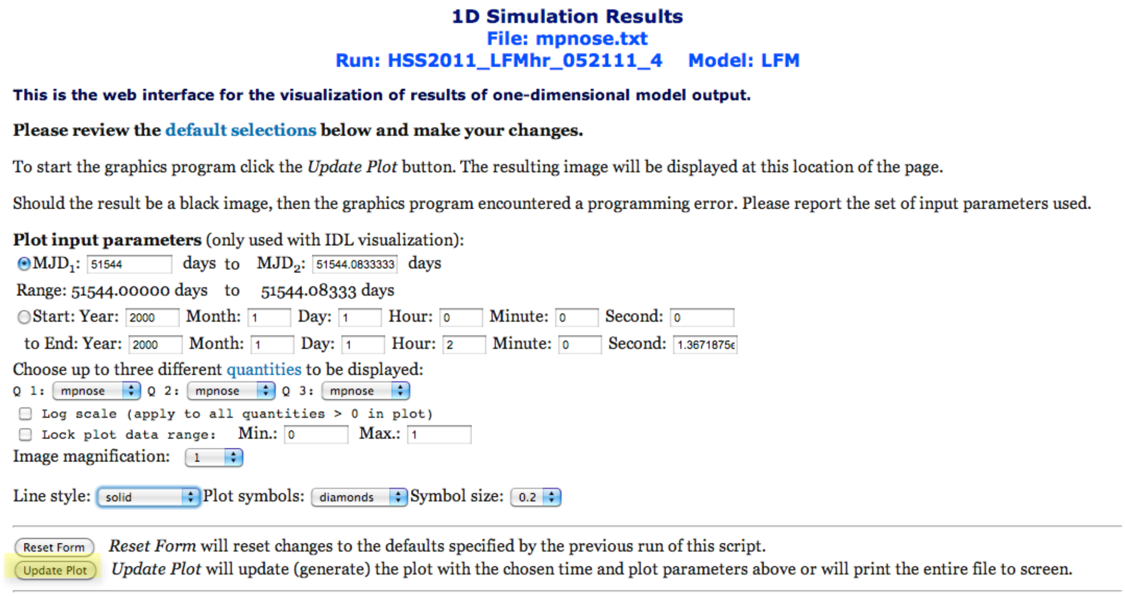
3D MHD Model: LFM
Simulation With Modeled Conditions
Inflow Boundary Conditions: Fixed
Start Time: 2000/01/01 00:00
End Time: 2000/01/01 02:00
Dipole Update With Time: yes
Ionospheric Conductance: uniform(p5h0)
Radio Flux 10.7 cm: 150.
Coordinate System for the Output: SM
Initial Solar Wind (SW) Parameters in GSM Coordinates:

SW Density: 5 n/cc
SW Temperature [Kelvin]: 232100 Kelvin
X Component of SW Velocity: -400 km/sec
Y Component of SW Velocity: 0 km/sec
Z Component of SW Velocity: 0 km/sec
IMF Bx: 0 nT
IMF By: 0 nT
IMF Bz: 5 nT
IMF |B|: 5.00 nT
IMF Clock Angle: 0.0 deg.

- View solar wind input data
- List solar wind input data in ASCII format (see format description here).
- View Magnetosphere
- Create Timeseries in Magnetosphere
- View Ionosphere
- View Northern hemisphere polar cap flux and area
- View Southern hemisphere polar cap flux and area
- View Magnetopause standoff and closest approach within 30 deg. of Sun-Earth line (local noon)
- View Polar cap boundary at 24 magnetic local times
- View Ionospheric dissipation

This lists all the salient features of the run with many options to plot and analyze the results.

6. We will use the results of the model to compute the standoff distance. Select the option: “View Magnetopause standoff and closest approach within 30 deg. of Sun-Earth line (local noon)”. (Third from the bottom). This will plot the standoff distance using an algorithm traces fieldlines to determine the open closed boundary (finding the boundary of fieldlines that are connected to the Earth, versus ones that are connected to the sun). You should then get the following page



1D Simulation Results
File: mpnose.txt
Run: HSS2011_LFMhr_052111_4 Model: LFM

This is the web interface for the visualization of results of one-dimensional model output.

Please review the default selections below and make your changes.

To start the graphics program click the *Update Plot* button. The resulting image will be displayed at this location of the page.

Should the result be a black image, then the graphics program encountered a programming error. Please report the set of input parameters used.

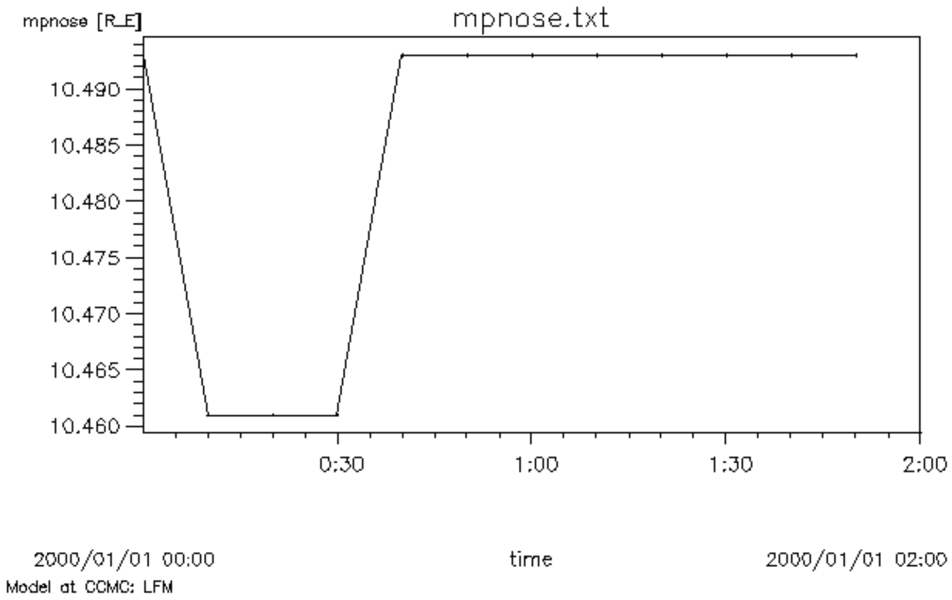
Plot input parameters (only used with IDL visualization):
● MJD$_1$: 51544 days to MJD$_2$: 51544.0833333 days
Range: 51544.00000 days to 51544.08333 days
○ Start: Year: 2000 Month: 1 Day: 1 Hour: 0 Minute: 0 Second: 0
to End: Year: 2000 Month: 1 Day: 1 Hour: 2 Minute: 0 Second: 1.3671875e
Choose up to three different quantities to be displayed:
Q 1: mpnose Q 2: mpnose Q 3: mpnose
☐ Log scale (apply to all quantities > 0 in plot)
☐ Lock plot data range: Min.: 0 Max.: 1
Image magnification: 1

Line style: solid Plot symbols: diamonds Symbol size: 0.2

Reset Form will reset changes to the defaults specified by the previous run of this script.

Update Plot will update (generate) the plot with the chosen time and plot parameters above or will print the entire file to screen.

7. Select a solid line style and hit the 'Update Plot' option, you should get a plot that looks like this:



The plot shows the position of the magnetopause as a function of simulation. The standoff distance at the end of this run is ~10.5 Re.

LFM **(**(Ionospheric conductance = 5 S, IMF Bz=5 nT)**)**

Solar Wind Speed v_x (km/s)	Run number/link	Standoff distance (R_e)
200	HSS2011_LFMhr_060311_1 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_060311_1.php	
400	HSS2011_LFMhr_052111_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_052111_4.php	10.5
600	HSS2011_LFMhr_060211_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_060211_4.php	

8. Now we will see what happens to the standoff distance when we vary the solar wind speed. Repeat steps 4-7 for the LFM for the following conditions and fill in the following table
9. Plot the standoff distance for the 3 runs and compare the results to Table 1 based on equation (2). [To make plots you can use whatever plotting tool you feel comfortable with, there is an online plotting tool called: graphtools.com (http://graphtools.com/line.html) that allows you to make line plots and save them.
10. [**Homework**] Repeat this exercise for the other 2 global MHD models (OpenGGCM and SWMF) and compare.

OpenGGCM All runs have a solar wind density of 5 particles/cc. **(**Ionospheric conductance = 5 S, IMF Bz=5 nT**)**

Solar Wind Speed v_x (km/s)	Run number/link	Standoff distance (R_e)
200	HSS2011_OpenGGCM_060311_1 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_060311_1.php	
400	HSS2011_OpenGGCM_052111_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_052111_4.php	
600	HSS2011_OpenGGCM_060211_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_060211_4.php	

SWMF (Important: There are several runs from SWMF using different resolutions, it is best to use the ones labeled: HSS2011, equinox, quiet, increased resolution. 3 M cells). **(**Ionospheric conductance = 5 S, IMF B_z=5 nT**)**

Solar Wind Speed v_x (km/s)	Run Number/link	Standoff distance (R_e)
200	HSS2011_SWMF_060311_1 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_060311_1.php	
400	HSS2011_SWMF_051111_4b http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_051111_4b.php	
600	HSS2011_SWMF_060211_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_060211_4.php	

11. Now we will repeat the exercise for the LFM, but with a different IMF Bz (-5 nT) and Ionospheric conductance of 5S.

Solar Wind Speed v_x (km/s)	Run Number/link	Standoff distance (R_e)
200	HSS2011_LFMhr_060211_1 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_060211_1.php	
400	HSS2011_LFMhr_052111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_052111_2.php	
600	HSS2011_LFMhr_060211_2 http://ccmc.gsfc.nasa.gov/databa\se_MHD/HSS2011_LFMhr_060211_2.php	

What do you notice about the standoff distance when the IMF Bz is negative? How does it compare to the analytic formula?

12. [**Homework**] Repeat the above exercise for the other 2 Global MHD models

OpenGGCM IMF B_z (-5 nT) and Ionospheric conductance of 5S.

Solar Wind Speed v_x (km/s)	Run Number/link	Standoff distance (R_e)
200	HSS2011_OpenGGCM_060211_1 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_060211_1.php	
400	HSS2011_OpenGGCM_052111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_052111_2.php	
600	HSS2011_OpenGGCM_060211_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_060211_2.php	

SWMF (Important: There are several runs from SWMF using different resolutions, it is best to use the ones labeled: HSS2011, equinox, quiet, increased resolution. 3 M cells). IMF Bz (-5 nT) and Ionospheric conductance of 5S.

Solar Wind Speed v_x (km/s)	Run Number/link	Standoff distance (R_e)
200	HSS2011_SWMF_060211_1 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_060211_1.php	
400	HSS2011_SWMF_051111_2b http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_051111_2b.php	
600	HSS2011_SWMF_060211_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_060211_2.php	

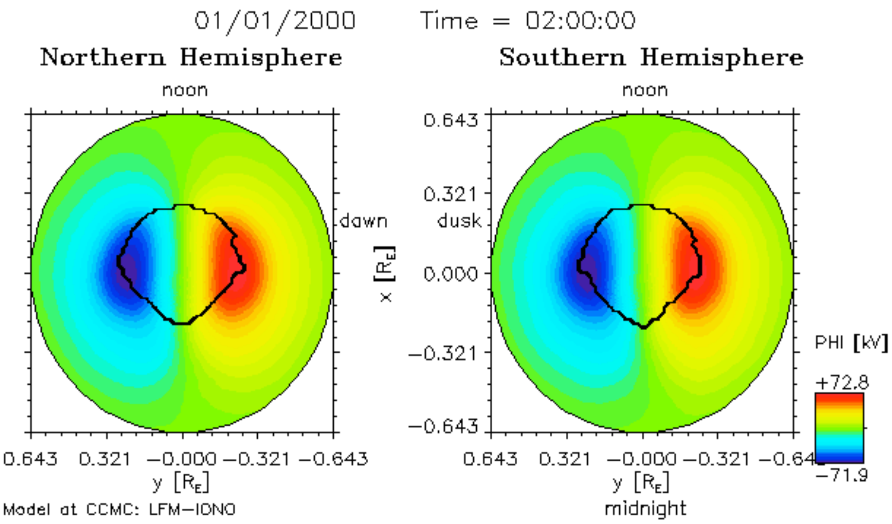
B. The effects of ionospheric conductance on the cross polar cap potential

In this section we will explore the effects of the ionosphere on the magnetosphere. During southward IMF, reconnection at the magnetopause drives convection in the ionosphere and the magnetosphere. A measure of the strength of the convection is the potential across the polar cap. We will find that the ionosphere plays a significant role in controlling the coupling of the solar wind to the magnetosphere.

1. Proceed again to the HSS runs on request site for the magnetosphere under artificial condition: http://ccmc.gsfc.nasa.gov/support/HSS_2011/results21.php
2. The runs we will look at here are for the following inputs for the LFM (v_x=-400km/s, IMF B_z=-5nT):

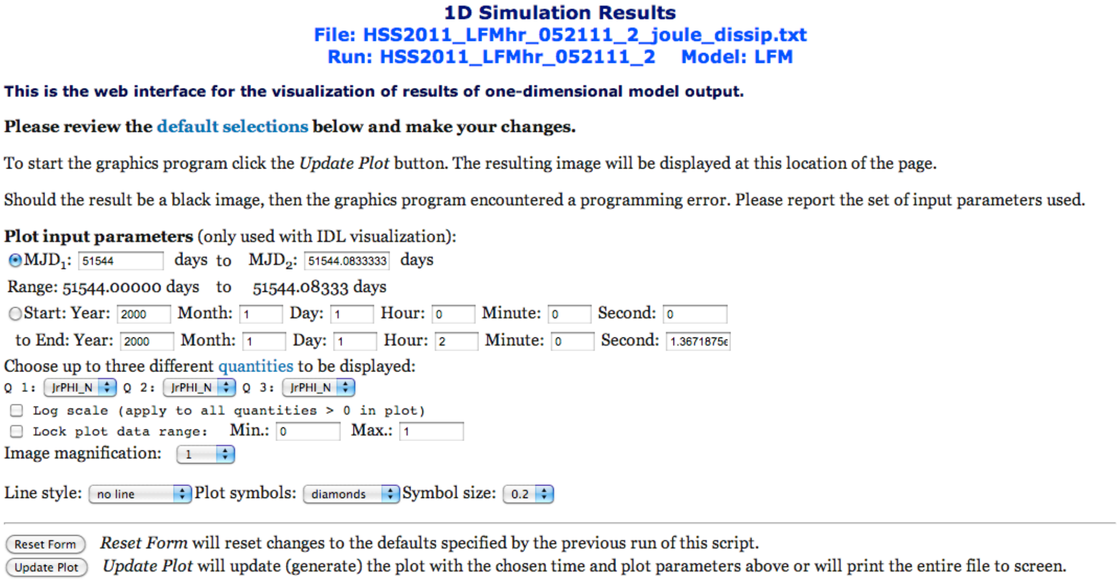
Ionospheric Conductance (S)	Run Label/links	Cross polar cap potential (kV)	Total current (mA)
2.5	HSS2011_LFMhr_053011_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_053011_2.php		
5	HSS2011_LFMhr_052111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_052111_2.php		
10	HSS2011_LFMhr_053111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_053111_2.php		

3. Select the LFM run HSS2011_LFMhr_052111_2 (which corresponds to the middle option in the above table).
4. If you select 'View Ionosphere' and plot the ionosphere (by pressing 'update plot'), you should get the following plot



It shows the potential contours (in color) and the open/closed boundary (dark line) in the ionospheres of the model. From the legend scale you can obtain the cross polar cap potential (72.8+71.9 ~ 145 kV).

5. But there is an easier way to get the cross polar cap potential. If you go back to the run (HSS2011_LFMhr_052111_2) and select 'ionospheric dissipation' (Bottom option), you should get the following screen:



1D Simulation Results
File: HSS2011_LFMhr_052111_2_joule_dissip.txt
Run: HSS2011_LFMhr_052111_2 Model: LFM

This is the web interface for the visualization of results of one-dimensional model output.

Please review the default selections below and make your changes.

To start the graphics program click the *Update Plot* button. The resulting image will be displayed at this location of the page.

Should the result be a black image, then the graphics program encountered a programming error. Please report the set of input parameters used.

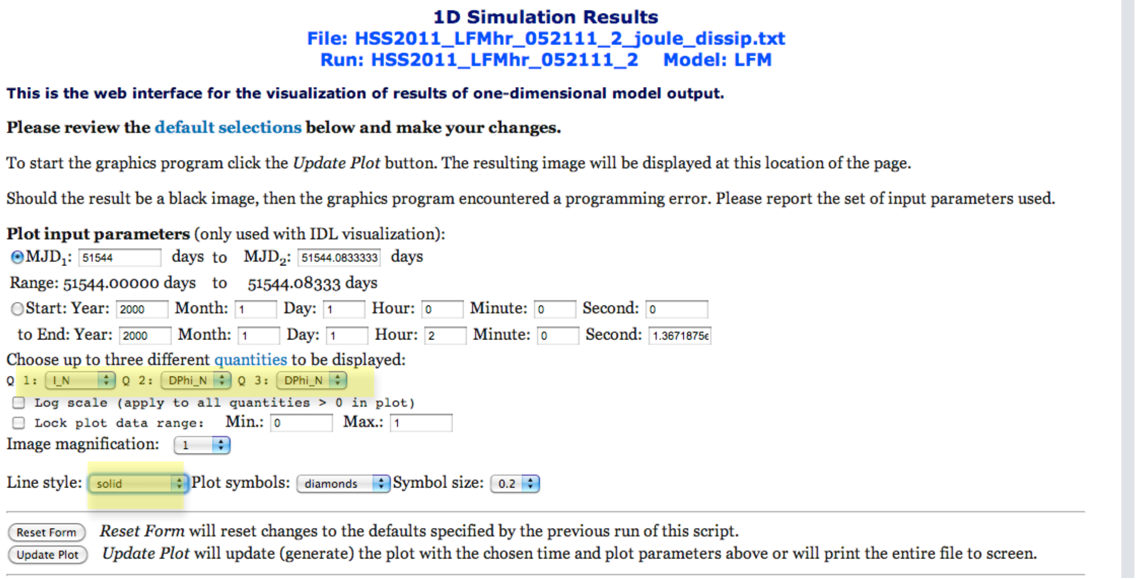
Plot input parameters (only used with IDL visualization):
● MJD$_1$: 51544 days to MJD$_2$: 51544.0833333 days
Range: 51544.00000 days to 51544.08333 days
○ Start: Year: 2000 Month: 1 Day: 1 Hour: 0 Minute: 0 Second: 0
to End: Year: 2000 Month: 1 Day: 1 Hour: 2 Minute: 0 Second: 1.3671875e
Choose up to three different quantities to be displayed:
Q 1: JrPHI_N Q 2: JrPHI_N Q 3: JrPHI_N
☐ Log scale (apply to all quantities > 0 in plot)
☐ Lock plot data range: Min.: 0 Max.: 1
Image magnification: 1

Line style: no line Plot symbols: diamonds Symbol size: 0.2

Reset Form will reset changes to the defaults specified by the previous run of this script.
Update Plot will update (generate) the plot with the chosen time and plot parameters above or will print the entire file to screen.

6. For the options to be displayed, select I_N (total current) and Dphi_N (cross polar cap potential). Also, under 'line style' select 'solid line'. Before hitting 'update plot', your screen should look something like

this:



1D Simulation Results
File: HSS2011_LFMhr_052111_2_joule_dissip.txt
Run: HSS2011_LFMhr_052111_2   Model: LFM

This is the web interface for the visualization of results of one-dimensional model output.

Please review the default selections below and make your changes.

To start the graphics program click the *Update Plot* button. The resulting image will be displayed at this location of the page.

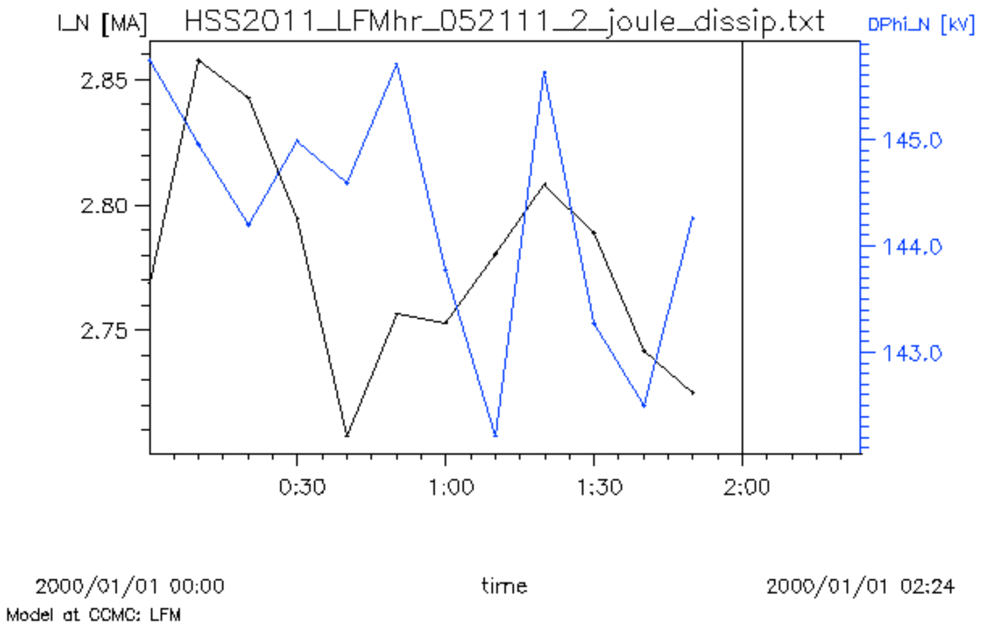
Should the result be a black image, then the graphics program encountered a programming error. Please report the set of input parameters used.

Plot input parameters (only used with IDL visualization):
● MJD$_1$: 51544 days to MJD$_2$: 51544.0833333 days
Range: 51544.00000 days to 51544.08333 days
○ Start: Year: 2000 Month: 1 Day: 1 Hour: 0 Minute: 0 Second: 0
to End: Year: 2000 Month: 1 Day: 1 Hour: 2 Minute: 0 Second: 1.3671875e
Choose up to three different quantities to be displayed:
Q 1: I_N Q 2: DPhi_N Q 3: DPhi_N
☐ Log scale (apply to all quantities > 0 in plot)
☐ Lock plot data range: Min.: 0 Max.: 1
Image magnification: 1
Line style: solid Plot symbols: diamonds Symbol size: 0.2

Reset Form will reset changes to the defaults specified by the previous run of this script.

Update Plot will update (generate) the plot with the chosen time and plot parameters above or will print the entire file to screen.

Once you update the plot you should get the following plot



From this, you can get the total cross polar cap potential (144 kV) and the total current (2.72 MA). Use this to fill in part of the table in part 2.

7. Repeat the above to fill in the table above.
8. Plot the total current (x-axis) versus potential from your table. What do you notice about the trend?
9. [**Homework**] Repeat the above for the OpenGGCM and SWMF and plot all 3 models as you did in part 8. Is there agreement?

OpenGGCM (v_x=-400km/s, IMF B_z=-5nT):

Ionospheric Conductance (S)	Run Label/links	Cross polar cap potential (kV)	Total current (mA)
2.5	HSS2011_OpenGGCM_053011_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_053011_2.php		
5	HSS2011_OpenGGCM_052111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_052111_2.php		
10	HSS2011_OpenGGCM_053111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_053111_2.php		

SWMF (v_x=-400km/s, IMF B_z=-5nT):

Ionospheric Conductance (S)	Run Label/links	Cross polar cap potential (kV)	Total current (mA)
2.5	HSS2011_SWMF_053011_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_053011_2.php		
5	HSS2011_SWMF_051111_2b http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_051111_2b.php		
10	HSS2011_SWMF_053111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_053111_2.php		

C. Variation of cross polar cap potential with IMF direction

In this section we will explore how well the models reproduce what effect changing the direction of the IMF has on the cross polar cap potential. We will basically be doing the same steps as in part 'B', but using the 5S conductance runs and varying the IMF. We will compare the model outputs to a well-known empirical model known as the Boyle Model (Boyle, C. B., P. H. Reiff, and M. R. Hairston (1997), Empirical polar cap potentials, *J. Geophys. Res.*, *102*(A1), 111–125, doi:10.1029/96JA01742.) The model is based on looking a many DMSP satellite passes and binning the cross polar cap potential versus solar wind conditions. They came up with a rather simple formula

$$\Phi_{Boyle}(kV) = 10^{-4}(v(km/s))^2 + 11.7|B|\sin^3\frac{\theta}{2} \qquad (3)$$

where v is the solar wind speed in km/s, B is the magnitude of the IMF, and θ is the angle the solar wind makes with the north pole (so that for a northward IMF, θ =0 and southward IMF θ =90°). For the cases we will be looking at the cross polar cap potential from the Boyle model is shown in the table below (v_x=-400km/s, IMF B_z=-5nT):

IMF B_z (nT)	Run Label/links	Cross polar cap potential from Boyle (kV)	Cross polar cap potential from LFM (kV)
5	HSS2011_LFMhr_052111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_052111_2.php	16	
0	HSS2011_LFMhr_052111_3 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_052111_3.php	16	
-5	HSS2011_LFMhr_052111_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_LFMhr_052111_4.php	74.5	

Note that we will be using the 5S conductance runs, but in reality the real ionosphere is more complex and variable so the comparison is not quite fair. Nevertheless it is interesting to see if the overall trends are comparable. Note also, that for the case of IMF Bz=0, the Boyle model predicts a non-zero cross polar cap potential. This is attributed to the so-call viscous interaction (not reconnection) and it is interesting to see if the MHD models have the same behavior. Note also that for the simple case done here the Boyle formula predicts the same potential for northward IMF as for zero IMF. Your task then is to fill in the table for the LFM and plot the 2 results.

[**Homework**] Complete the table to include the other 2 MHD models.

OpenGGCM: (v_x=-400km/s, IMF B_z=-5nT, Conductance=5S):

IMF B_z (nT)	Run Label/links	Cross polar cap potential from Boyle (kV)	Cross polar cap potential from OpenGGCM (kV)
5	HSS2011_OpenGGCM_052111_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_052111_4.php	16	
0	HSS2011_OpenGGCM_052111_3 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_052111_3.php	16	
-5	HSS2011_OpenGGCM_052111_2 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_OpenGGCM_052111_2.php	74.5	

SWMF: (v_x=-400km/s, IMF B_z=-5nT, Conductance=5S):

IMF B_z (nT)	**Run Label/links**	**Cross polar cap potential from Boyle (kV)**	**Cross polar cap potential from SWMF (kV)**
5	HSS2011_SWMF_060211_4 http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_060211_4.php	16	
0	HSS2011_SWMF_051111_3b http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_051111_3b.php	16	
-5	HSS2011_SWMF_051111_2b http://ccmc.gsfc.nasa.gov/database_MHD/HSS2011_SWMF_051111_2b.php	74.5	

Make a plot as you did above to include these models. How do they compare?

[**Homework – optional**] There are lots of other comparisons you can make, for example.

1. Repeat the conductance dependence runs but for the cases when the IMF B_z is 5 nT and 0.

2. In ideal steady MHD, the magnetic field lines are equipotentials. To see how well this is satisfied in the MHD codes it is interesting to compare the cross polar cap potential in the ionosphere versus the potential drop in the magnetosphere. To this end, make a plot of E_y in the MHD code across a line of constant x in the equatorial plane and estimate the potential by integrating Ey, ie, $\Phi = \int E_y \, dy$ and compare that to the cross polar cap potential.

3. There are 3 runs for IMF Bz=-5 in which a realistic (auroral) conductance were use. Repeat the comparison with the Boyle model for these 3 runs. The runs are: HSS2011_LFM_051111_1, HSS2011_OpenGGCM_051111_1, HSS2011_SWMF_051111_1

4. There are sets of runs using different solvers and resolutions (e.g., for SWMF there are runs using the high order Sokolov Solver (mc3 limiter) versus the default Rusanov solver used for CCMC runs (minmod limiter). Compare the results you get for these runs. What you should find for the case of the SWMF; that the cross polar cap potential increases with resolution and order of the solver. For a discussion of this see: Ridley, A. J., Gombosi, T. I., Sokolov, I. V., Toth, G., & Welling, D. T. (2010). Numerical considerations in simulating the global magnetosphere. Annales Geophysicae, 28(8), 1589–1614. doi:10.5194/angeo-28-1589-2010.