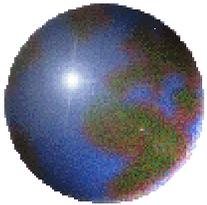
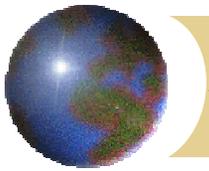


Effect of Multiple Substorms on Buildup of the Ring Current



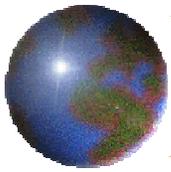
Kristi A. Keller, Mei-Ching Fok, Ayris Falasca, Michael Hesse, Lutz Rastaetter, Maria M. Kuznetsova
Goddard Space Flight Center

Tamas I. Gombosi, Darren L. DeZeeuw
University of Michigan



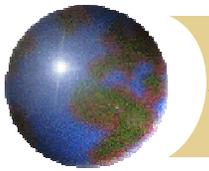
Outline

- Description of Models
- Results of Three Different Cases
- Analysis of Energization Mechanisms



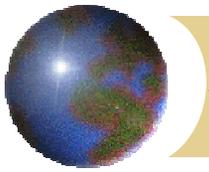
BATSRUS Information

- BATSRUS solves the ideal MHD equations using an adaptive mesh. In this run the smallest resolution was $1/8 R_E$. After the initial setup, the grid was fixed.
- The box was from -255 to $33 R_E$ in the GSM x direction and -48 to $48 R_E$ in the other two directions.
- The FACs at $4 R_E$ are mapped along dipole field lines to the ionosphere to calculate the electrostatic potential in the ionosphere.



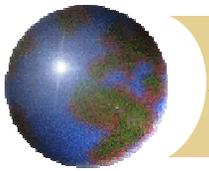
Fok Model

- The Fok Ring Current Model calculates the evolution of the ring current particle fluxes by solving a bounce-averaged Boltzmann transport equation.
- The model uses a combined drift-diffusion approach.
 - The particle drift terms include gradient-curvature drift and $E \times B$ drift (includes corotation and the ionospheric electric field).
 - The diffusion term is radial diffusion.
- The model also calculates losses due to charge exchange.

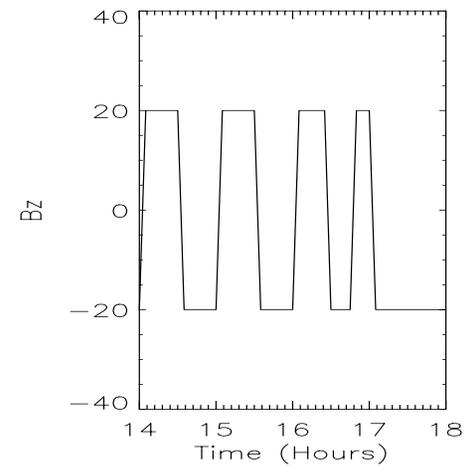
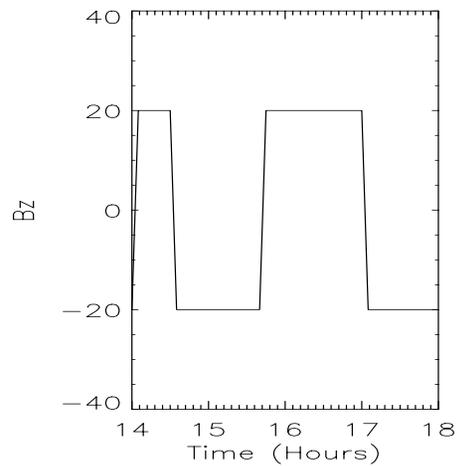
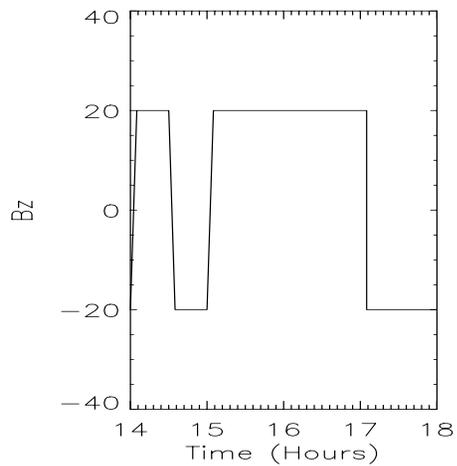
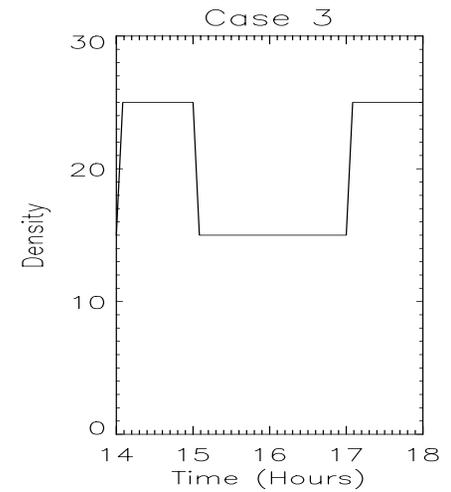
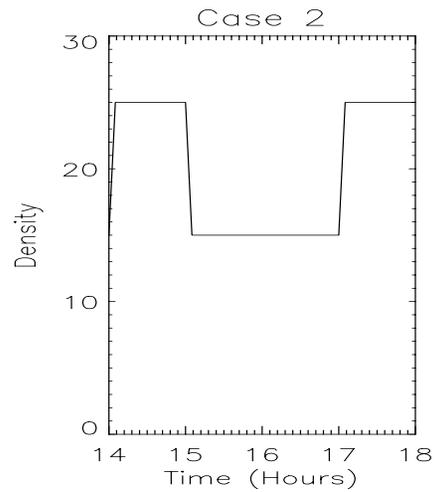
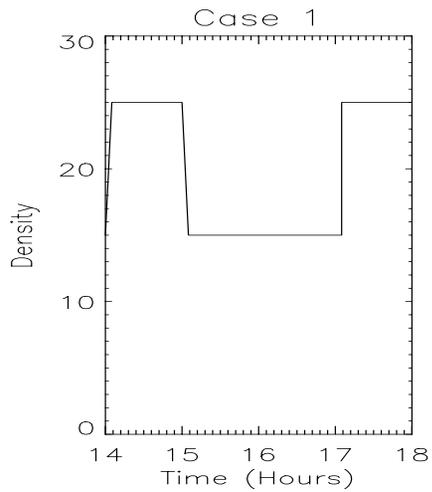


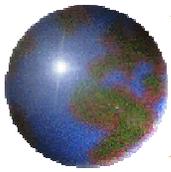
Fok Model

- The Fok Ring Current Model uses the ionospheric potential and magnetic field from the BATSRUS model.
- The Fok Ring Current Model uses the density and temperature from the BATSRUS model at the Ring Current Model's outer boundary.
- The pitch-angle distribution at the model's outer boundary is assumed to be isotropic.
- For the initial source population, the energy distribution is assumed to be a Kappa distribution.

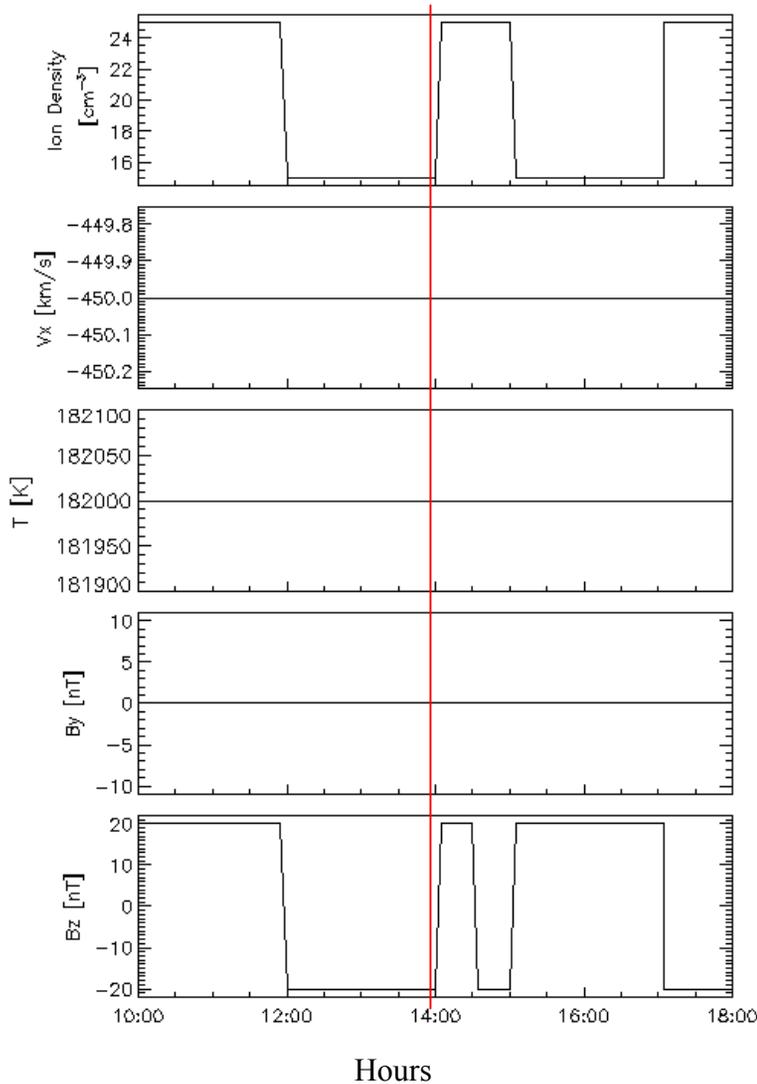


Solar Wind Input



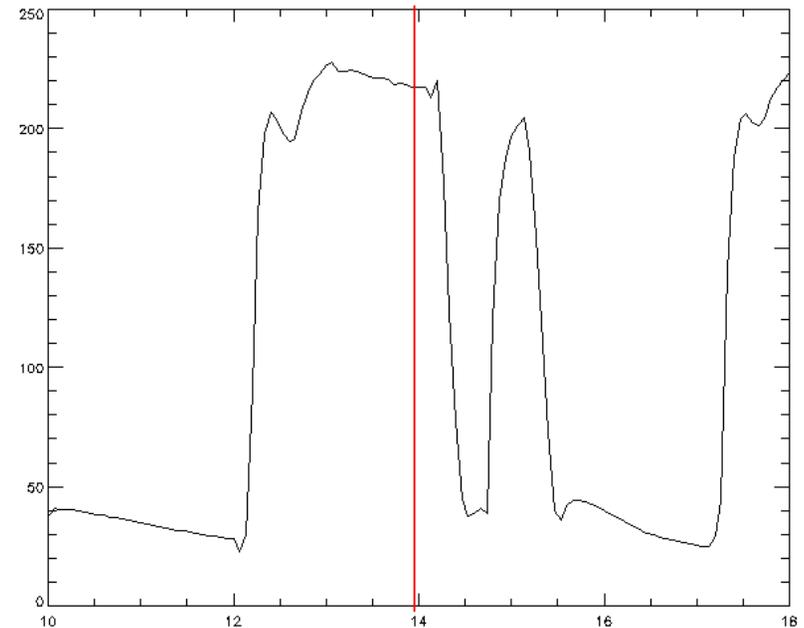


Run with Model Solar Wind Conditions Case 1



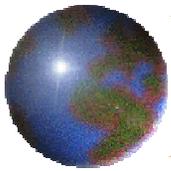
Cross Polar Cap Potential in Northern Hemisphere

ϕ (kV)



Universal Time (hours)

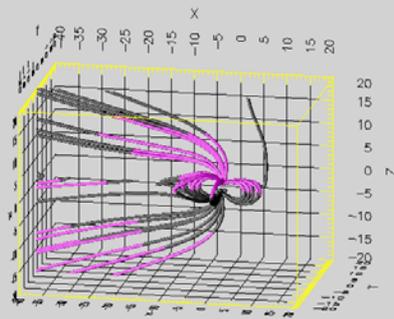
The period before the red line corresponds to a “warm-up” period for the ring current.



Magnetosphere Case 1

Space Weather Explorer

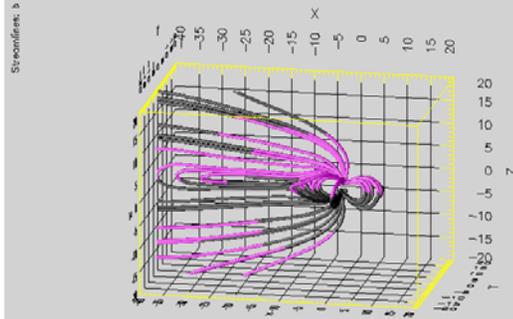
03/21/2002
14:08:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_060403_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

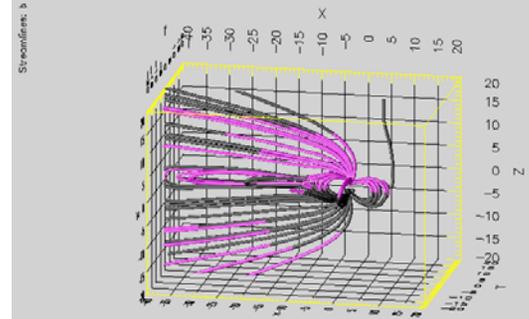
03/21/2002
14:52:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_060403_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

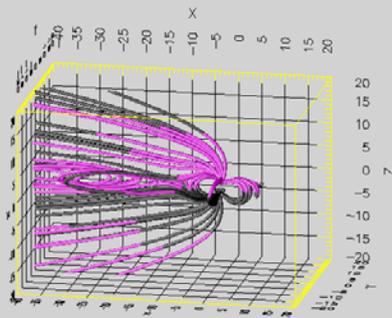
03/21/2002
14:56:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_060403_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

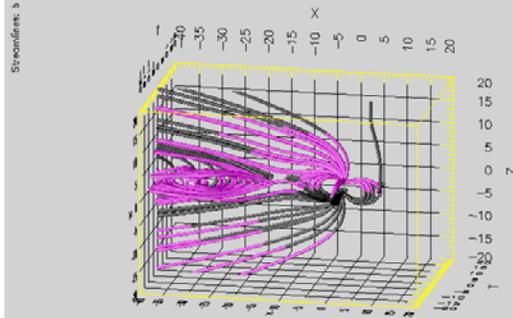
03/21/2002
15:00:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_060403_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

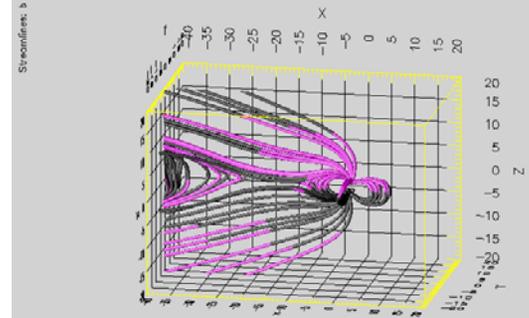
03/21/2002
15:04:00



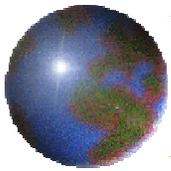
Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_060403_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

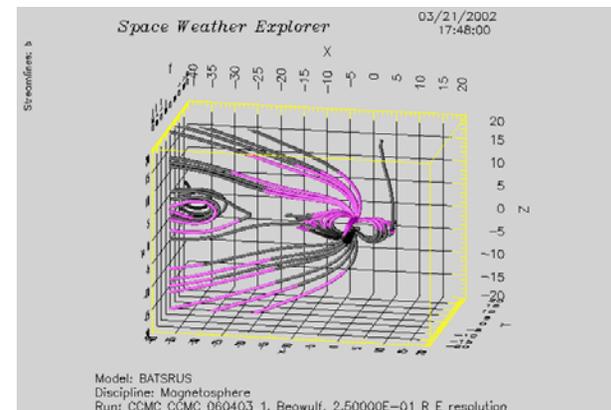
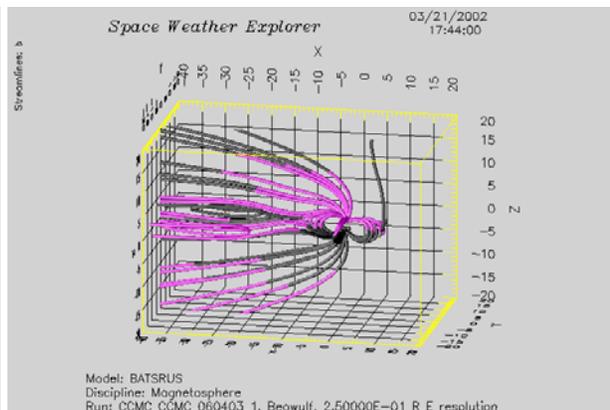
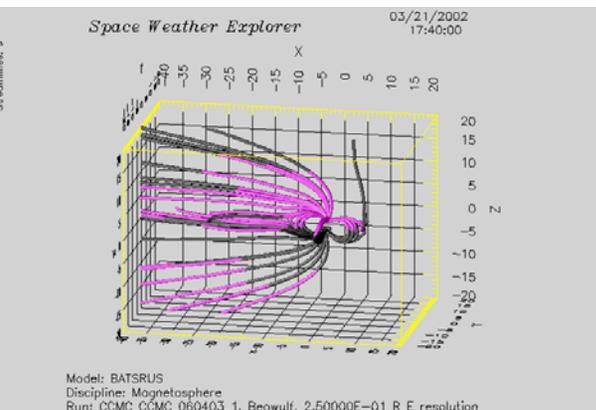
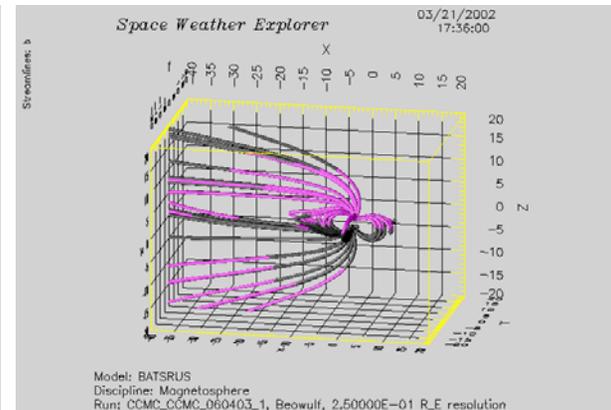
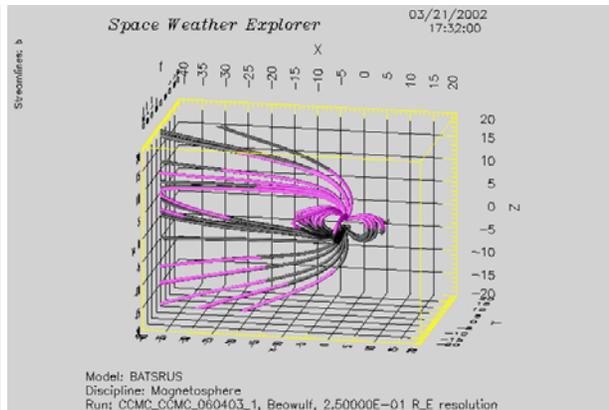
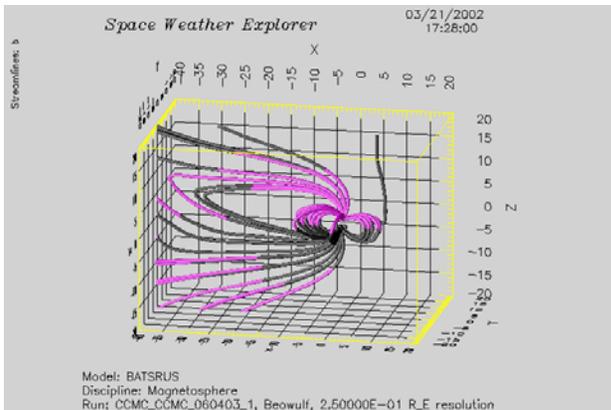
03/21/2002
15:08:00

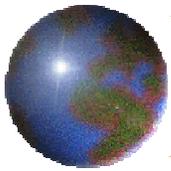


Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_060403_1, Beowulf, 2.50000E-01 R_E resolution



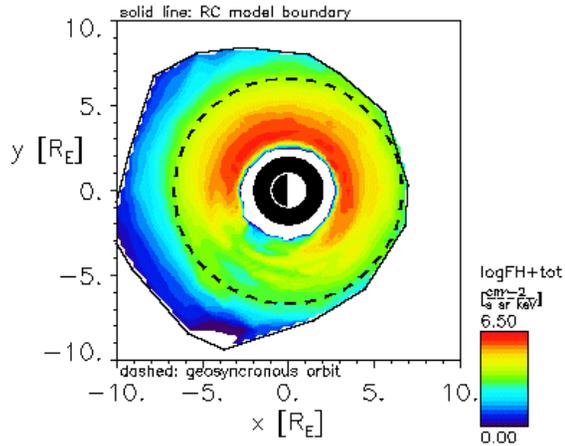
Magnetosphere Case 1



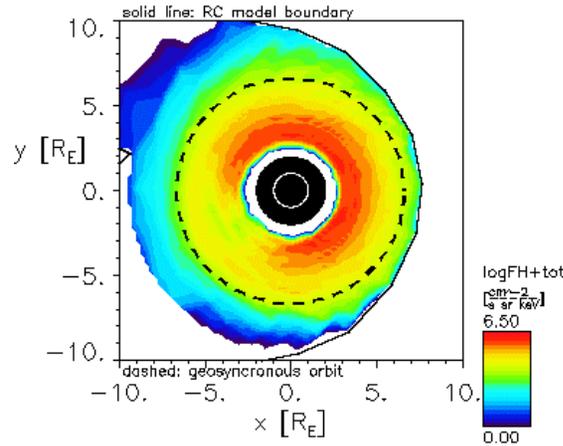


Ring Current Case 1

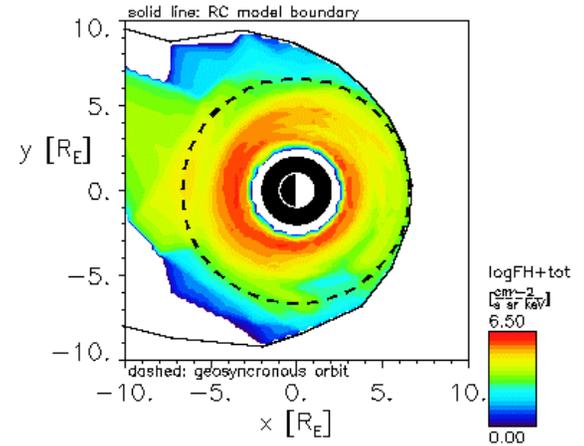
03/21/2002 Time = 14:00:00 En.= 150.keV



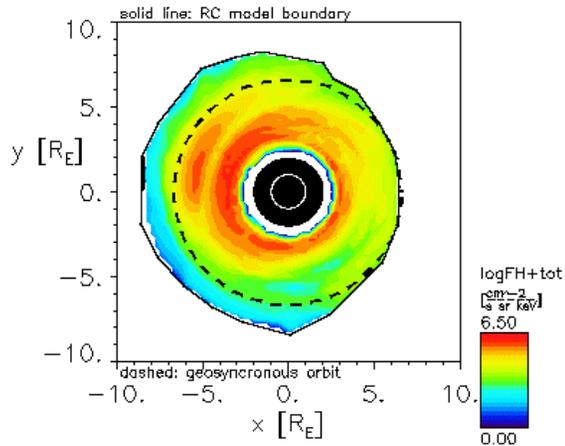
03/21/2002 Time = 14:31:59 En.= 150.keV



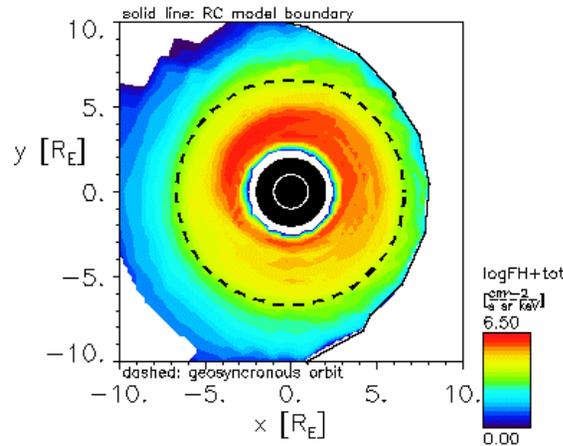
03/21/2002 Time = 15:04:01 En.= 150.keV



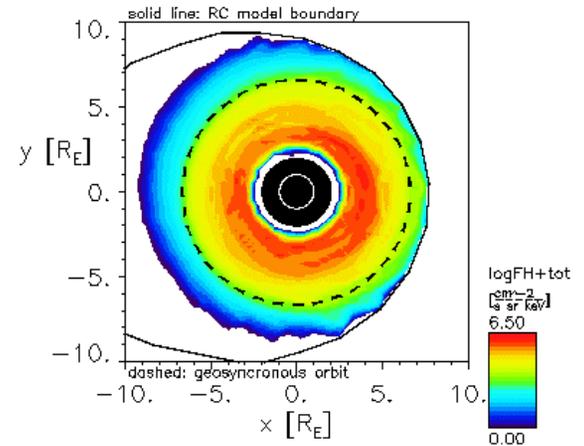
03/21/2002 Time = 15:07:59 En.= 150.keV

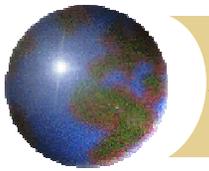


03/21/2002 Time = 15:31:59 En.= 150.keV



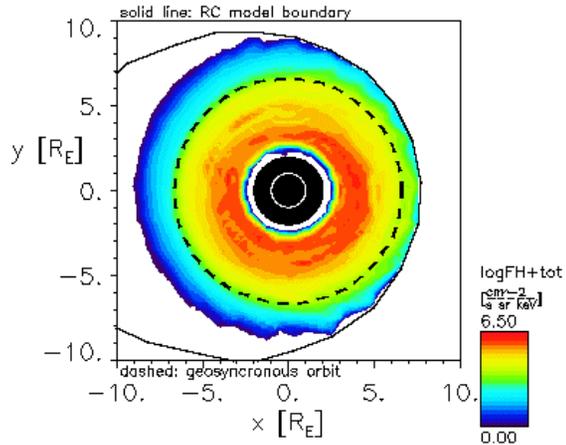
03/21/2002 Time = 16:12:00 En.= 150.keV



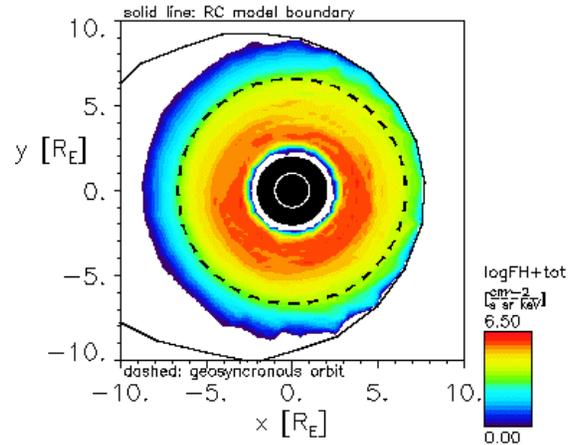


Ring Current Case 1

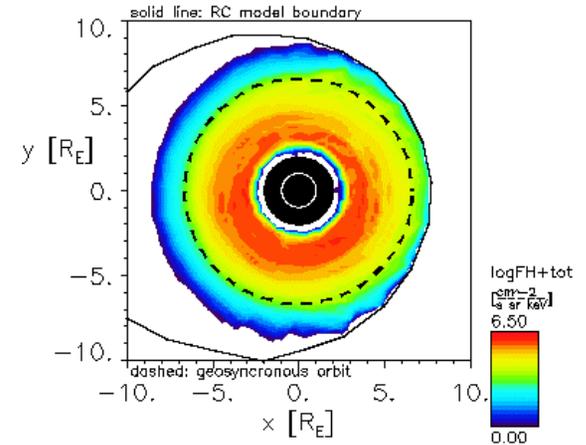
03/21/2002 Time = 16:18:01 En.= 150.keV



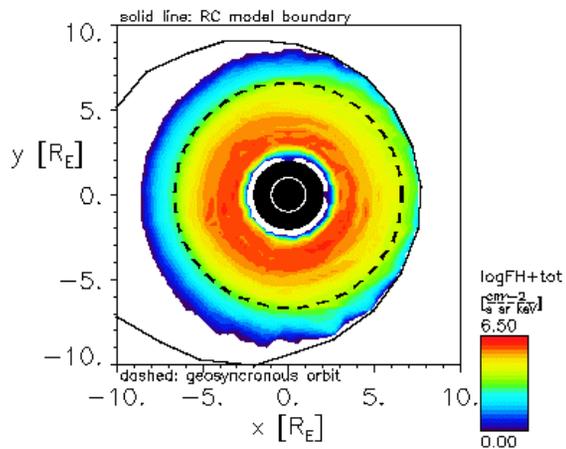
03/21/2002 Time = 16:24:00 En.= 150.keV



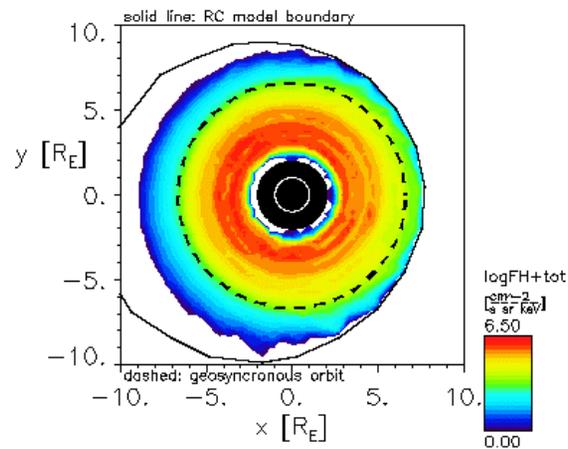
03/21/2002 Time = 16:31:59 En.= 150.keV



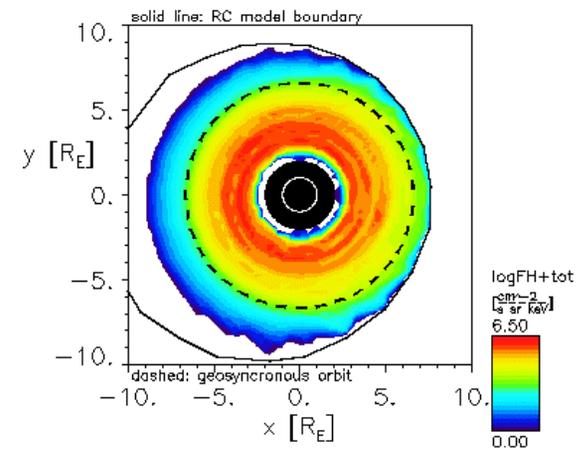
03/21/2002 Time = 16:40:01 En.= 150.keV

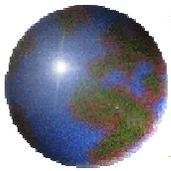


03/21/2002 Time = 17:07:59 En.= 150.keV



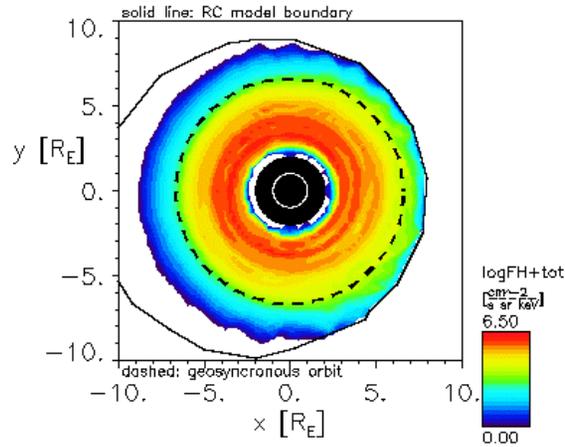
03/21/2002 Time = 17:12:00 En.= 150.keV



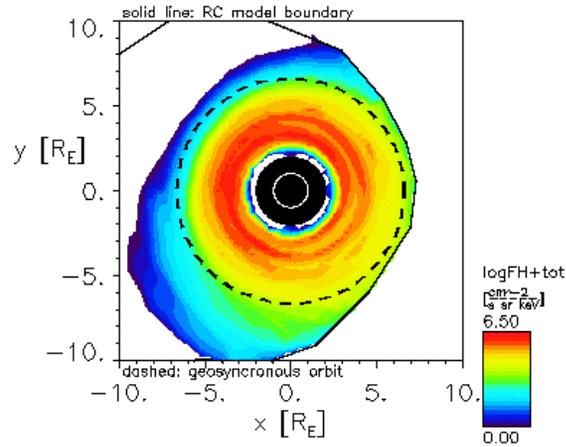


Ring Current Case 1

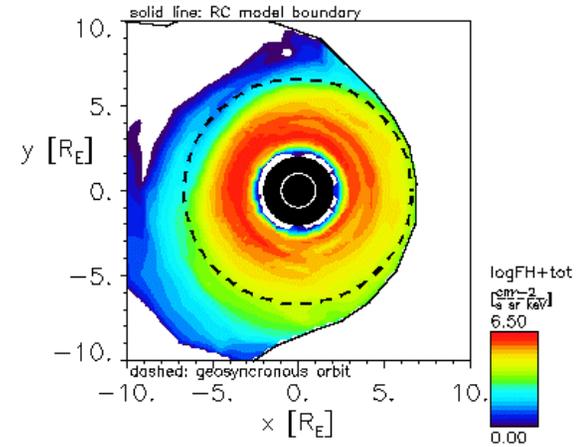
03/21/2002 Time = 17:19:59 En.= 150.keV



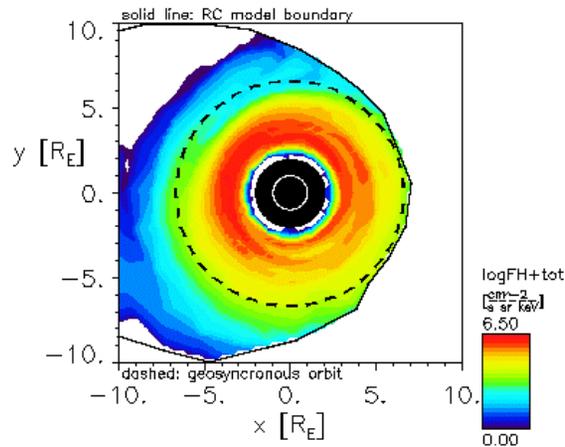
03/21/2002 Time = 17:28:01 En.= 150.keV



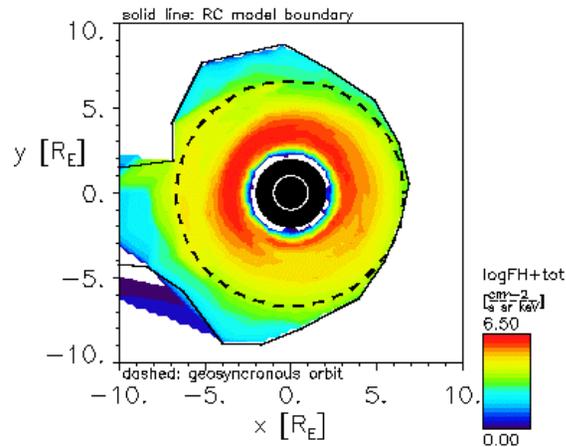
03/21/2002 Time = 17:31:59 En.= 150.keV



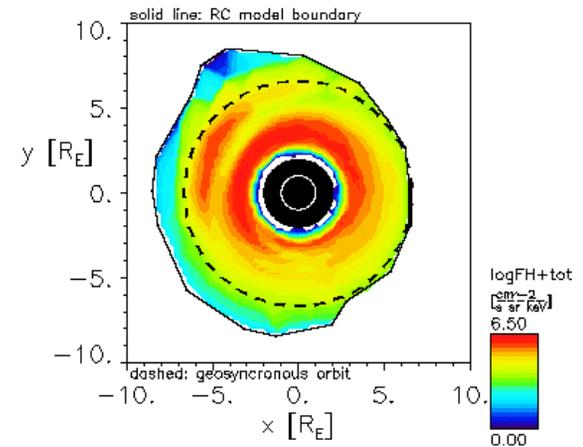
03/21/2002 Time = 17:38:00 En.= 150.keV

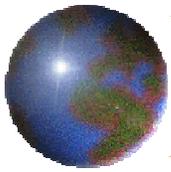


03/21/2002 Time = 17:43:59 En.= 150.keV



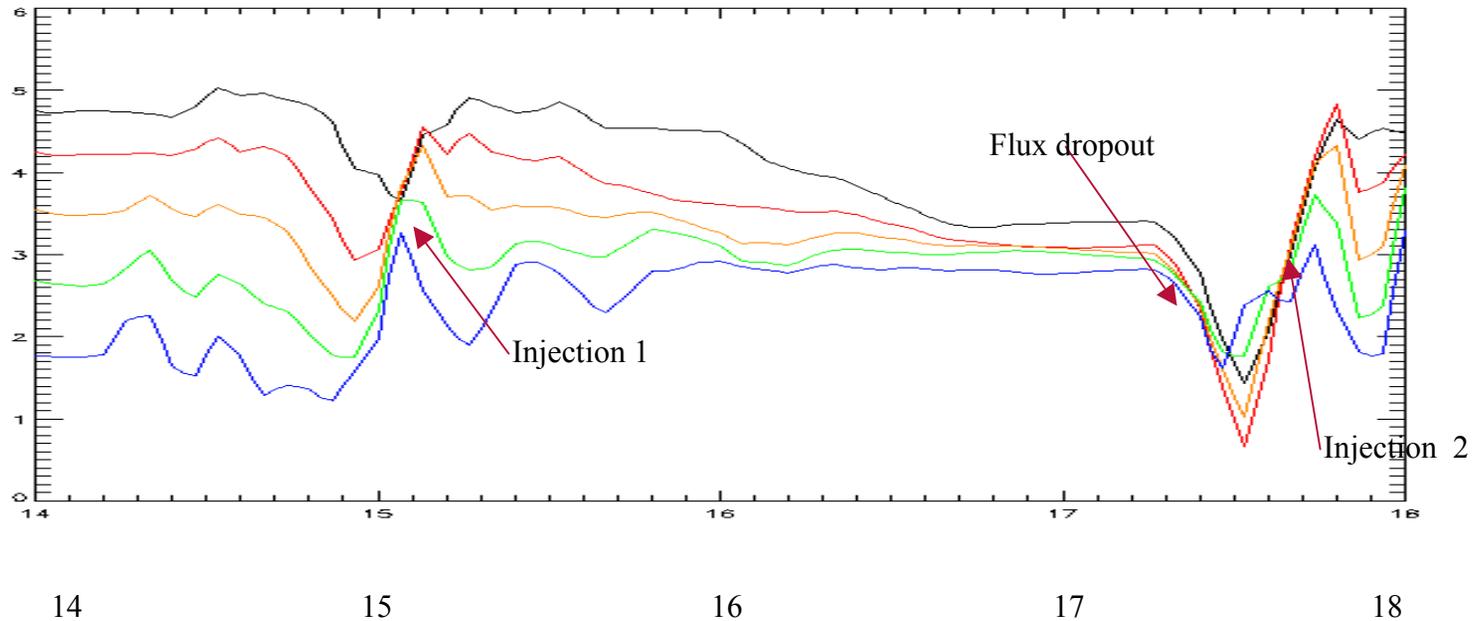
03/21/2002 Time = 17:48:00 En.= 150.keV





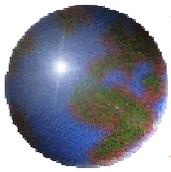
Log (Model Proton Flux) at 21:00 MLT for Case 1 at Geosynchronous Orbit

Log (Model Proton Flux)
(#/cm²/s/sr/keV)

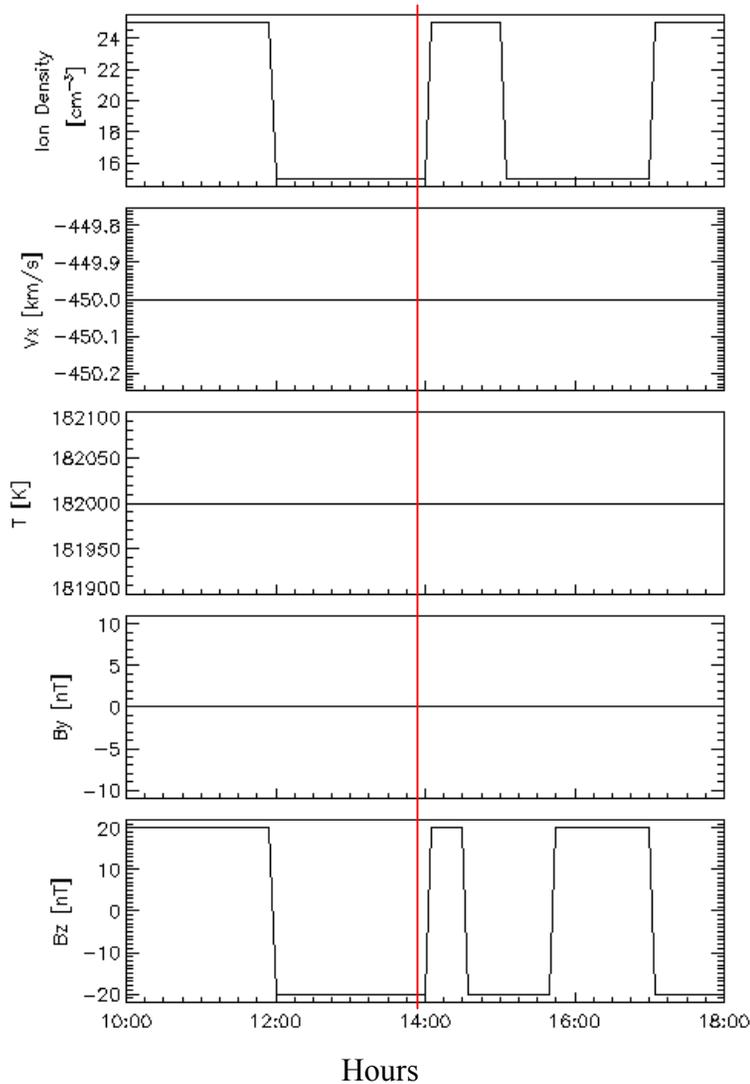


Energies (keV):

62.5 black 94 red 141.5 orange 210 green 300 blue

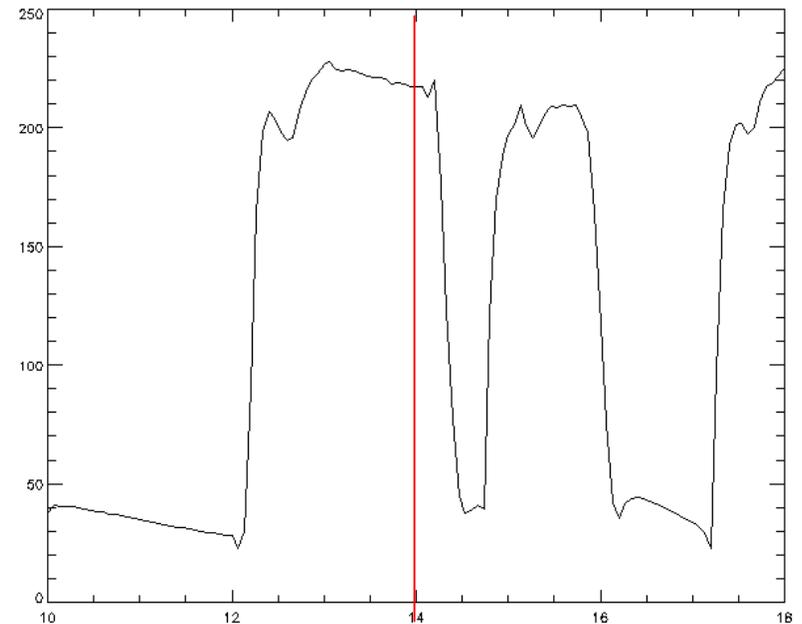


Run with Model Solar Wind Conditions Case 2



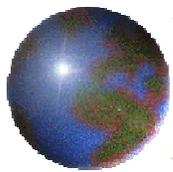
Cross Polar Cap Potential in Northern Hemisphere

ϕ (kV)



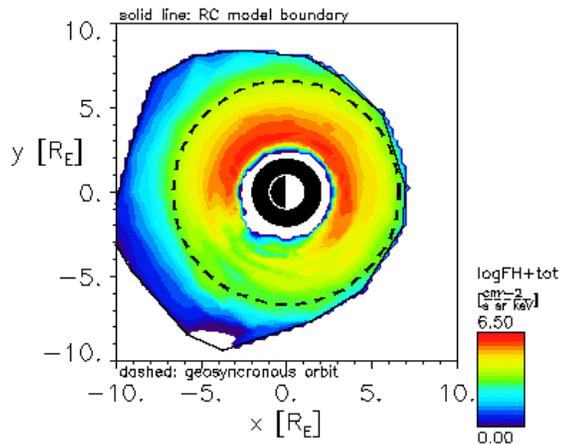
Universal Time (hours)

The period before the red line corresponds to a “warm-up” period for the ring current.

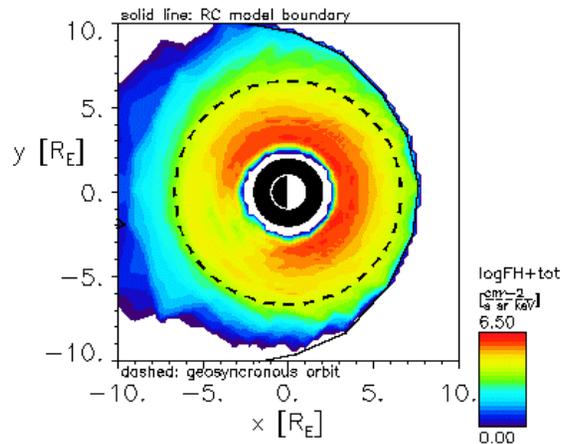


Ring Current Case 2

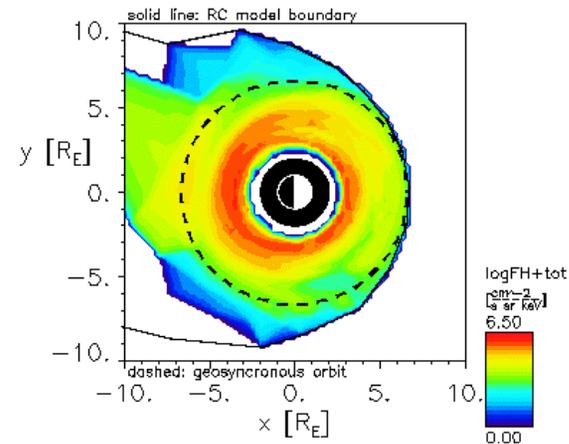
03/21/2002 Time = 14:00:00 En.= 150.keV



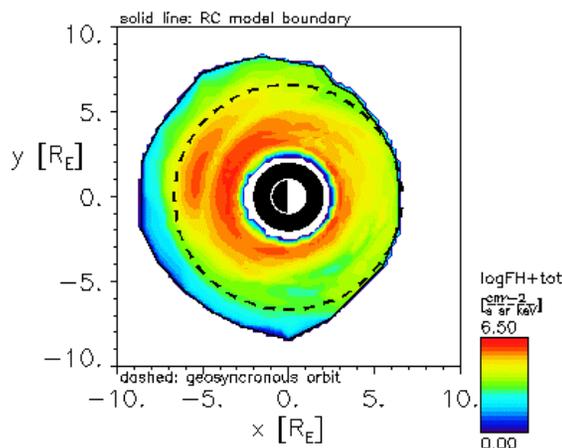
03/21/2002 Time = 14:31:59 En.= 150.keV



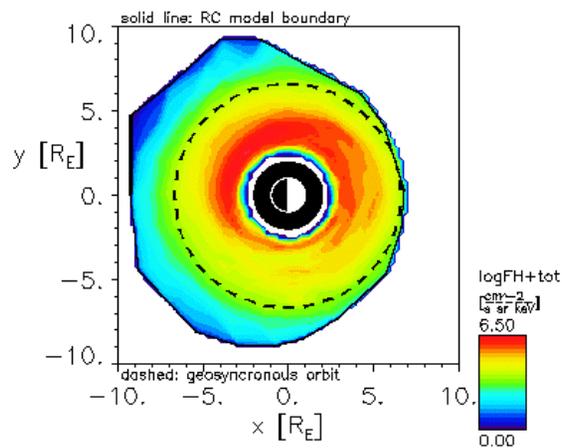
03/21/2002 Time = 15:04:01 En.= 150.keV



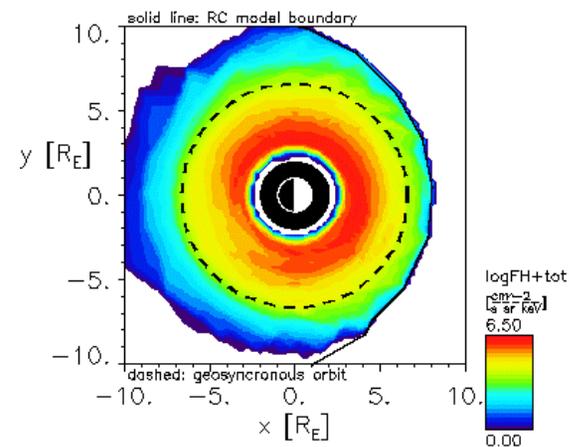
03/21/2002 Time = 15:07:59 En.= 150.keV

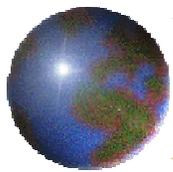


03/21/2002 Time = 15:31:59 En.= 150.keV



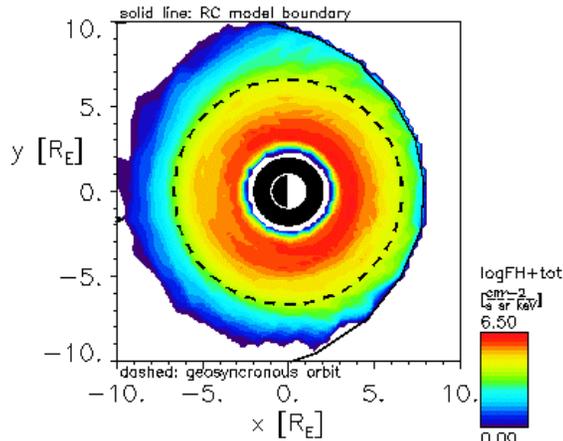
03/21/2002 Time = 16:12:00 En.= 150.keV



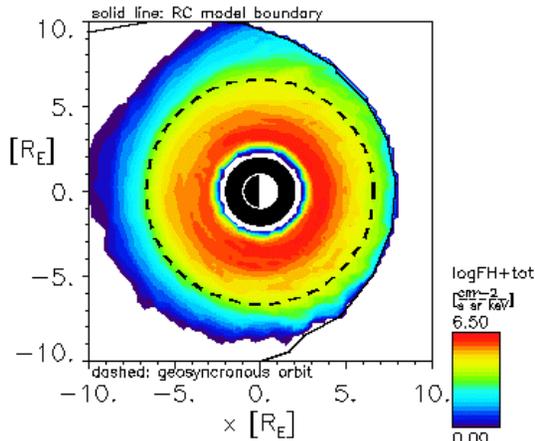


Ring Current Case 2

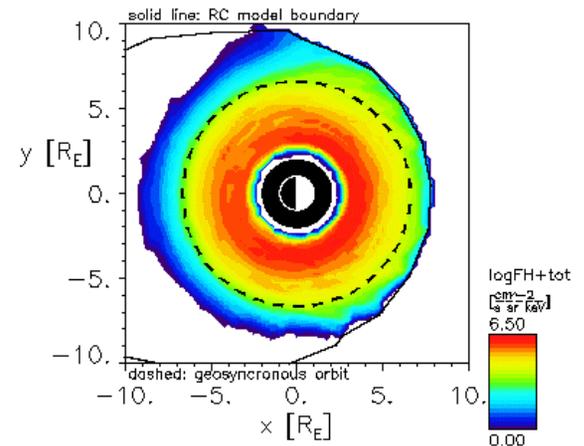
03/21/2002 Time = 16:19:59 En.= 150.keV



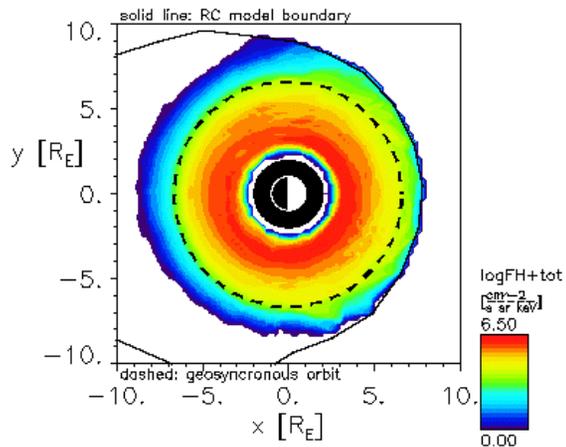
03/21/2002 Time = 16:24:00 En.= 150.keV



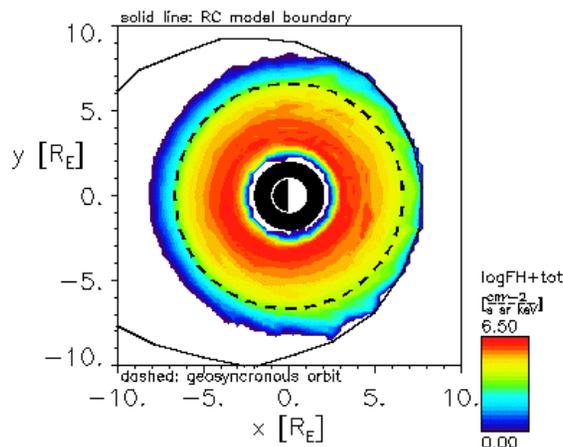
03/21/2002 Time = 16:31:59 En.= 150.keV



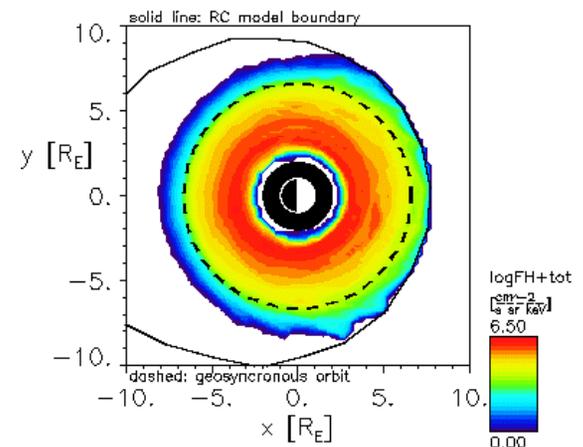
03/21/2002 Time = 16:40:01 En.= 150.keV

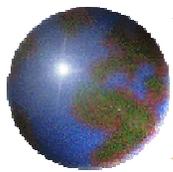


03/21/2002 Time = 17:07:59 En.= 150.keV



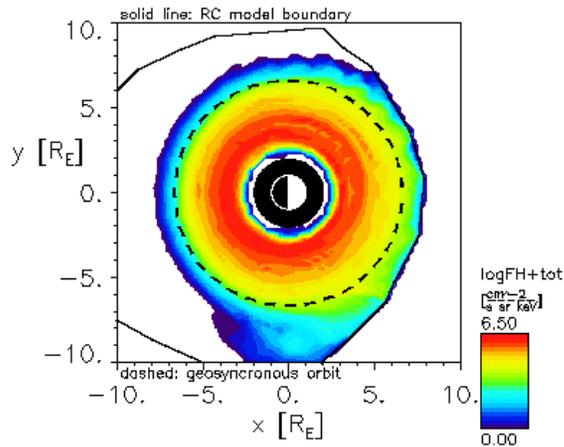
03/21/2002 Time = 17:12:00 En.= 150.keV



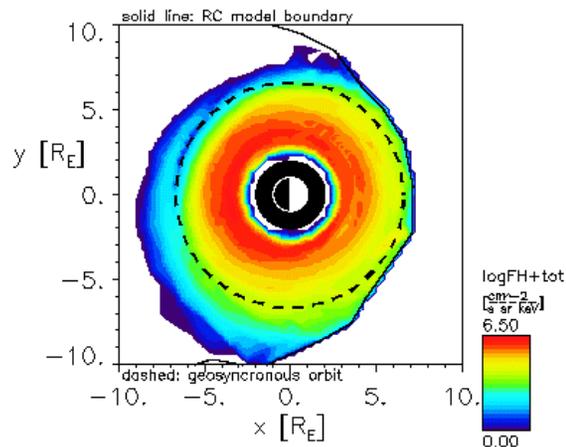


Ring Current Case 2

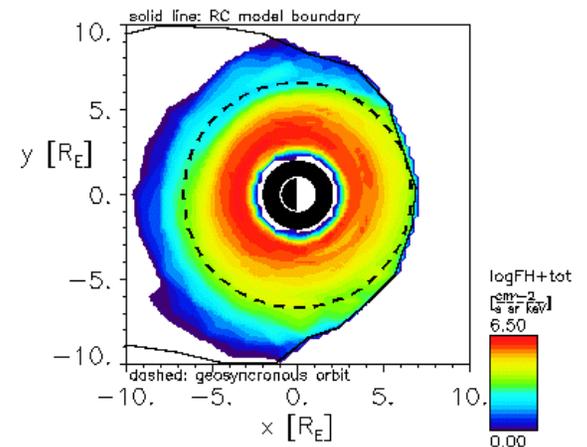
03/21/2002 Time = 17:19:59 En.= 150.keV



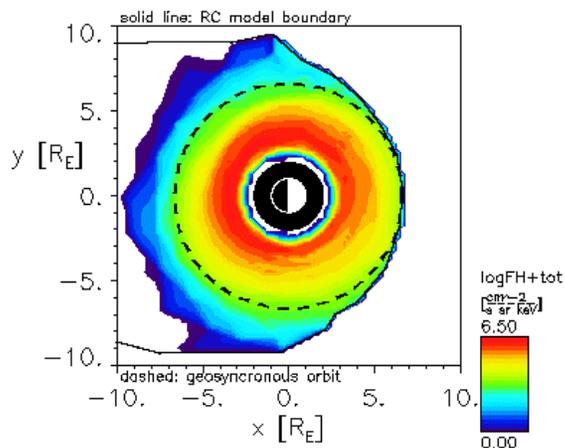
03/21/2002 Time = 17:28:01 En.= 150.keV



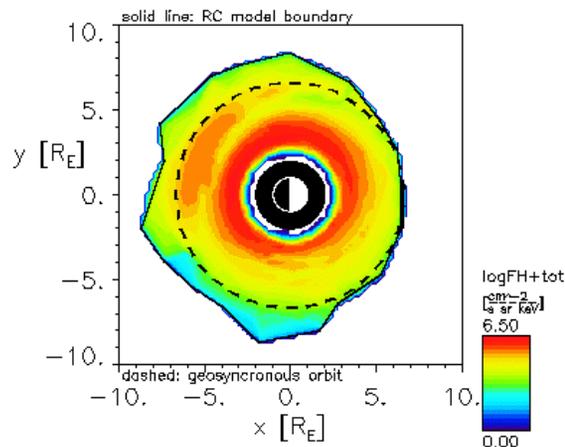
03/21/2002 Time = 17:31:59 En.= 150.keV



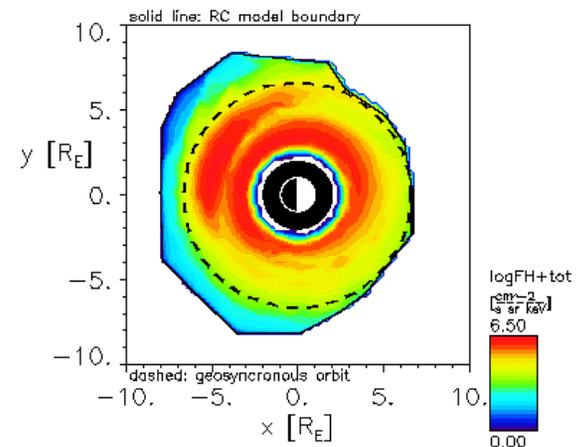
03/21/2002 Time = 17:38:00 En.= 150.keV

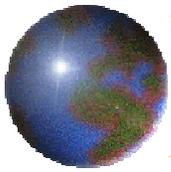


03/21/2002 Time = 17:43:59 En.= 150.keV



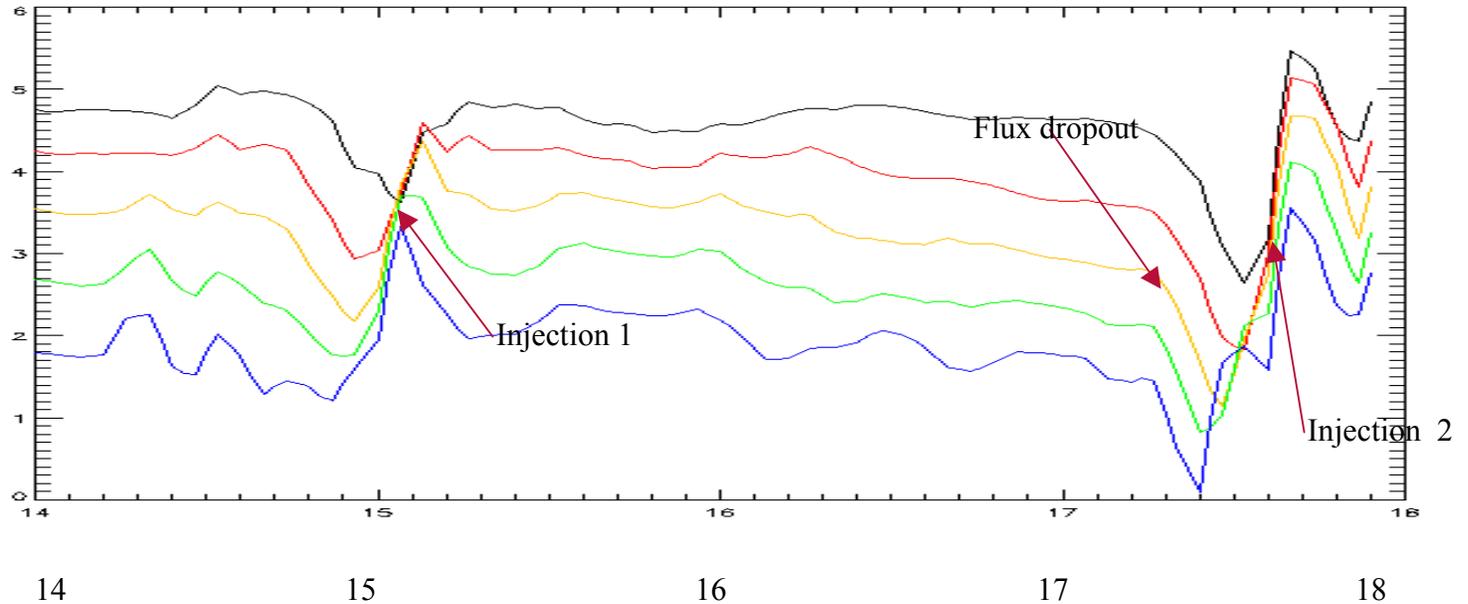
03/21/2002 Time = 17:48:00 En.= 150.keV





Log (Model Proton Flux) at 21:00 MLT for Case 2 at Geosynchronous Orbit

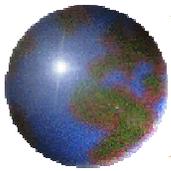
Log (Model Proton Flux)
(#/cm²/s/sr/keV)



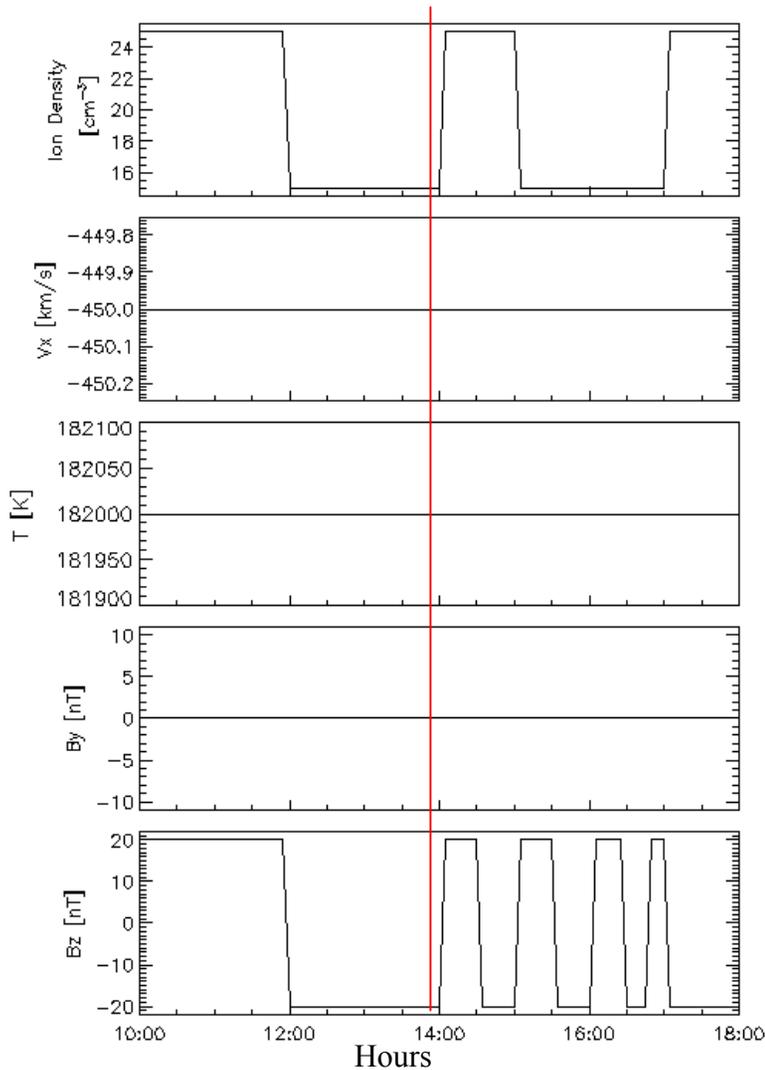
Universal Time (Hours)

Energies (keV):

62.5 black 94 red 141.5 orange 210 green 300 blue

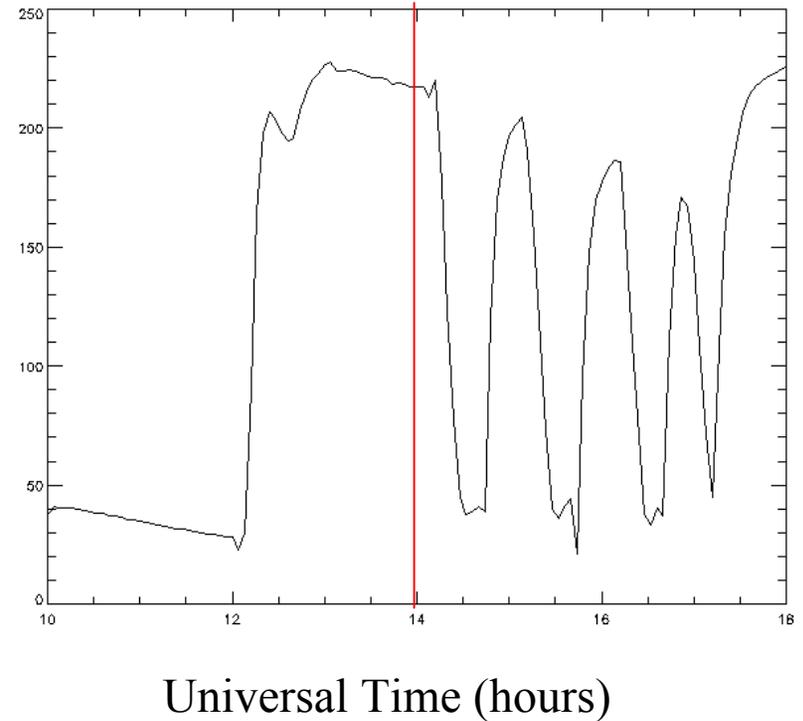


Run with Model Solar Wind Conditions Case 3

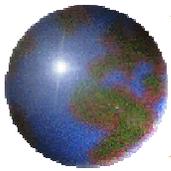


Cross Polar Cap Potential in Northern Hemisphere

ϕ (kV)



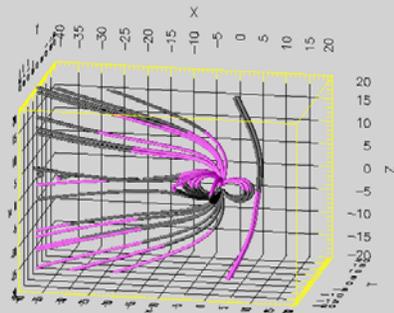
The period before the red line corresponds to a “warm-up” period for the ring current.



Magnetosphere Case 3

Space Weather Explorer

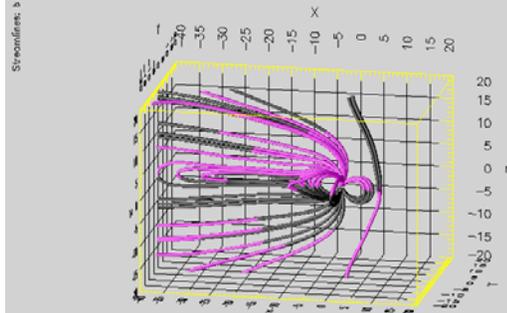
03/21/2002
14:04:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_061003_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

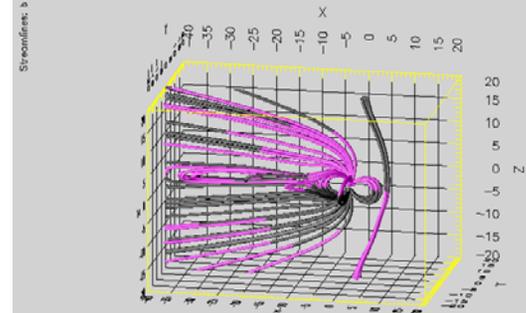
03/21/2002
14:52:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_061003_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

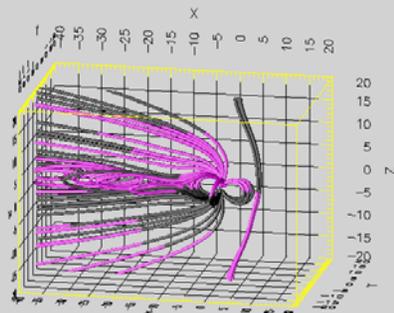
03/21/2002
14:56:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_061003_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

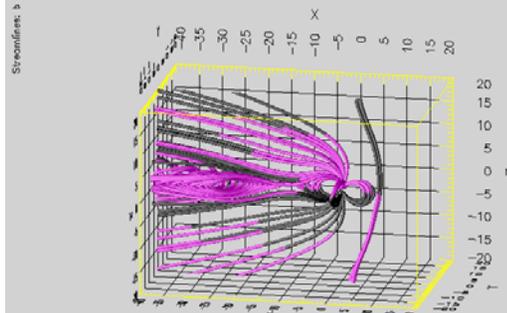
03/21/2002
15:00:00



Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_061003_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

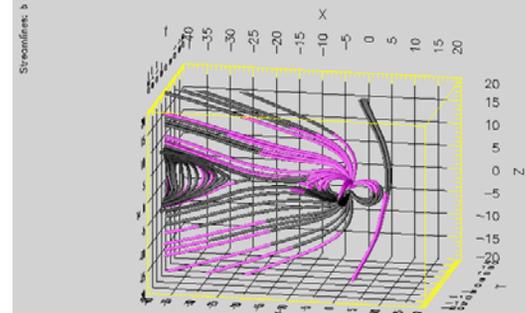
03/21/2002
15:04:00



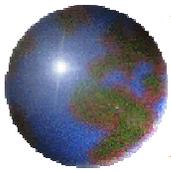
Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_061003_1, Beowulf, 2.50000E-01 R_E resolution

Space Weather Explorer

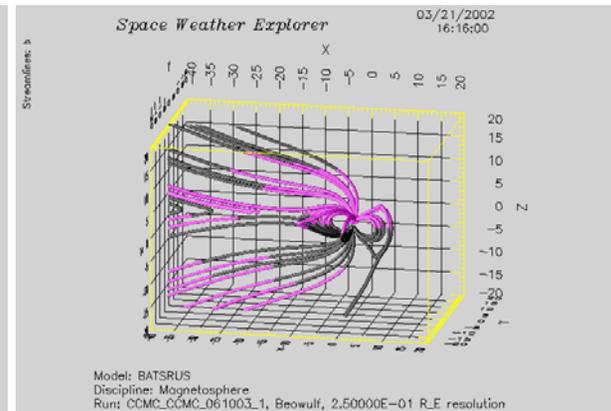
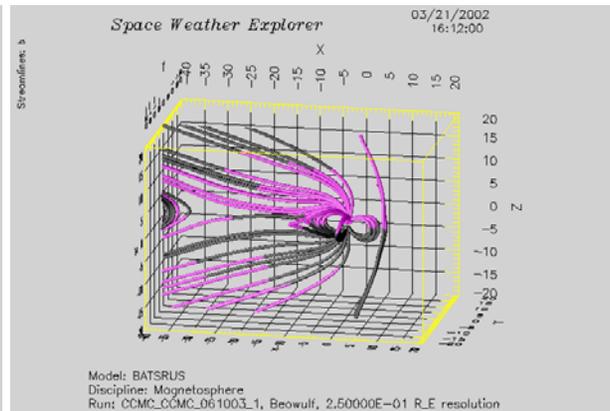
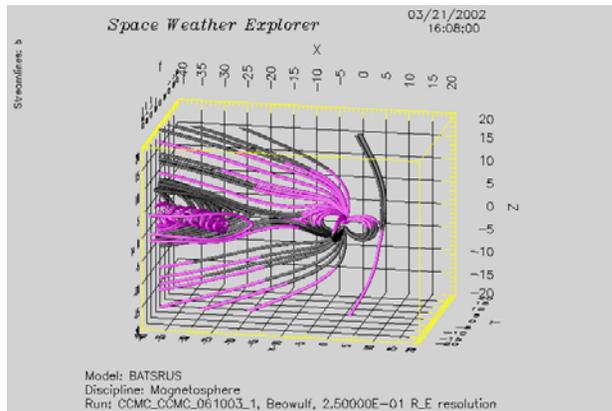
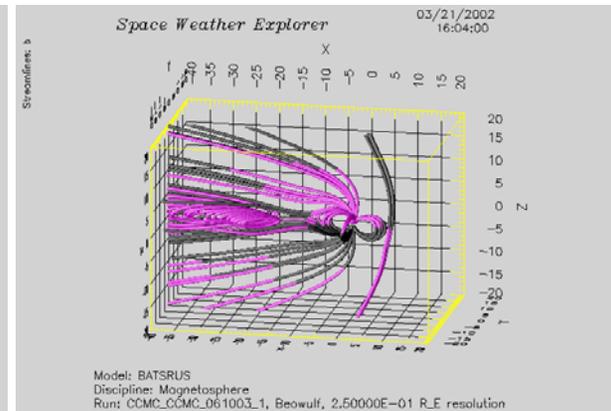
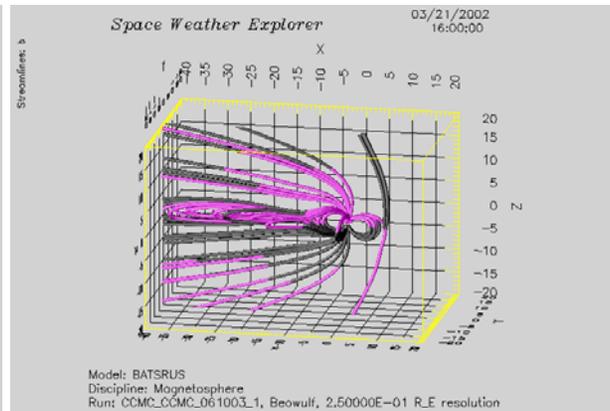
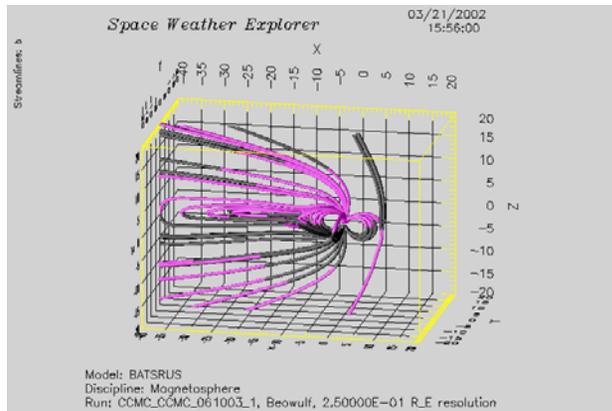
03/21/2002
15:08:00

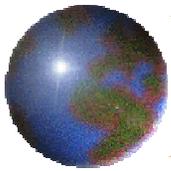


Model: BATSRUS
Discipline: Magnetosphere
Run: CCMC_CCMC_061003_1, Beowulf, 2.50000E-01 R_E resolution

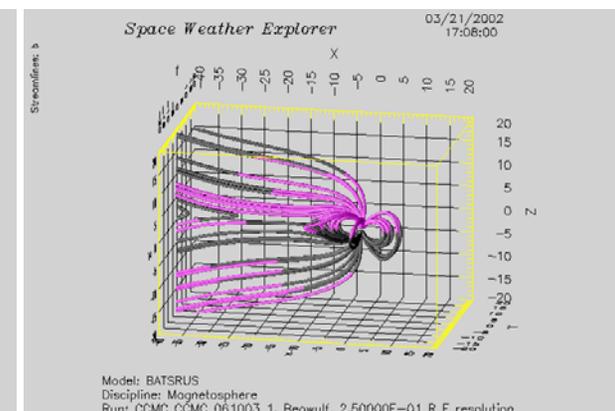
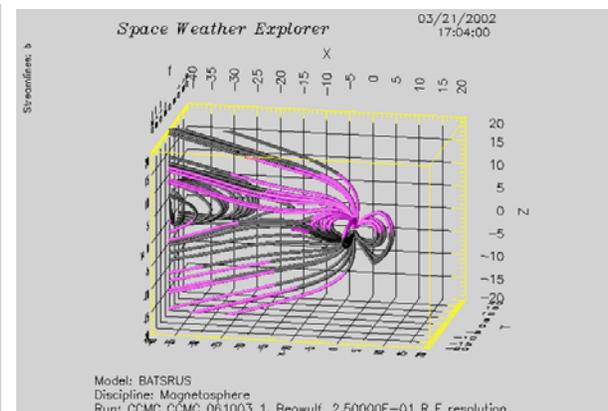
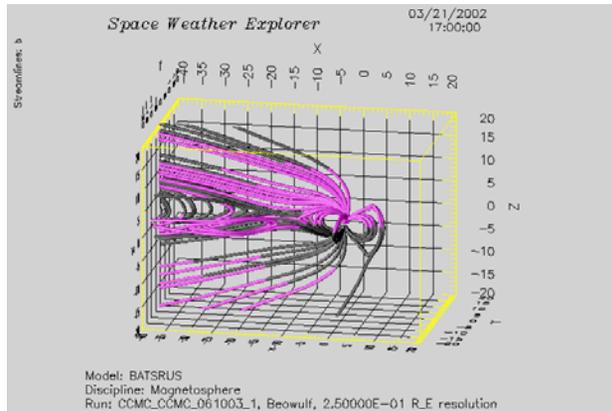
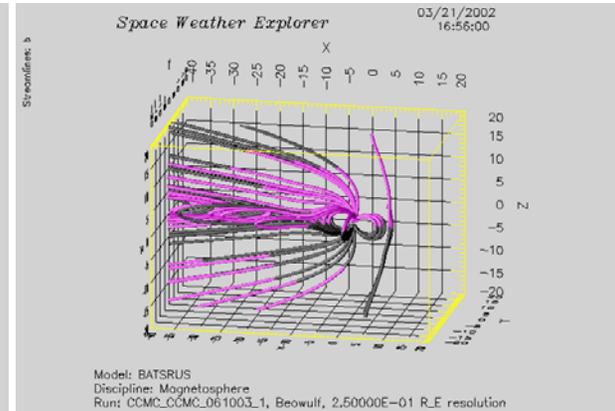
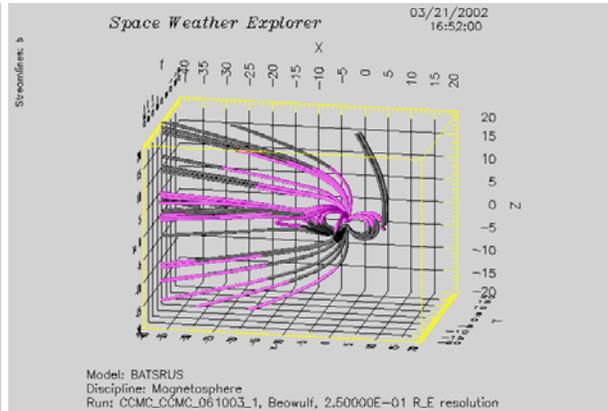
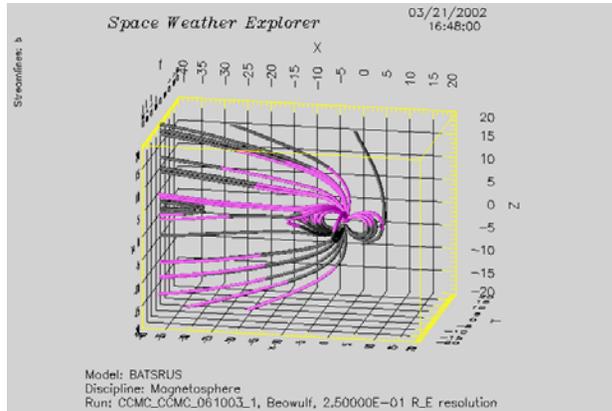


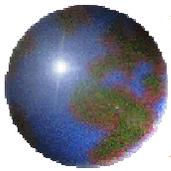
Magnetosphere Case 3



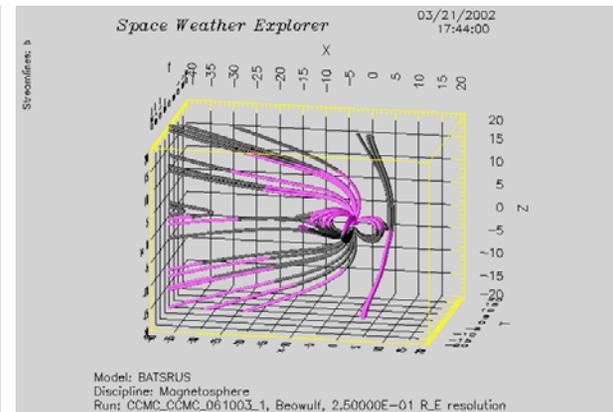
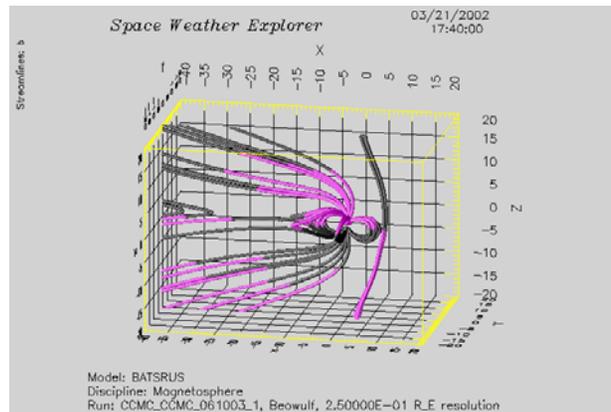
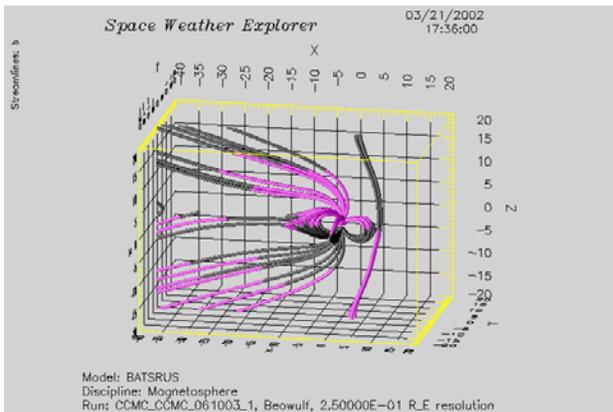
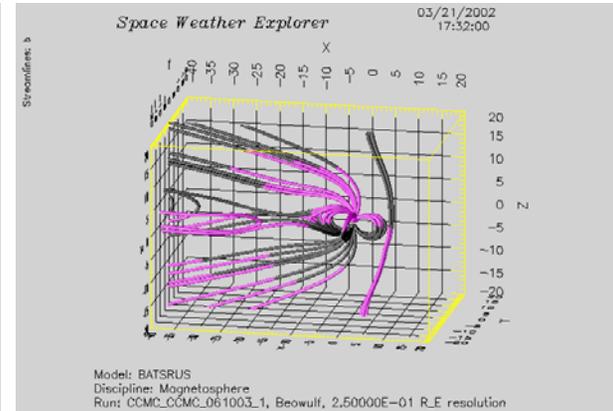
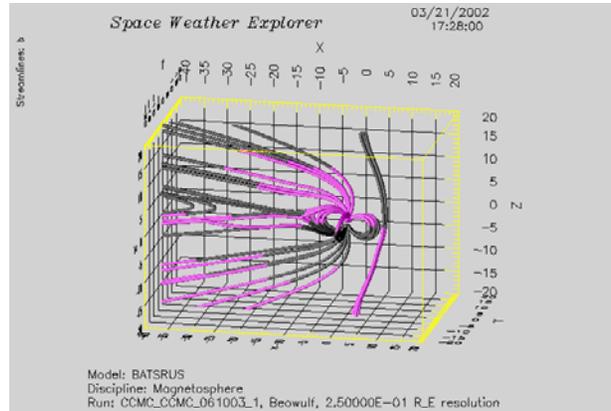
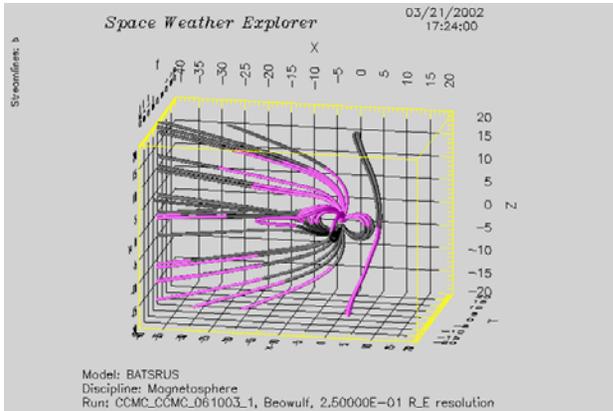


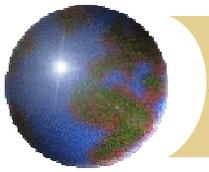
Magnetosphere Case 3





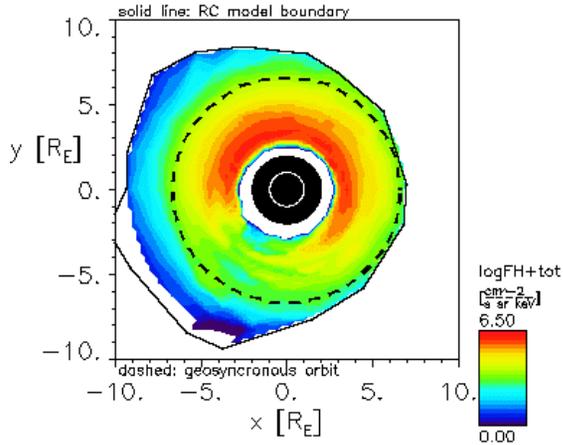
Magnetosphere Case 3



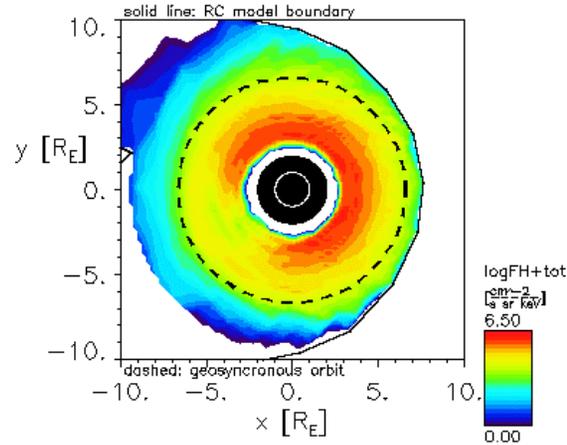


Ring Current Case 3

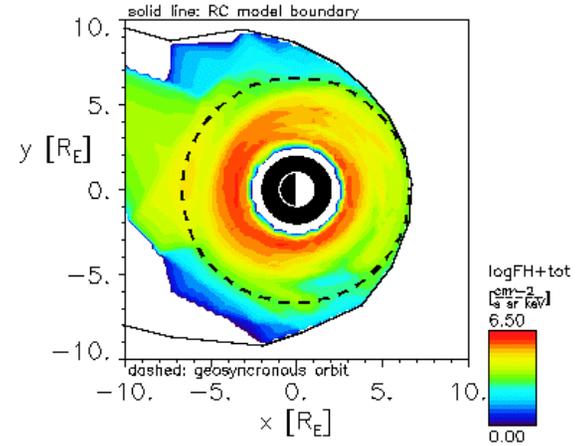
03/21/2002 Time = 14:00:00 En.= 150.keV



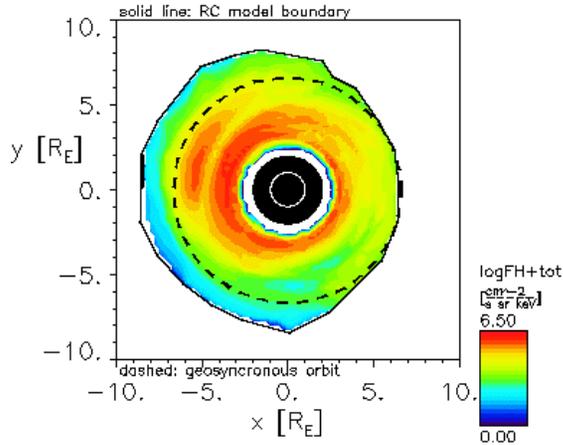
03/21/2002 Time = 14:31:59 En.= 150.keV



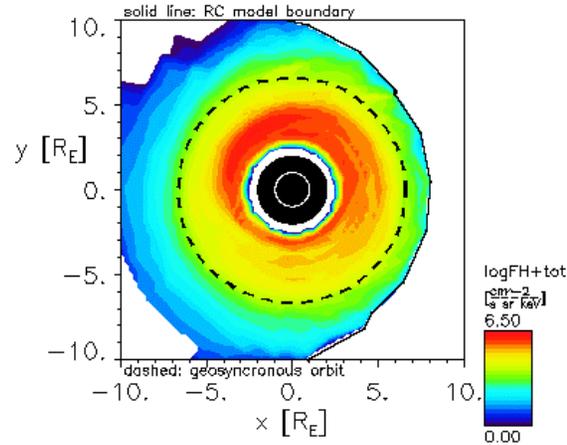
03/21/2002 Time = 15:04:01 En.= 150.keV



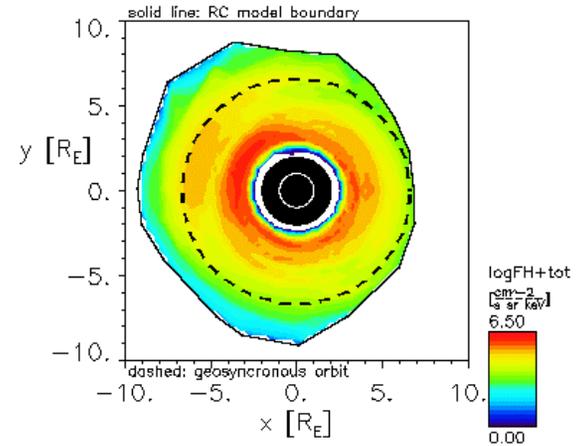
03/21/2002 Time = 15:07:59 En.= 150.keV

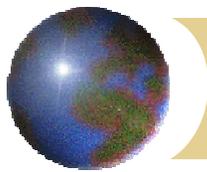


03/21/2002 Time = 15:31:59 En.= 150.keV



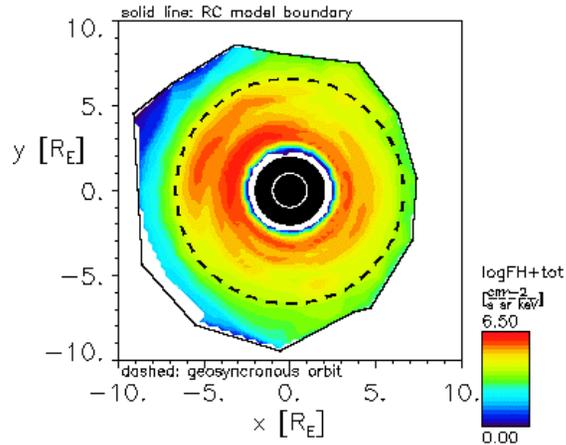
03/21/2002 Time = 16:12:00 En.= 150.keV



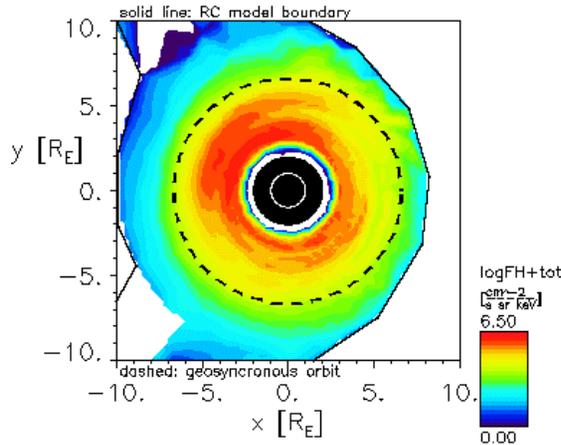


Ring Current Case 3

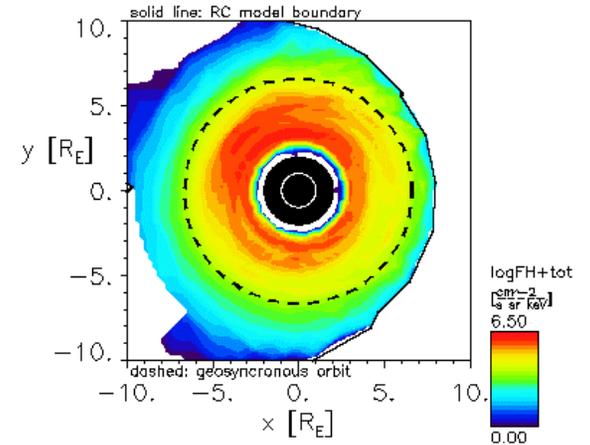
03/21/2002 Time = 16:18:01 En.= 150.keV



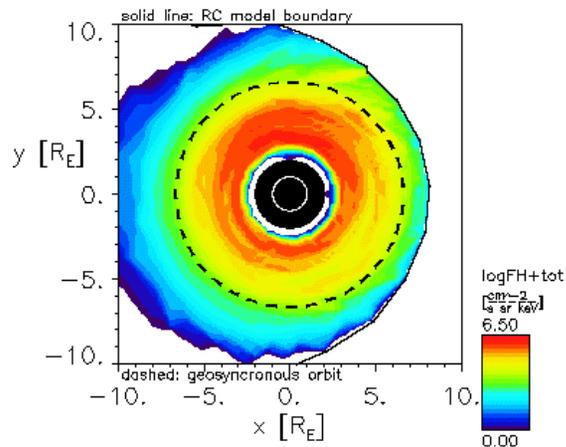
03/21/2002 Time = 16:24:00 En.= 150.keV



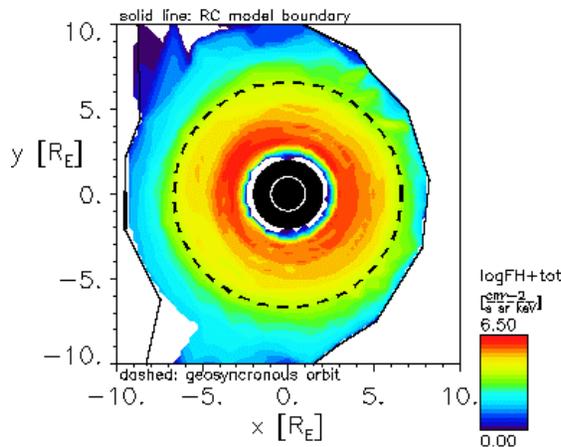
03/21/2002 Time = 16:31:59 En.= 150.keV



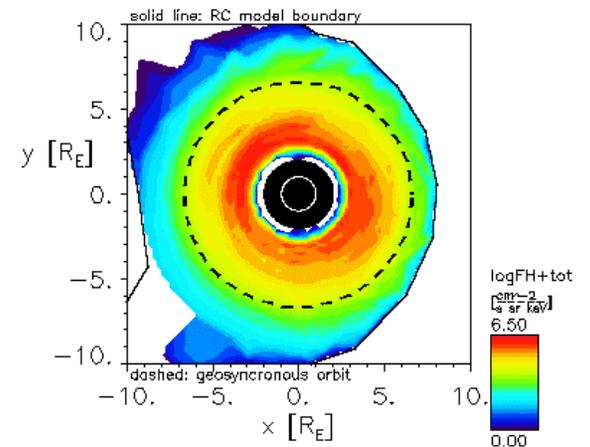
03/21/2002 Time = 16:40:01 En.= 150.keV

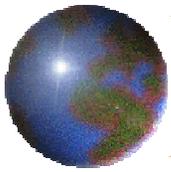


03/21/2002 Time = 17:07:59 En.= 150.keV



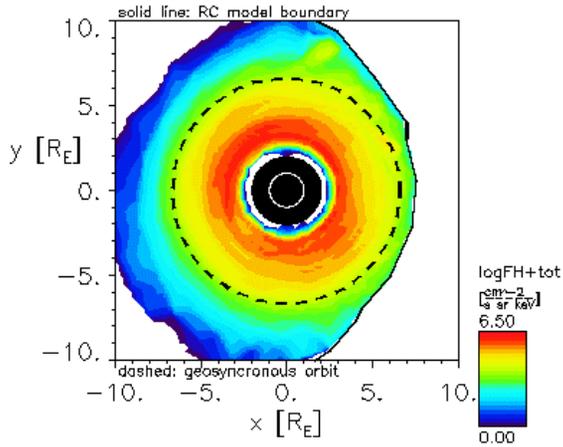
03/21/2002 Time = 17:12:00 En.= 150.keV



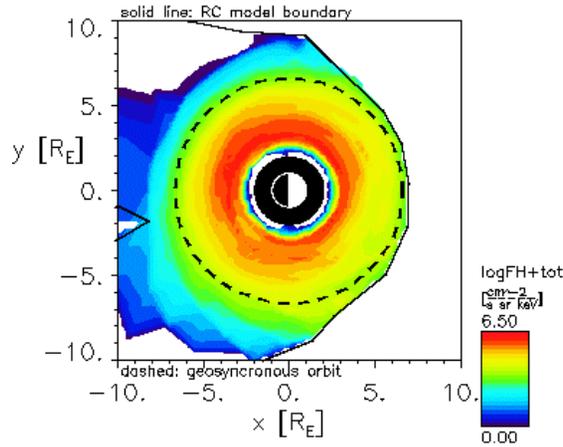


Ring Current Case 3

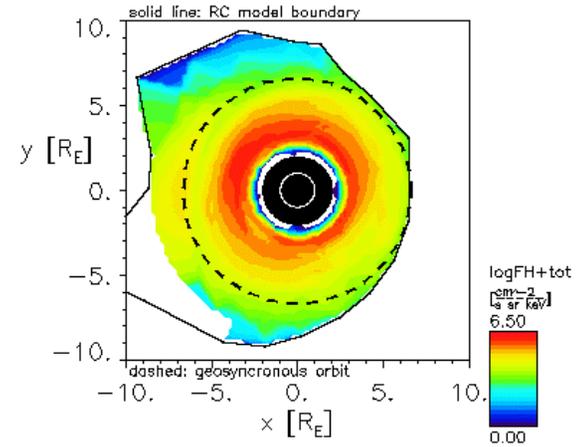
03/21/2002 Time = 17:19:59 En.= 150.keV



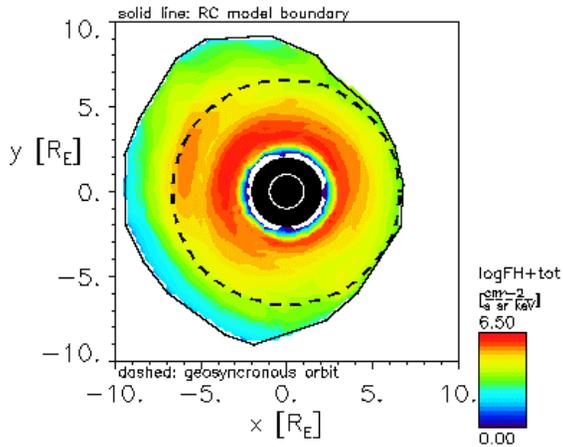
03/21/2002 Time = 17:28:01 En.= 150.keV



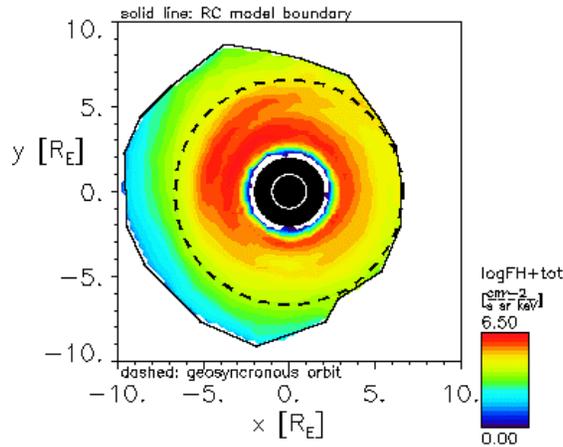
03/21/2002 Time = 17:31:59 En.= 150.keV



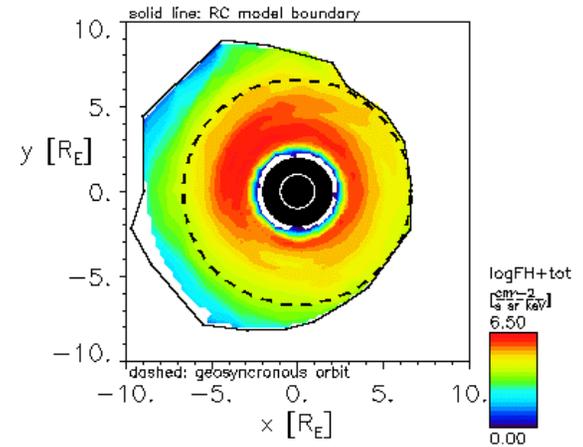
03/21/2002 Time = 17:38:00 En.= 150.keV

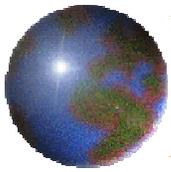


03/21/2002 Time = 17:43:59 En.= 150.keV



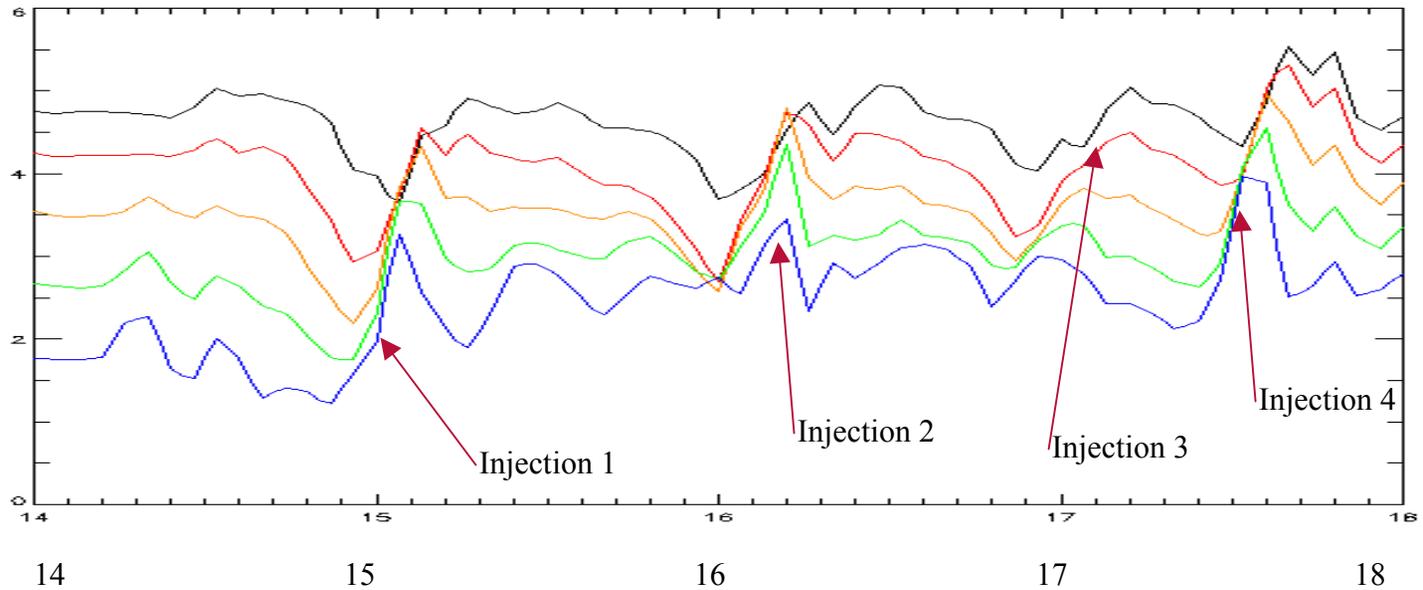
03/21/2002 Time = 17:48:00 En.= 150.keV





Log (Model Proton Flux) at 21:00 MLT for Case 3 at Geosynchronous Orbit

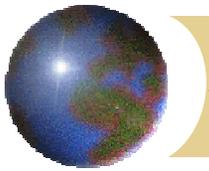
Log (Model Proton Flux)
(#/cm²/s/sr/keV)



Universal Time (Hours)

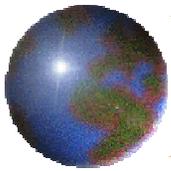
Energies (keV):

62.5 black 94 red 141.5 orange 210 green 300 blue

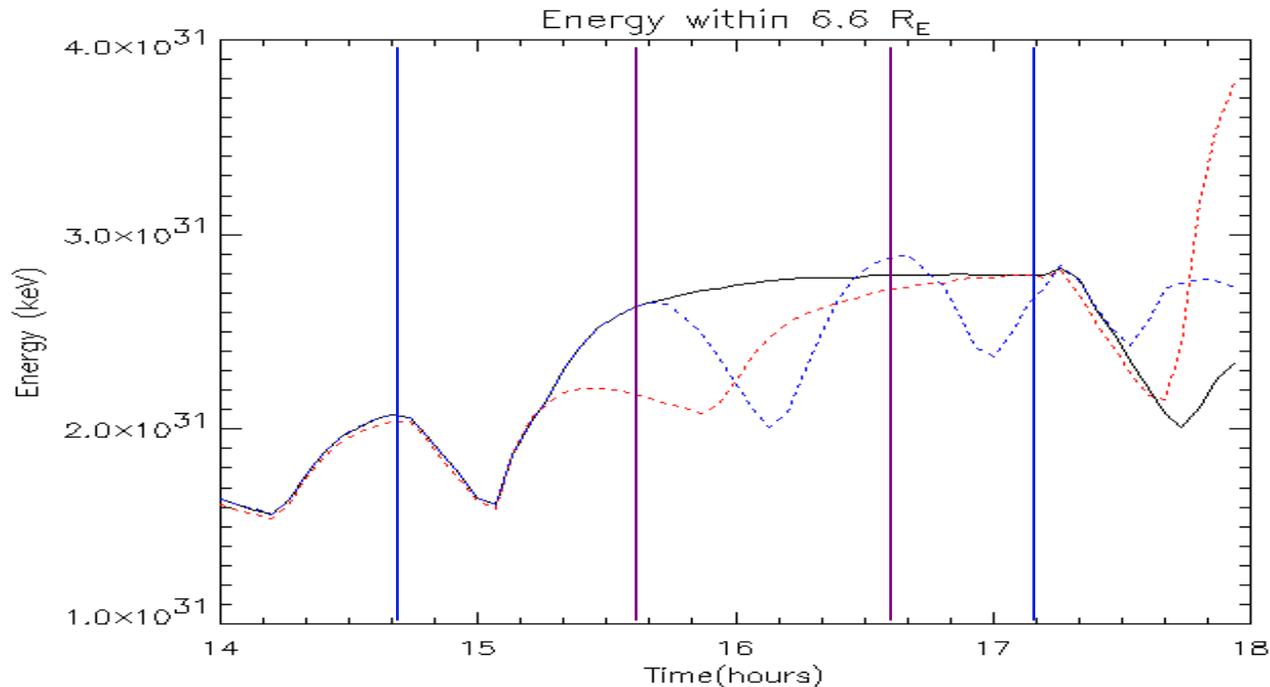


Discussion

- ✚ In cases 1 and 2, the higher energy fluxes become symmetric between 15:30 and 17:00.
- ✚ In case 3, the run is not as symmetric as cases 1 and 2 between 15:00 and 17:00.
- ✚ In case 3, there are more particle injections than cases 1 and 2. The particle injections tended to occur shortly after a plasmoid being released down the tail.
- ✚ In cases 1 and 2, a flux dropout occurs around 17:28. There was no flux dropout in case 3.
- ✚ In case 3, the second and third particle injections are smaller than the first particle injection. At the time of the injections, the density at $10 R_E$ is smaller. The potential is also smaller.



Energy in the Ring Current

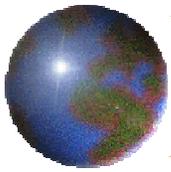


Black – Case 1

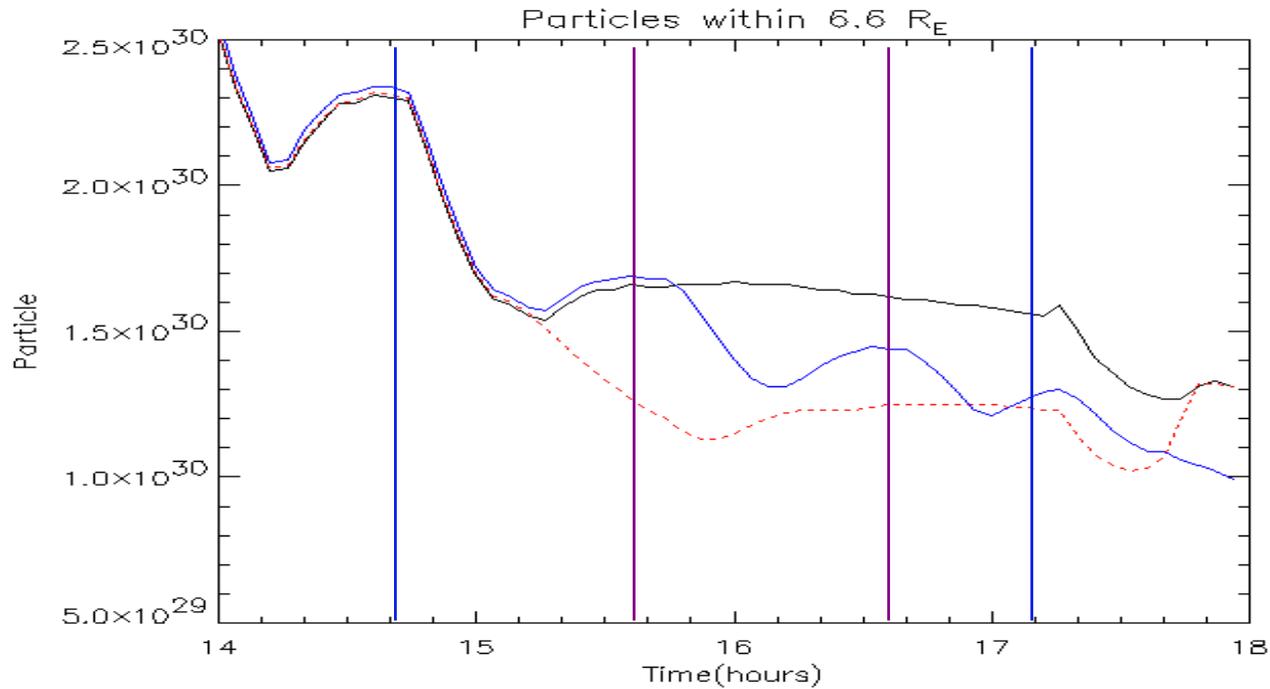
Red – Case 2

Blue – Case 3

The blue line shows the approximate times that the southward IMF hits the magnetopause for both case 1 and case 2. The purple line shows the approximate times that the southward IMF hits the magnetopause for case 2. Injections in the ring current occur around 15:04 and 17:44. These times correspond to the second and third increases in the energy for the ring current. Injections occurred around 15:04, 16:12, 17:08 and 17:32. These times correspond to the last four increases in energy in the ring current for case 2. In case 2, the increases in energy are smaller for injections that occurred around 16:12 and 17:08. During the time from 15:00 to 17:00 the solar wind density was constant. After 17:00, the solar wind density was increased.



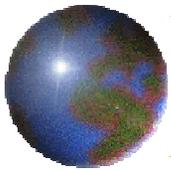
Particles in the Ring Current



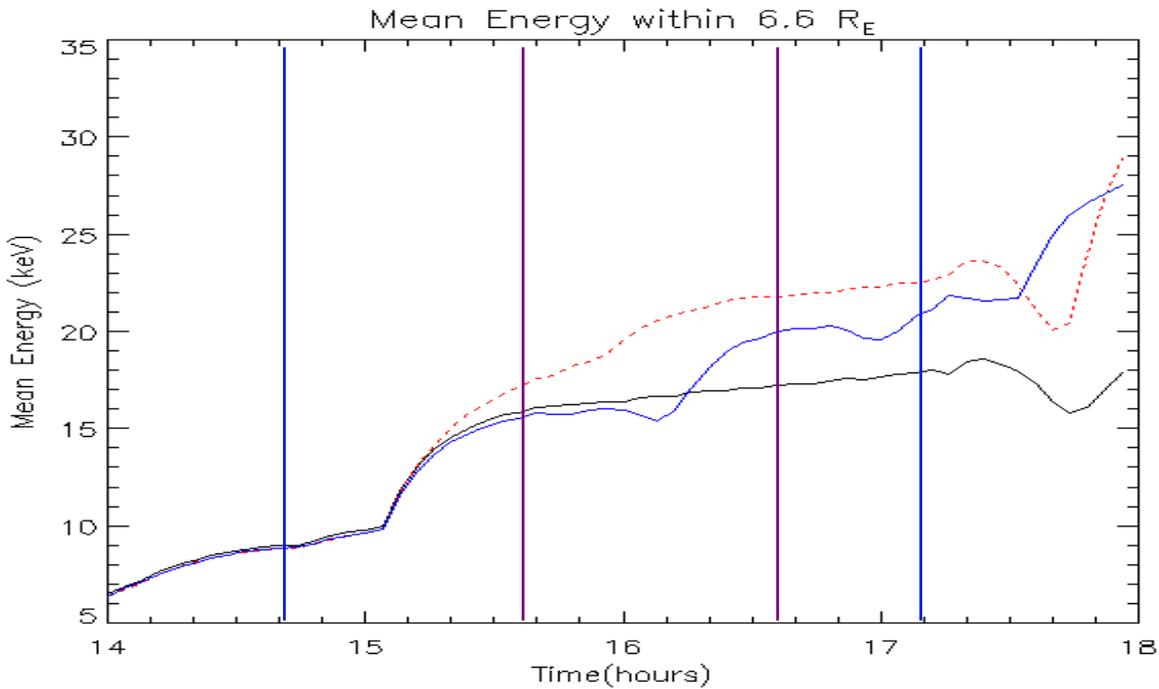
Black – Case 1

Red – Case 2

Blue – Case 3



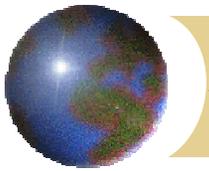
Mean Energy in the Ring Current



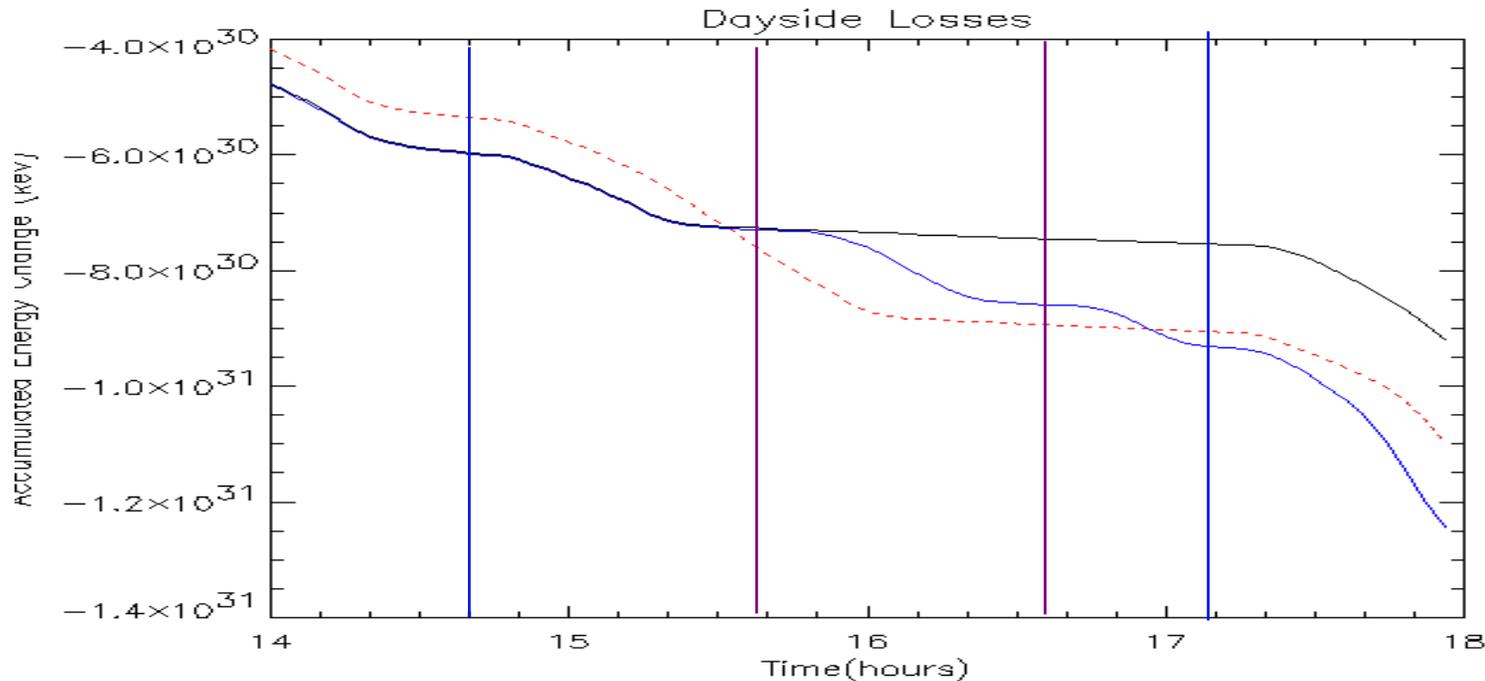
Black – Case 1

Red – Case 2

Blue – Case 3



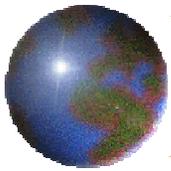
Losses out the Dayside



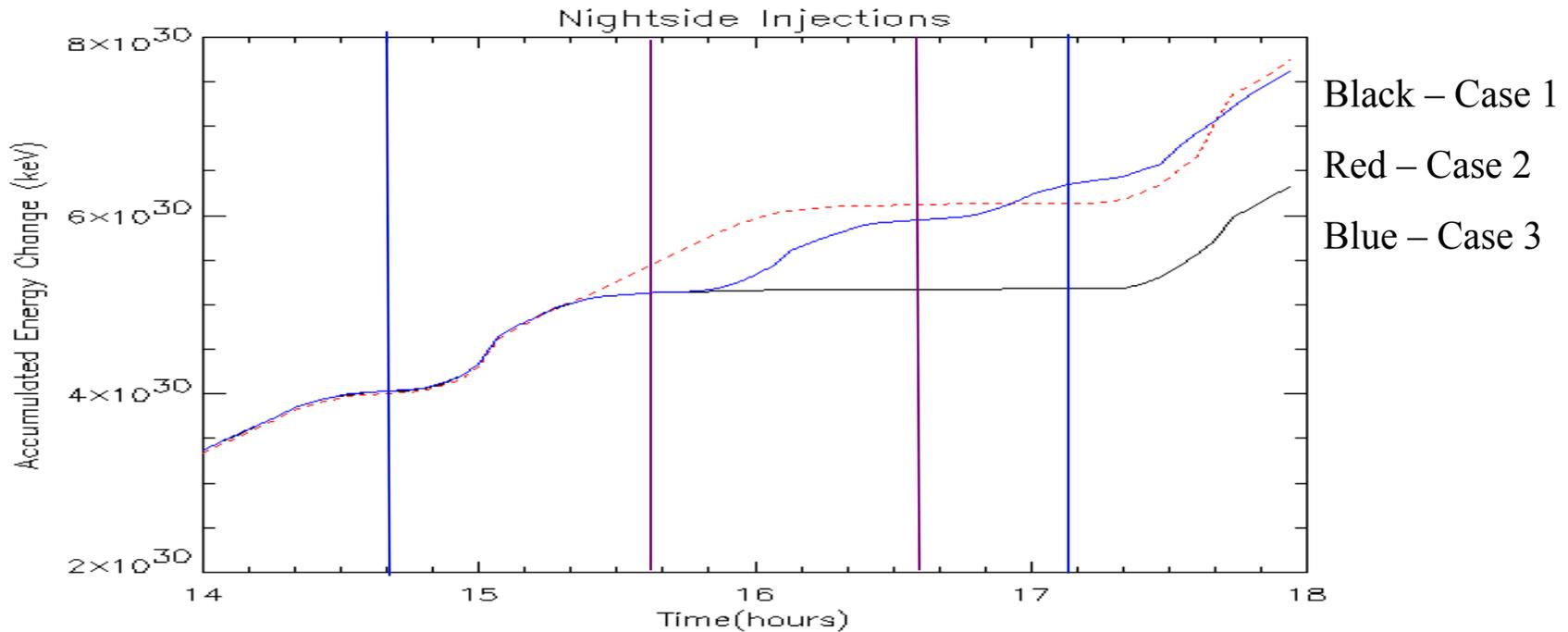
Black – Case 1
Red – Case 2
Blue – Case 3

This is a plot of the accumulated energy change for the dayside boundary. The slope of the curve indicates where losses occur. Whenever the curve is flat, there are no additional losses or gains in energy. The blue line shows the approximate times that the southward IMF hits the magnetopause for both case 1 and case 2. The purple line shows the approximate times that the southward IMF hits the magnetopause for case 2.

There are large losses on the dayside approximately 12 minutes after the IMF turns southward. Approximately 6-8 minutes after the southward turning, the potential starts to increase and the magnetopause moves inward on the dayside. When the IMF turns southward for the first three times, the solar wind dynamic pressure is kept constant. Reconnection on the dayside causes the open/closed field boundary to move closer to the Earth. Case 2 has a larger loss after 17:40. The potential for case 2 is slightly higher than case 1 from 17:20 onwards.

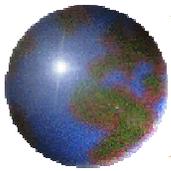


Nightside

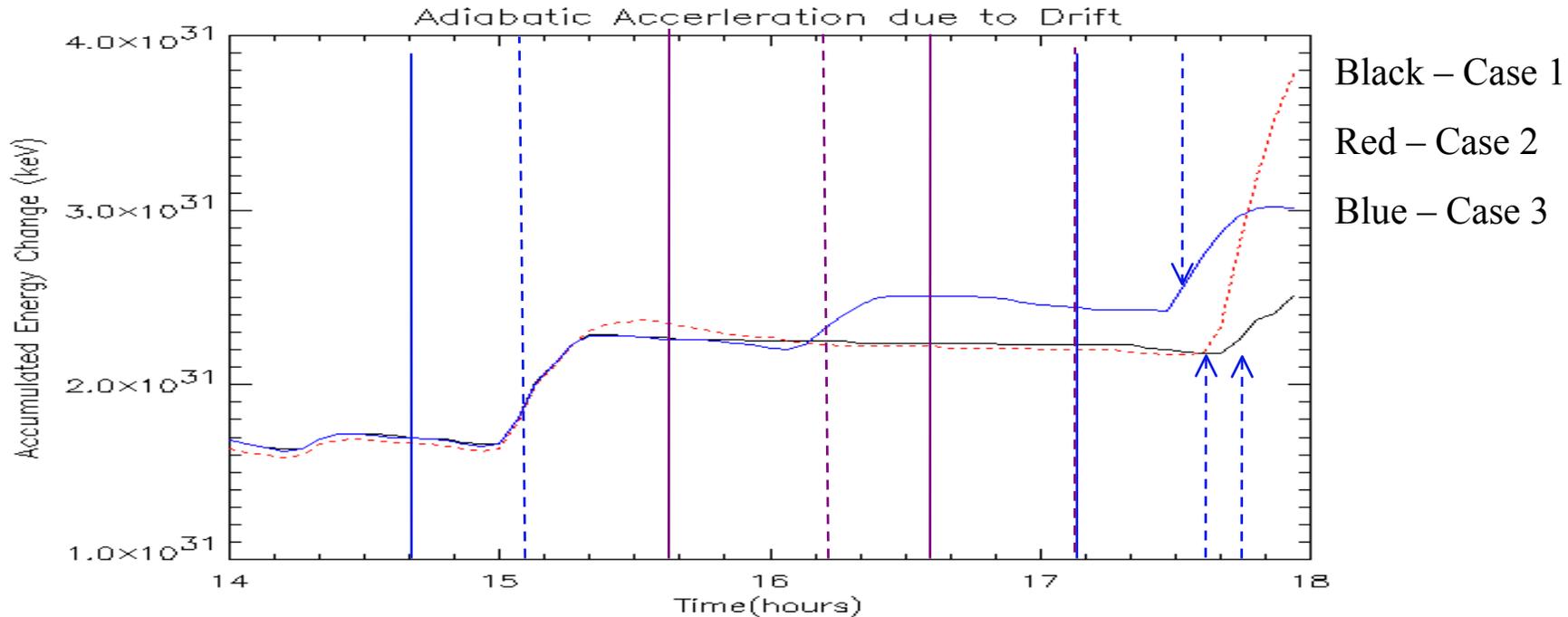


This is a plot of the accumulated energy change for the nightside boundary. The slope of the curve indicates where gains occur. Whenever the curve is flat, there are no additional losses or gains in energy. The blue line shows the approximate times that the southward IMF hits the magnetopause for both case 1 and case 2. The purple line shows the approximate times that the southward IMF hits the magnetopause for case 2.

There are large increases on the nightside approximately 12 minutes after the IMF turns southward. Approximately 6-8 minutes after the southward turning, the potential starts to increase. The increases in energy on the nightside boundary correspond to the losses on the dayside. The increases in energy on the nightside are slightly smaller than the decreases on the dayside boundary. These changes are not enough to account for the changes in energy.

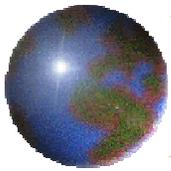


Energy Changes due to Drift

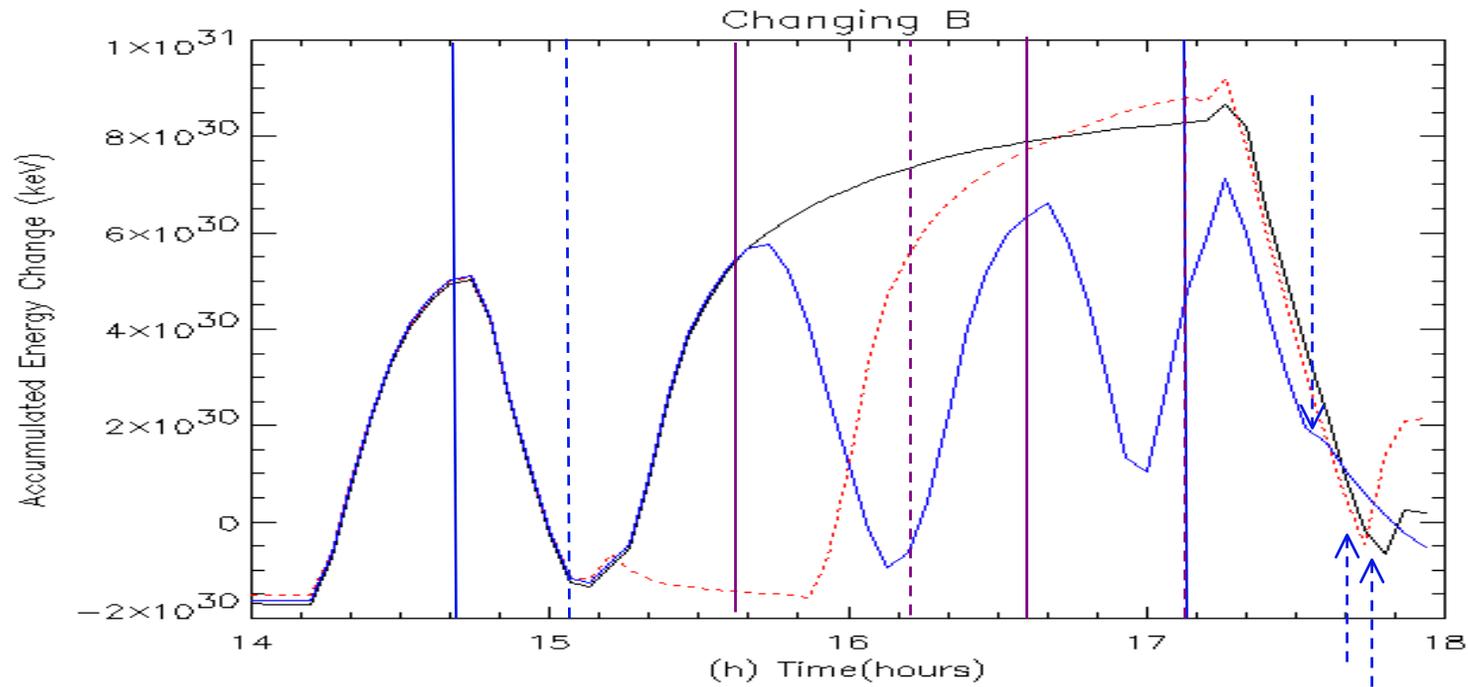


This is a plot of the accumulated energy change due to the drift terms. This acceleration is due to an increase in convection. As convection is increased, particles are pushed toward the Earth. The slope of the curve indicates where gains occur. Whenever the curve is flat, there are no additional losses or gains in energy. The blue line shows the approximate times that the southward IMF hits the magnetopause for both case 1 and case 2. The blue dashed line shows the approximate times where injections occur for both case 1 and case 2. The purple line shows the approximate times that the southward IMF hits the magnetopause for case 2. The purple dashed line shows the approximate times where injections occur for for case 2.

Increases occur around the time reconnection occurs in the tail. There is no increase for the third injection in case 2. This injection was very small. The time period corresponds to the lowest increase in ionospheric potential and density in the tail.

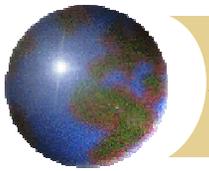


Energy Changes due to Changing B



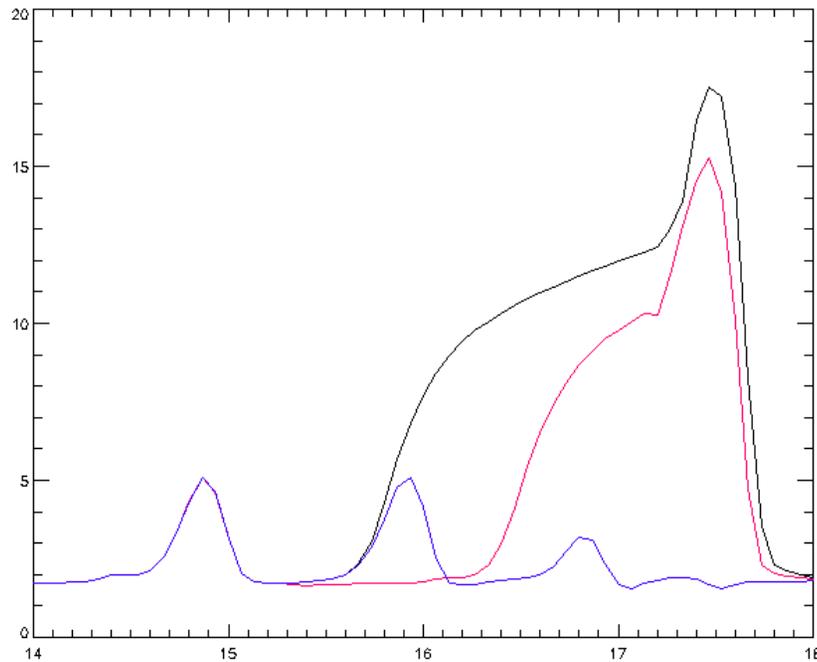
This is a plot of the accumulated energy change due to the changing B . This term assumes that the first and second adiabatic invariant are conserved. Changes in B then change the kinetic energy. The slope of the curve indicates where gains occur. Whenever the curve is flat, there are no additional losses or gains in energy. The blue line shows the approximate times that the southward IMF hits the magnetopause for both case 1 and case 2. The blue dashed line shows the approximate times where injections occur for both case 1 and case 2. The purple line shows the approximate times that the southward IMF hits the magnetopause for case 2. The purple dashed line shows the approximate times where injections occur for for case 2.

When dipolarization occurs, the energy increases. When the IMF turns southward, the magnetic field stretches and energy is lost.



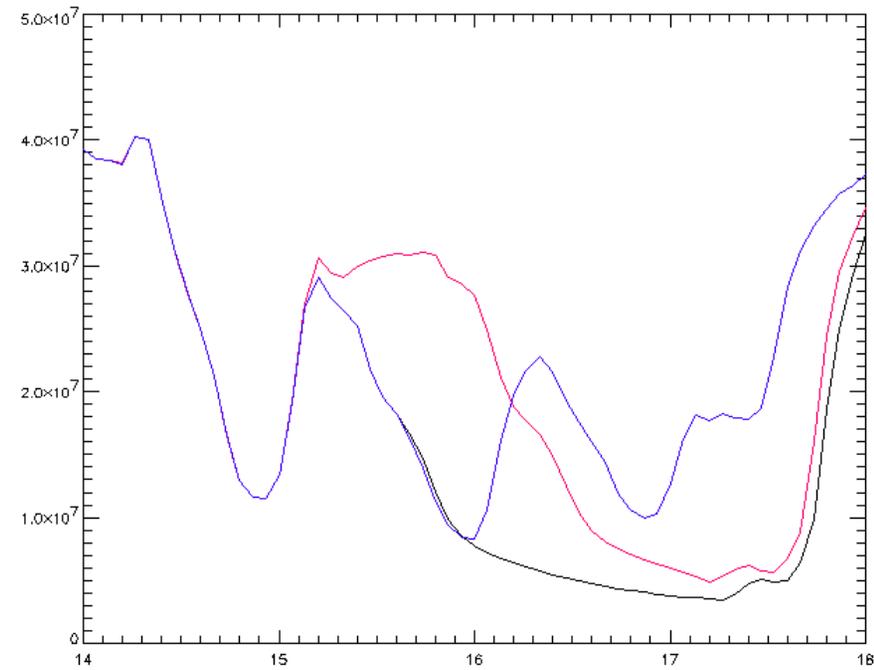
Differences in MHD input

Density



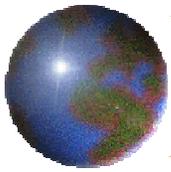
Time

Temperature



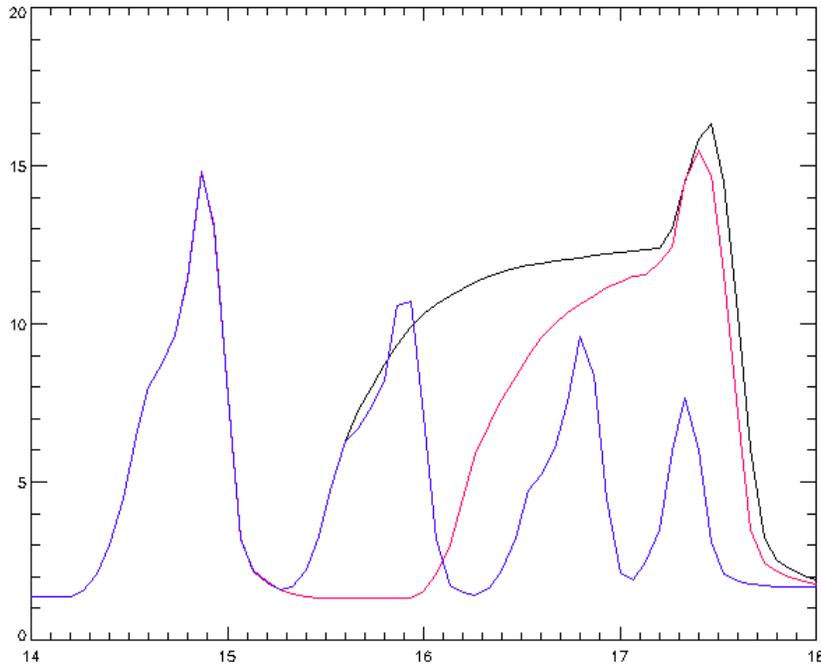
Time

Fixed position at 10 RE 0 MLT, Black case 1, Red case 2, Blue Case 3



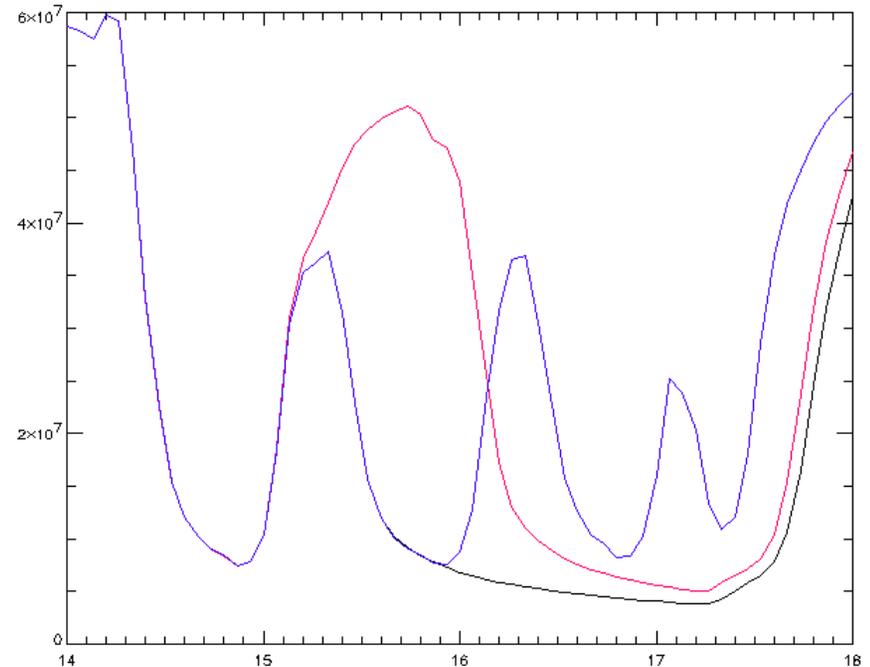
Differences in MHD input

Density



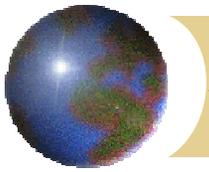
Time

Temperature

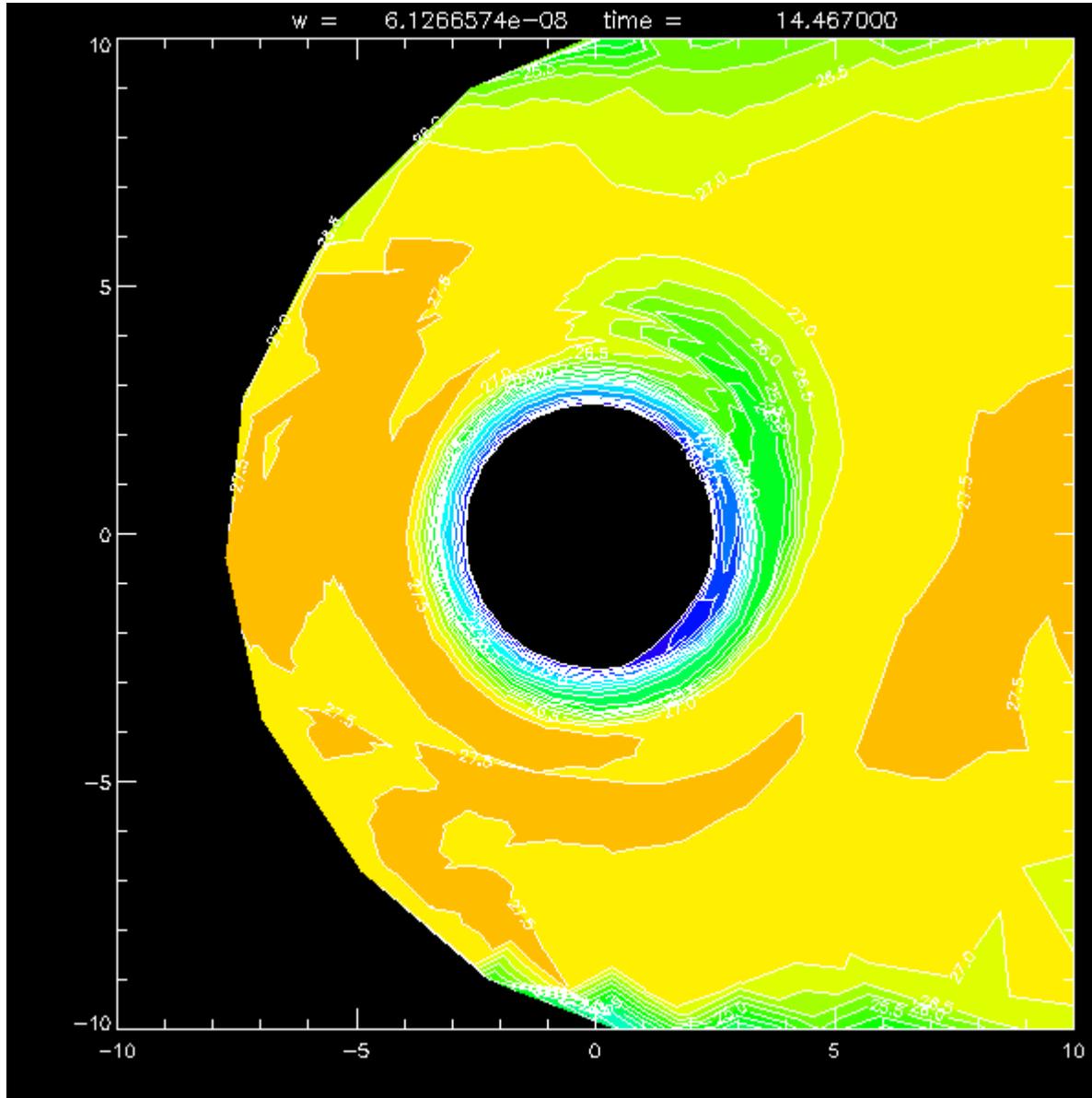


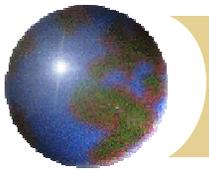
Time

Fixed position at 10 RE 21 MLT, Black case 1, Red case 2, Blue Case 3

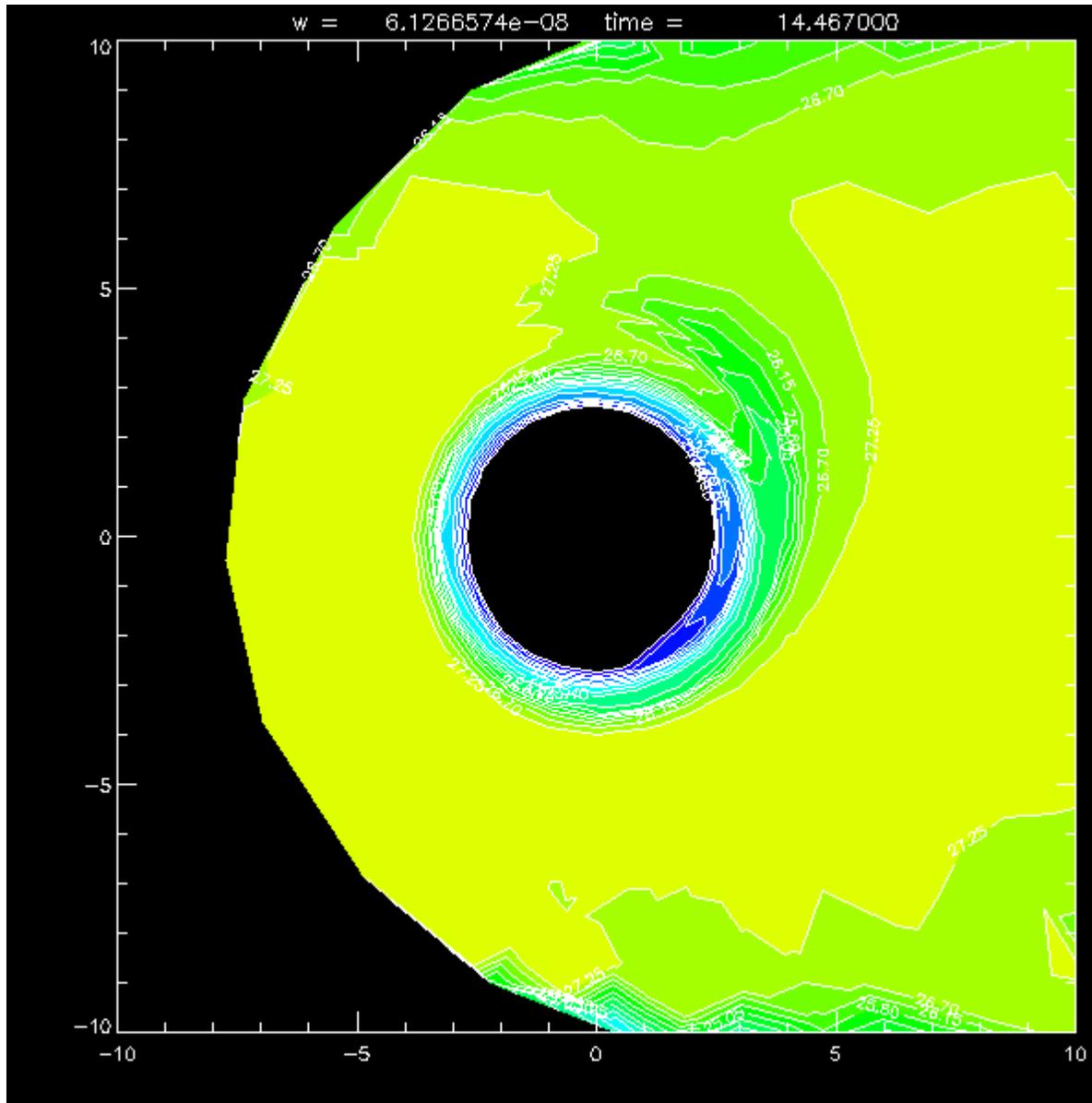


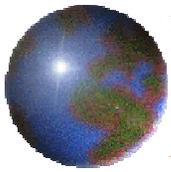
Phase Space Density Case 2





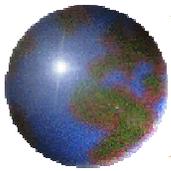
Phase Space Density Case 1





Summary

- Multiple substorms cause more injections into the ring current but do not cause a significant gain in energy at the end of a cycle.
- The amount of time that the IMF is southward seems to be the determining factor in the amount of gain in the mean energy.
- During multiple substorms, the ring current is more asymmetric with significant losses on the dayside causing decreases in the proton flux on the morning side.
- During multiple substorms, there is an oscillation in the energy. Energy is lost when the tail stretches during southward IMF. Energy is gained due to dipolarization in the tail and increases in ionospheric potential.



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