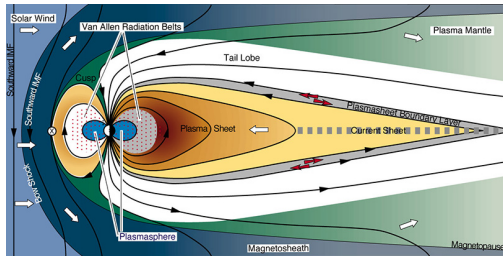


Space Weather

Lecture 7: Magnetospheric Substorms and Storms

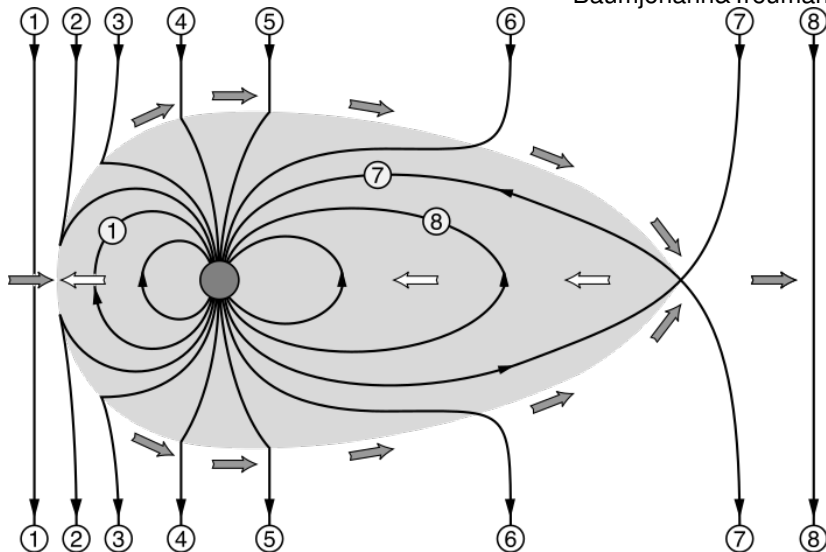


Elena Kronberg (Raum 442)
elana.kronberg@lmu.de

- A **substorm** is a brief disturbance in the Earth's magnetosphere that causes energy to be released from the “tail” of the magnetosphere and injected into the high latitude ionosphere.
- A **geomagnetic storm** is a temporary disturbance of the Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field (CME). The increase in the solar wind pressure compresses the magnetosphere. The solar wind's magnetic field interacts with the Earth's magnetic field and transfers an increased energy into the magnetosphere. Both interactions cause an increase in plasma movement through the magnetosphere (driven by increased electric fields inside the magnetosphere) and an increase in electric current in the magnetosphere and ionosphere.

Dungey Cycle

Baumjohann&Treumann



Key question: What is the difference between a magnetospheric substorm and a storm?



1st Difference: cause

substorms: regular southward turning of IMF

vs

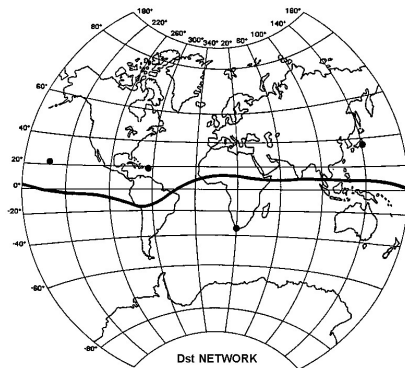
storms: prolonged southward turning of IMF (during CME)

substorms: ~ 3 hours
vs
storms: several days

3rd Difference: location of magnetic disturbances at the ground

Polar region: Substorms and Storms

Equatorial: Storms



Location of magnetic field observatories

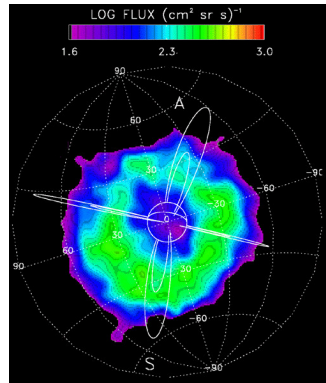
Source: World Data Center for Geomagnetism, Kyoto

4th Difference: associated physical phenomena

Aurora: Substorms and Storms

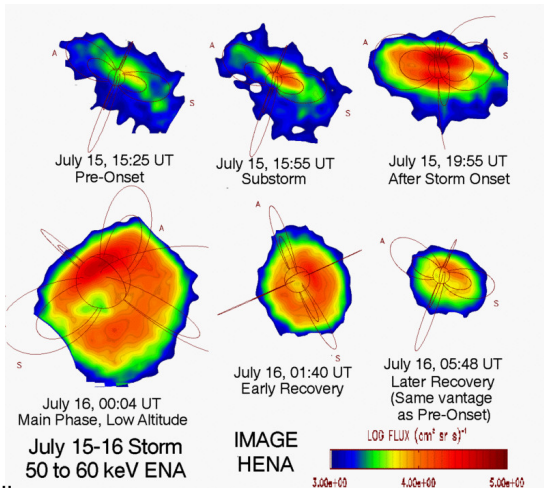


Ring Current: Storms



5th Difference: size of the disturbance

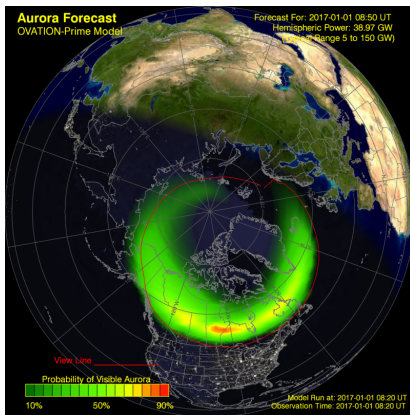
ENA images of the fluctuation of Earth's ring current during July 15–16, 2000 geomagnetic storm made by the IMAGE HENA Instrument



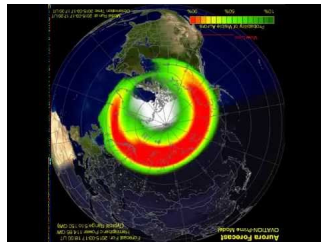
Source: Wikipedia

6th Difference: location and size of the aurora

Nightside: Substorms



Almost all auroral oval: Storms



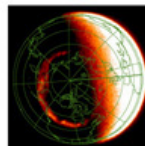
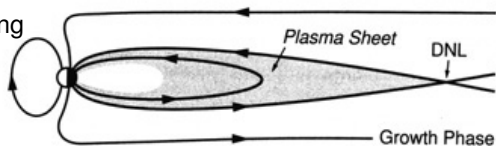
Credit:
<http://www.swpc.noaa.gov/products/aurora-30-minute-forecast>

Substorm phases

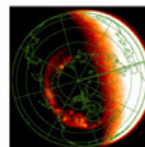
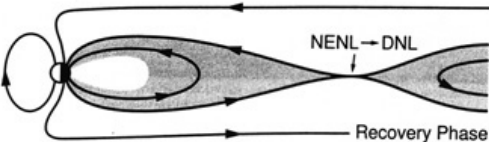
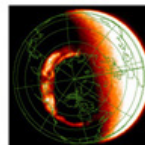
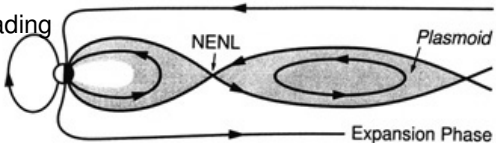
Baumjohann&Treumann

Duration \simeq 3 hours

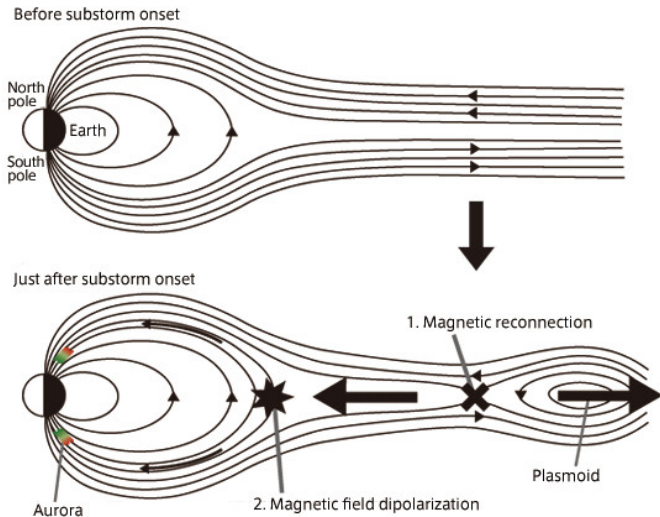
energy loading



energy unloading

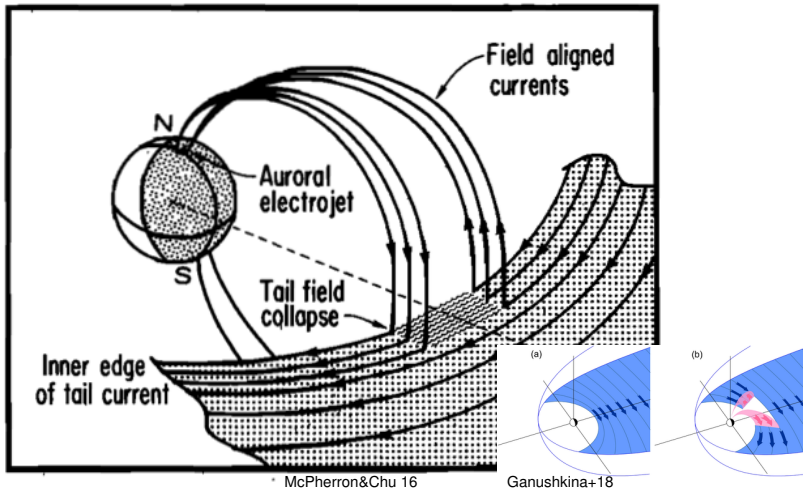


Substorm phases: before and after the onset

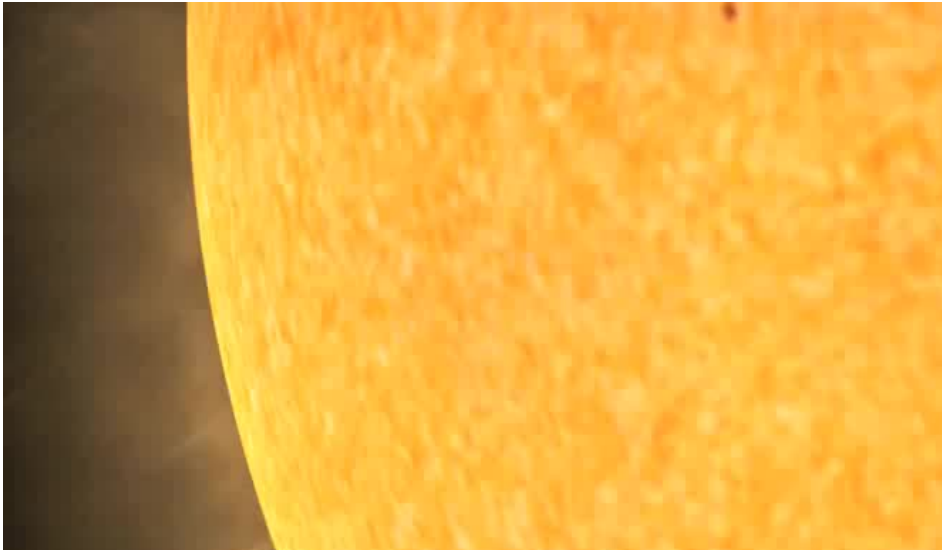


Current Wedge: underlying physics

- The substorm current wedge diverts part of the neutral sheet current along magnetic field lines through the ionosphere

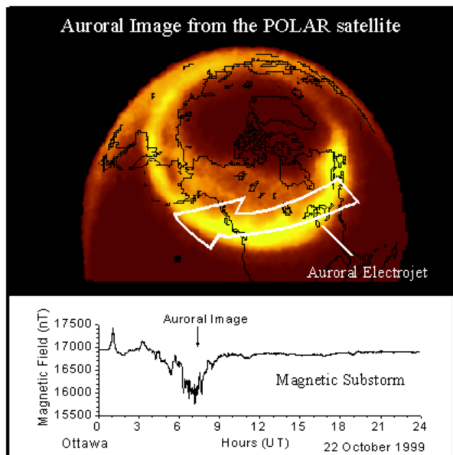


Substorm: visualization



Auroral Electrojet

- Total current $\sim 10^6$ A
- Disturbance of the magnetic field (ΔB): 100 ... 1000 nT, may reach 3000 nT, $\simeq 5\%$ of dipole field at high latitudes



AE, AU, AL indices

- Measure of global auroral electrojet activity
- 12 observatories between $\lambda \simeq 65^\circ$ and 70°

$$AU(t) = \max_{i=1,12} \{H(t) - H_0\}_i$$

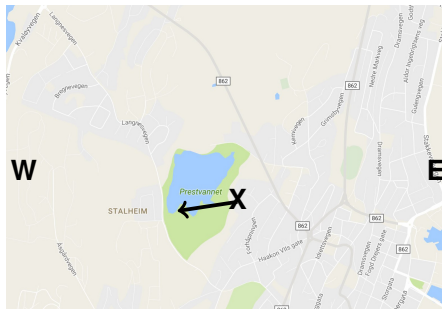
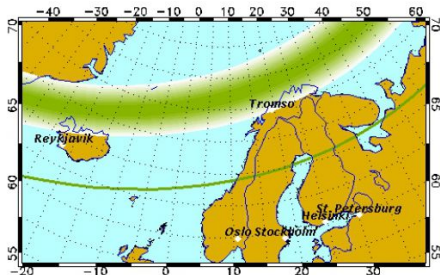
$$AL(t) = \min_{i=1,12} \{H(t) - H_0\}_i$$

$$AE(t) = AU(t) - AL(t)$$

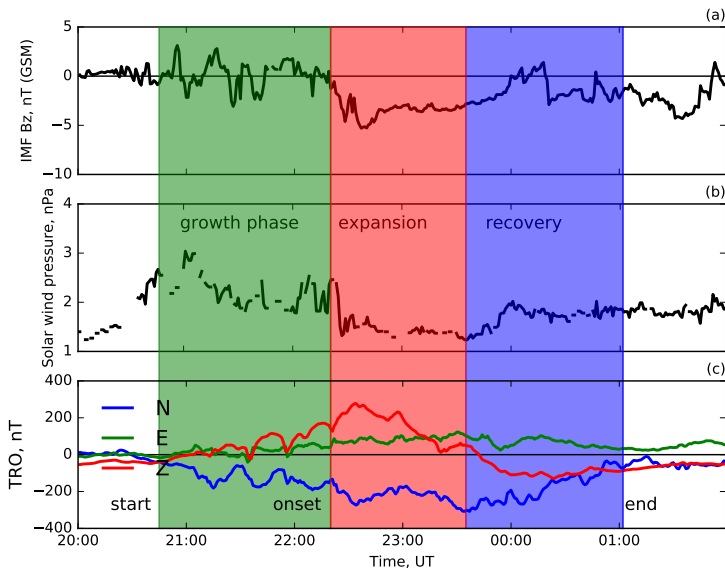
- AU – eastward electrojet current
- AL – westward electrojet current
- AE – the total maximum electrojet current

My experience: Tromsø, Norway

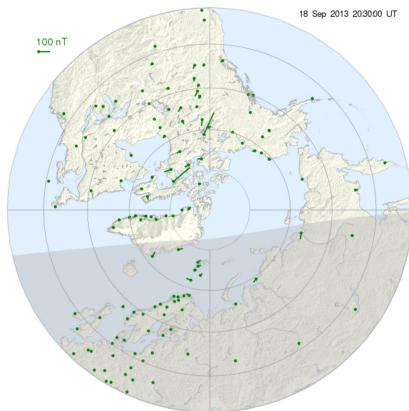
- Cluster Workshop Conference
- Geomagnetic Latitude, Longitude: 67.25, 116.0



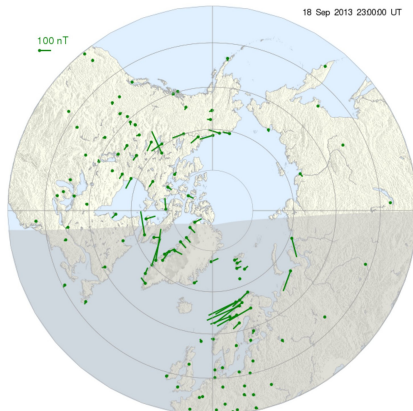
Magnetic field observations at TRO and by ACE



Ground-based observations: polar plots of SUPERMAG data

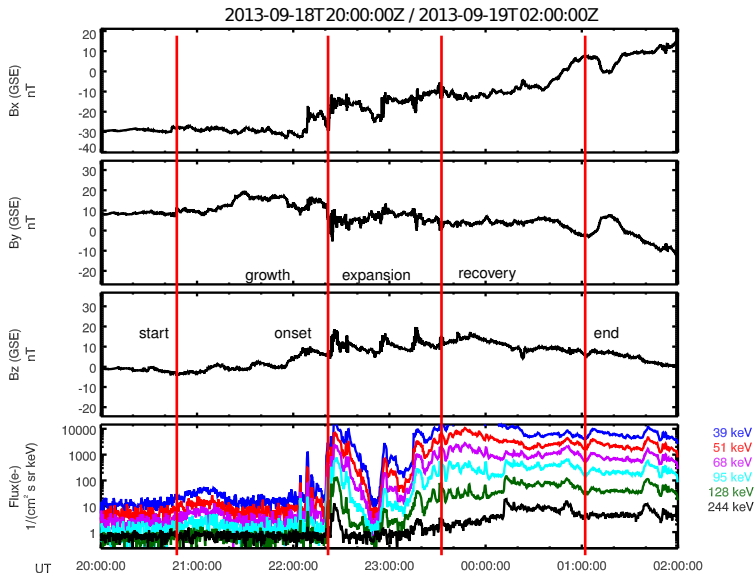


before substorm

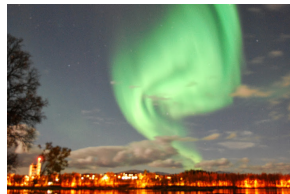
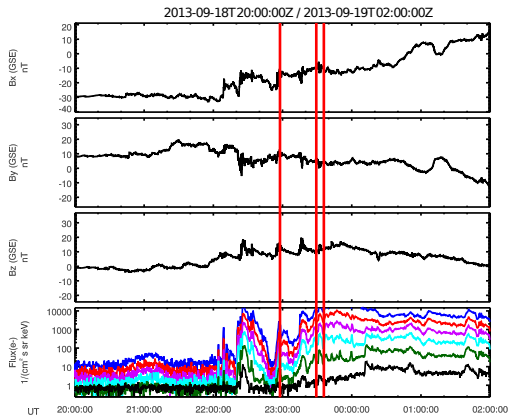


expansion phase

CLUSTER observations



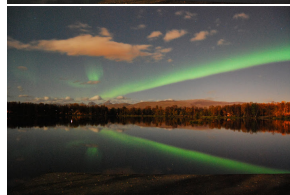
CLUSTER and aurora observations



22:58 UT



23:27 UT

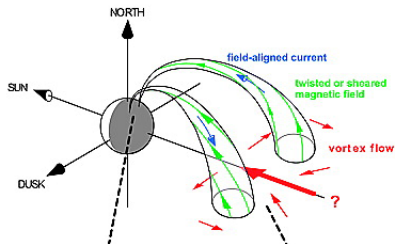
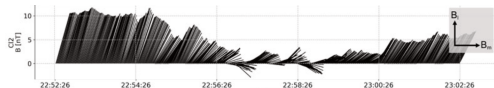


23:34 UT

Why do we observe auroral spiral?

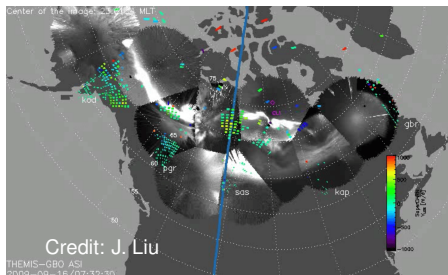
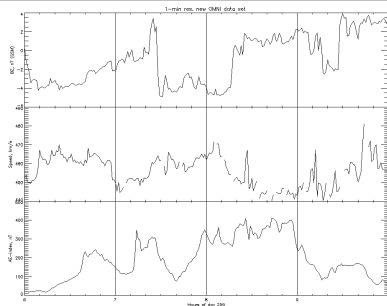
- Dipolarization fronts moving Earthward-Eastward produce vortices
- Vortices (KHI) lead to magnetic field twist
- This corresponds to a field-aligned current
- Electrons flowing in this current produce aurora with vortex pattern
- The current is called “upward” because ions flow towards the tail (electrons flow towards the ionosphere)

Cluster observations, Maetschke et al., 2023

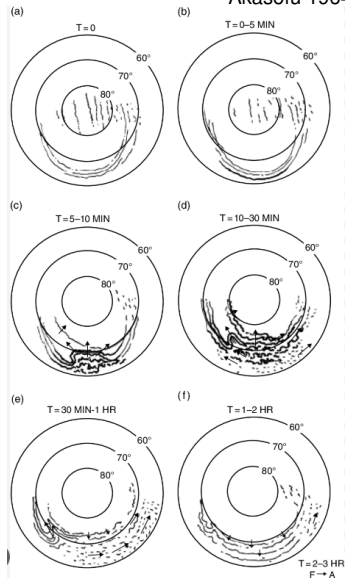


Keiling et al, 2009

All Sky Imagers observations of a substorm

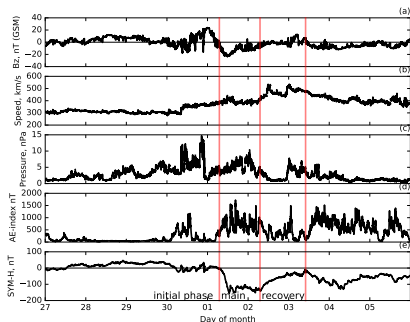
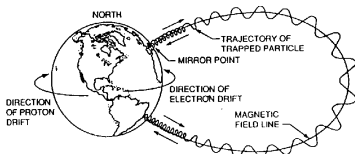


Akasofu 1964

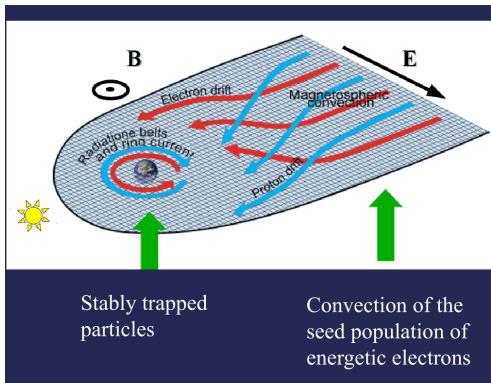


Magnetic Storms: Ring Current

- During a prolonged southward IMF (associated with CMEs) many particles penetrate the dipolar region of the magnetosphere.
- A particle in a dipole field will gyrate, bounce and drift at the same time.
- The ring current is a flow of charged particles trapped in the magnetosphere.



Particle trajectories in the magnetosphere



- Drift of lower energy particles is dominated by $E \times B$ drift
- Ring current particles are subject to the gradient and curvature drifts and drift around the Earth
- Electrons –eastward, ions – westward

Ring current: magnetic field disturbances at equatorial region

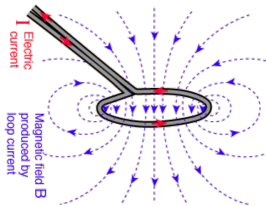
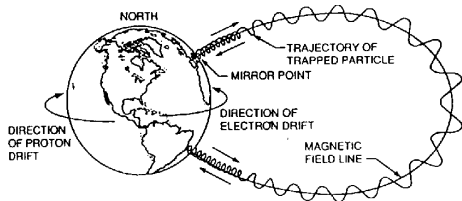
- From Biot-Savart's law of a circular current loop ,

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0 I}{4\pi} \int_C \frac{d\mathbf{r}' \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3},$$

- the magnetic field disturbance at the Earth's center is negative

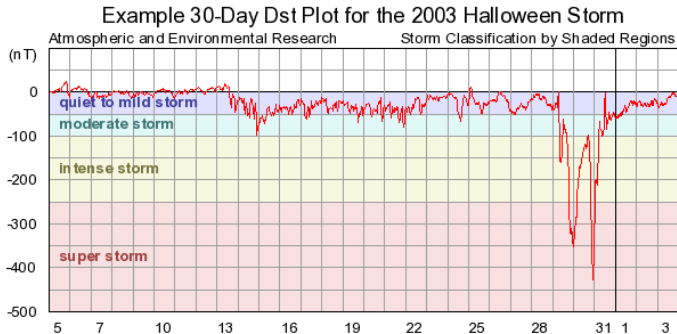
$$\Delta B_R = -\frac{\mu_0 U_R}{2\pi B_E R_E^3},$$

where U_R is total energy of all ring current particles.



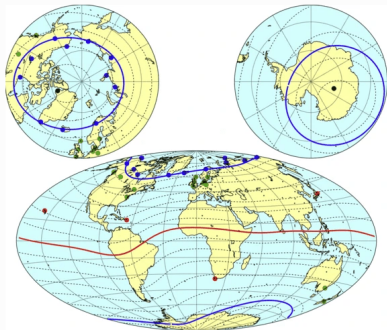
Ring current effect on the ground: magnetic storm

- Disturbance storm time (Dst) index homepage:
wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html
- Measured by stations at $\lambda \simeq \pm 20^\circ \dots 30^\circ$
- Duration can be several days, $Dst < -50$ nT, total current $\sim 10^7$ A



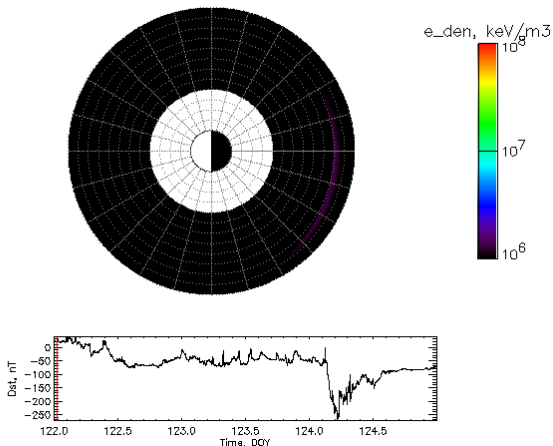
Kp -index

- Kp is a 3-hour index that describes the global level of all irregular disturbances of the geomagnetic field caused by solar wind



0 (Kp 0) Quiet	1 (Kp 1) Quiet	2 (Kp 2) Unsettled	3 (Kp 3) Unsettled	4 (Kp 4) Active
HIGH Geomagnetic latitudes WEAK & SLOW AURORA POSSIBLE	HIGH Geomagnetic latitudes WEAK & SLOW AURORA LIKELY	HIGH Geomagnetic latitudes MODERATE AURORAL DISPLAY	HIGH Geomagnetic latitudes ACTIVE AURORAL DISPLAY Significant substorms possible	HIGH Geomagnetic latitudes ACTIVE AURORAL DISPLAY Multiple significant substorms possible
LOW Geomagnetic latitudes AURORA EXTREMELY UNLIKELY	LOW Geomagnetic latitudes AURORA VERY UNLIKELY	LOW Geomagnetic latitudes AURORA UNLIKELY	LOW Geomagnetic latitudes WEAK AURORA DISPLAY POSSIBLE	LOW Geomagnetic latitudes WEAK AURORA DISPLAY POSSIBLE
Peaceful source Break value of particles due to some recombinations mostly at the magnetopause	Peaceful source Break value of particles due to some recombinations mostly at the magnetopause	Peaceful source Break value of particles due to some recombinations mostly at the magnetopause	Peaceful source Coronal hole windings take 10 days or less to reach Earth	Peaceful source Coronal hole windings take 10 days or less to reach Earth
9 (G5) Extreme Geomagnetic Storm	8 (G4) Severe Geomagnetic Storm	7 (G3) Strong Geomagnetic Storm	6 (G2) Moderate Geomagnetic Storm	5 (G1) Minor Geomagnetic Storm
HIGH Geomagnetic latitudes EXTREMELY STRONG AURORA Long periods of substorming	HIGH Geomagnetic latitudes EXTREMELY STRONG AURORA Long periods of substorming	HIGH Geomagnetic latitudes VERY STRONG AURORAL DISPLAY Long periods of substorming	HIGH Geomagnetic latitudes STRONG AURORAL DISPLAY larger substorms	HIGH Geomagnetic latitudes VERY ACTIVE DISPLAY Multiple substorms daily
LOW Geomagnetic latitudes VERY STRONG AURORAL DISPLAY extended aurora possible	LOW Geomagnetic latitudes STRONG AURORAL DISPLAY EXTREMELY LIKELY	LOW Geomagnetic latitudes STRONG AURORAL DISPLAY VERY LIKELY	LOW Geomagnetic latitudes ACTIVE AURORAL DISPLAY VERY LIKELY	LOW Geomagnetic latitudes AURORAL DISPLAY LIKELY
Peaceful source Super IMF4 - Geomagnetic storms Geomagnetic storms with auroral activity	Peaceful source Large IMF4, followed by active periods Geomagnetic storms with auroral activity	Peaceful source Large IMF4 observed by solar observatories in Solar Wind Large enhanced solar wind with strong auroral activity	Peaceful source Coronal hole sending fast winds for 10 days Coronal hole sending fast winds	Peaceful source Coronal hole sending fast winds for 10 days Coronal hole sending fast winds

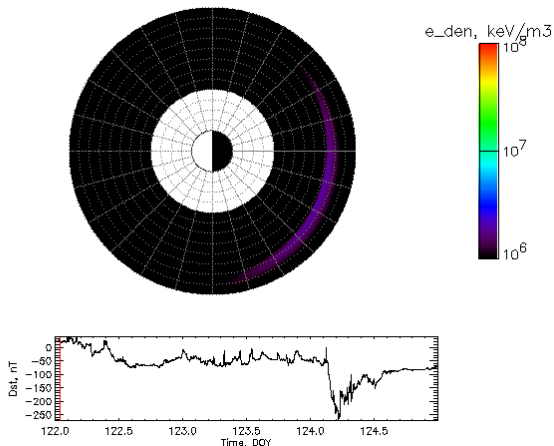
Ring Current Protons



Inner Magnetosphere
Particle Transport and
Acceleration Model
(IMPTAM)

Energy density,
3 days, May 2–4,
1998

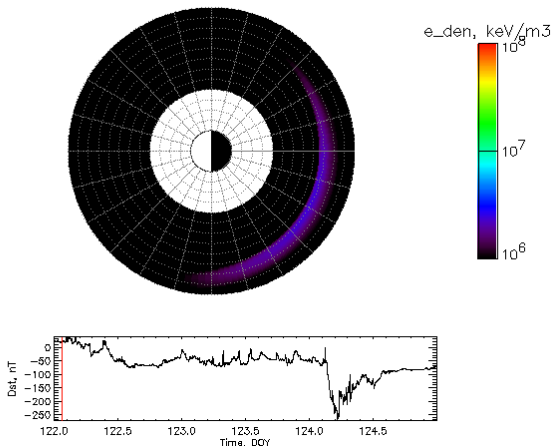
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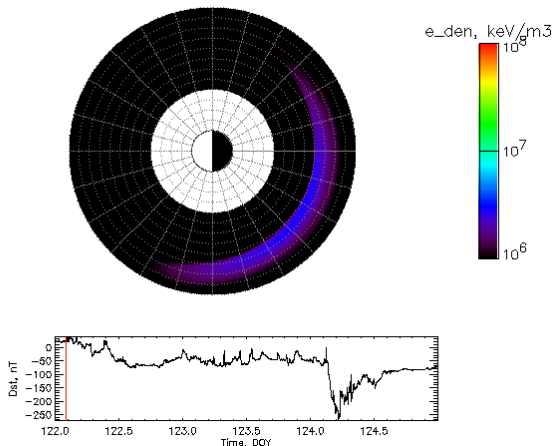
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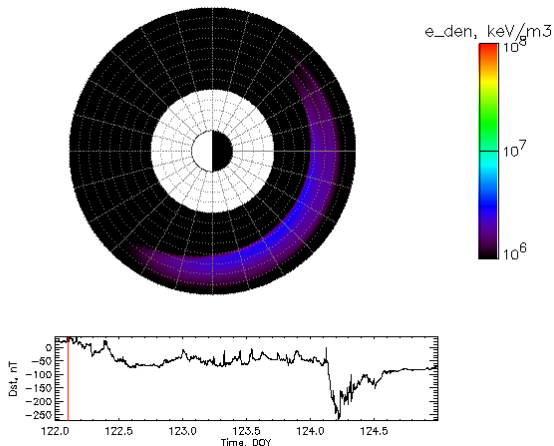
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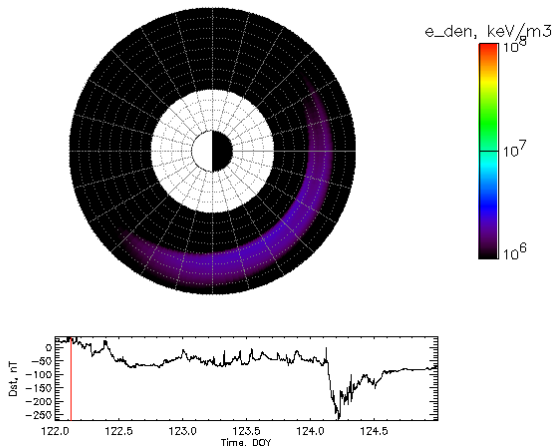
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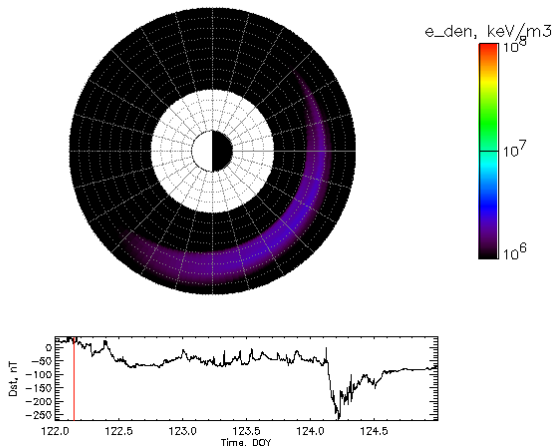
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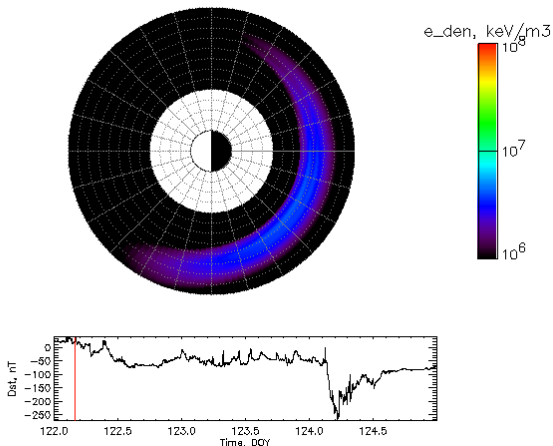
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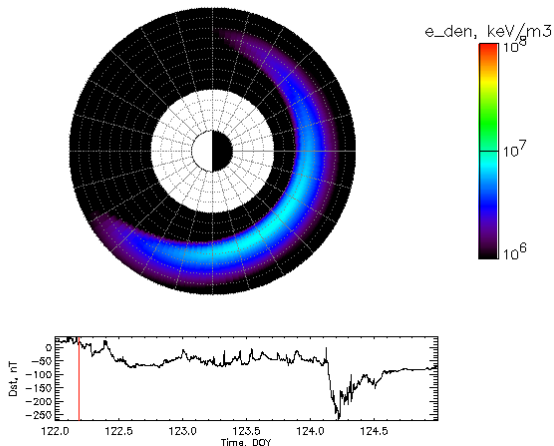
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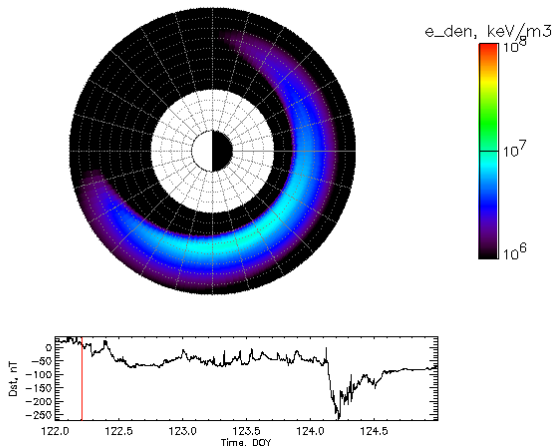
Energy density,
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Ring Current Protons



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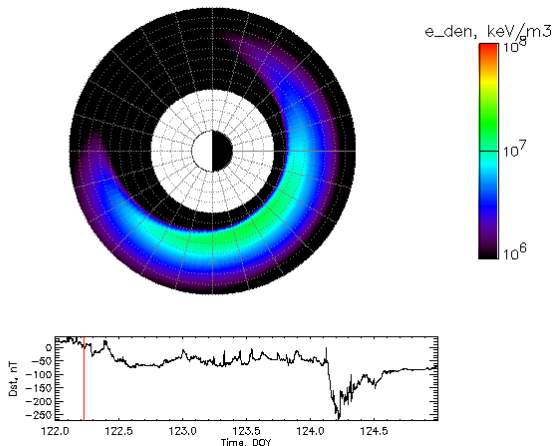
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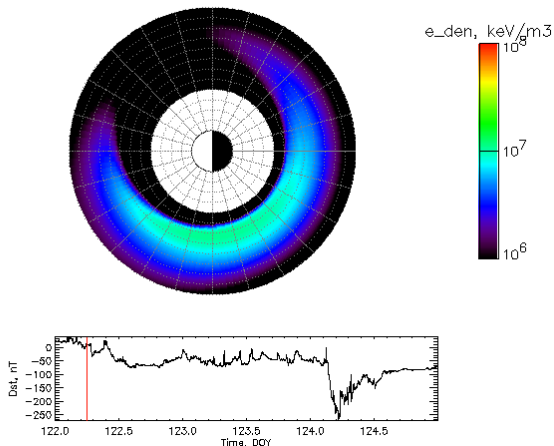
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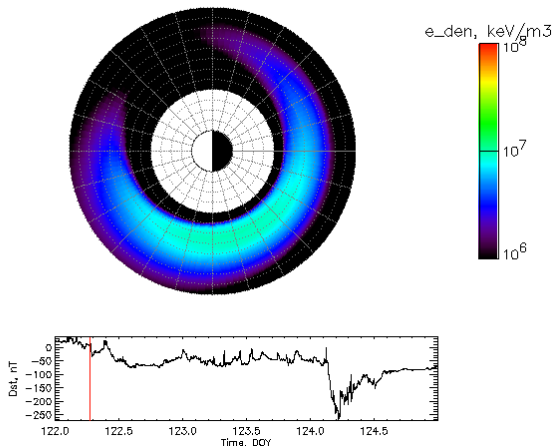
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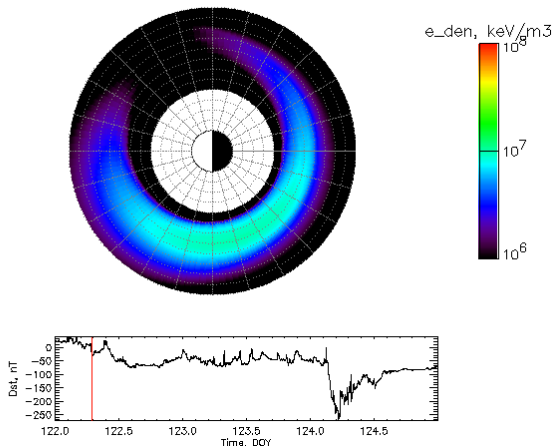
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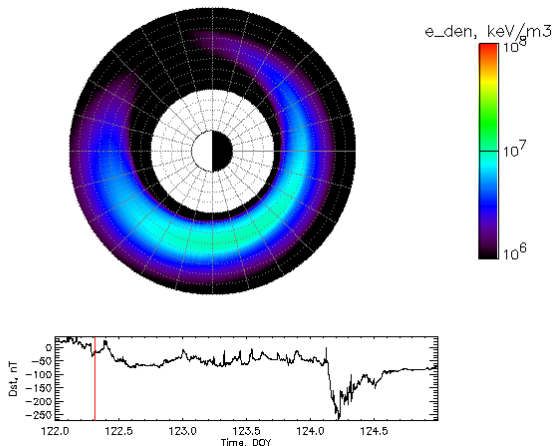
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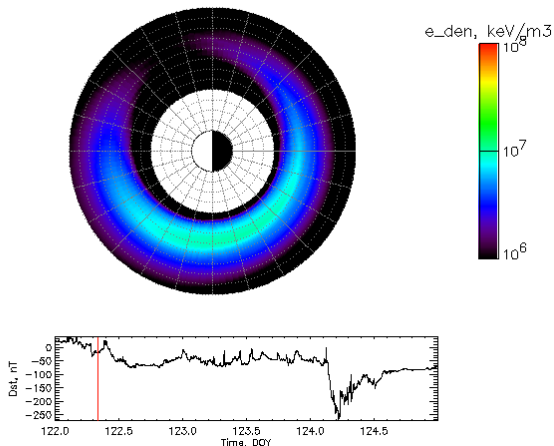
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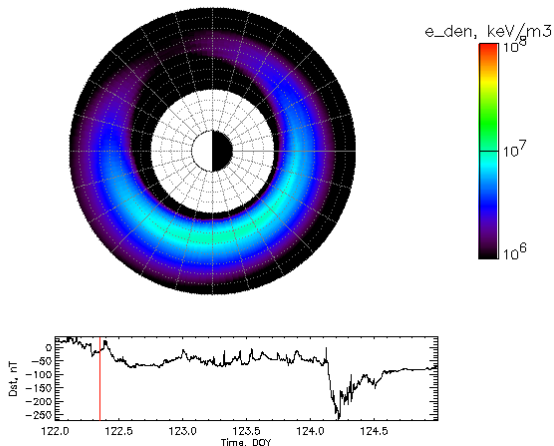
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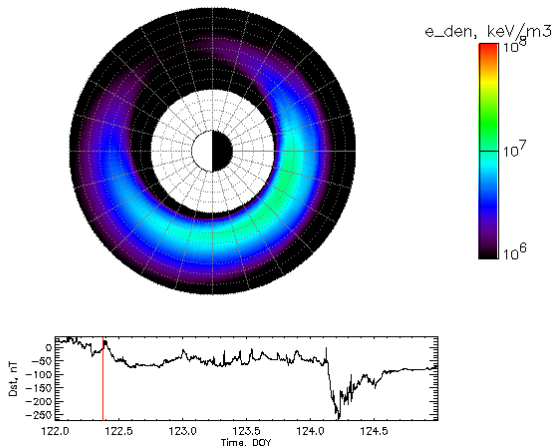
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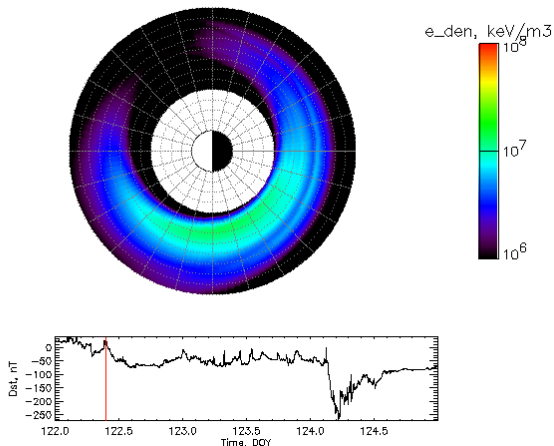
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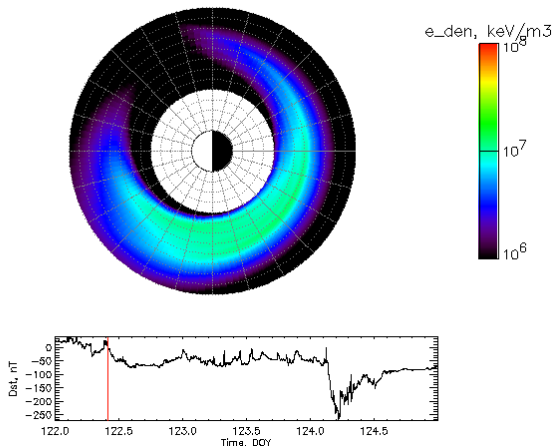
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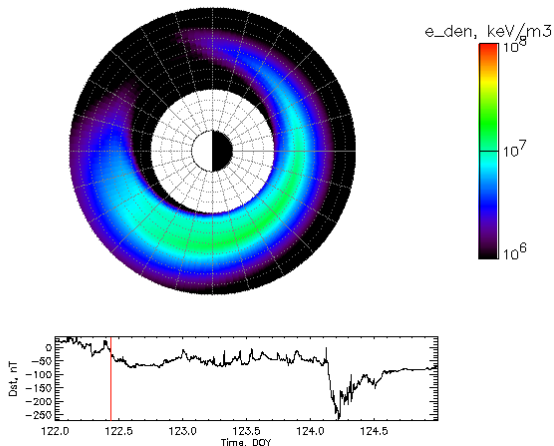
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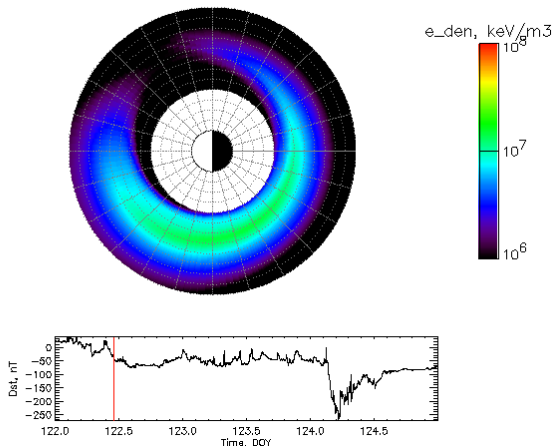
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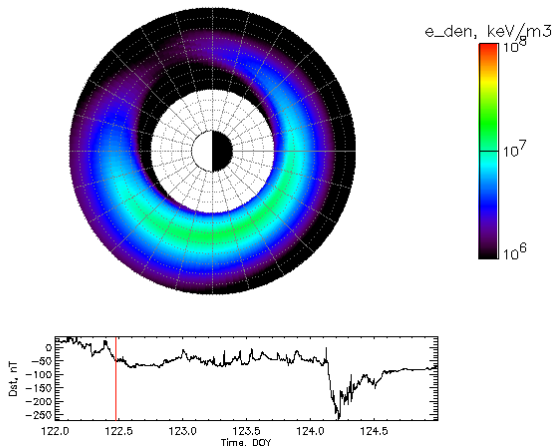
Ring Current Protons



Inner Magnetosphere
Particle Transport and
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Energy density,
3 days, May 2–4,
1998

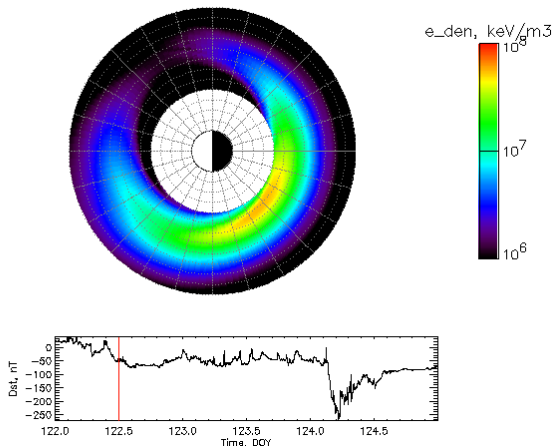
Ring Current Protons



Inner Magnetosphere
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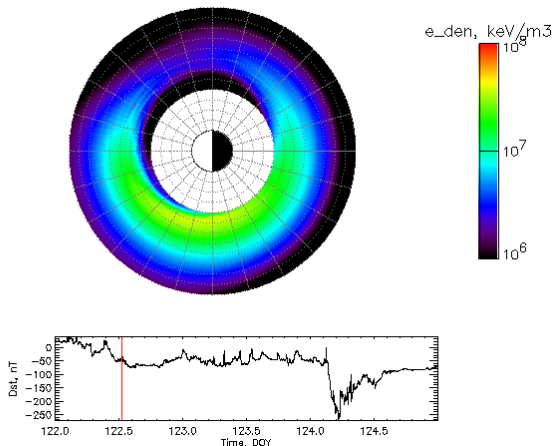
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1998

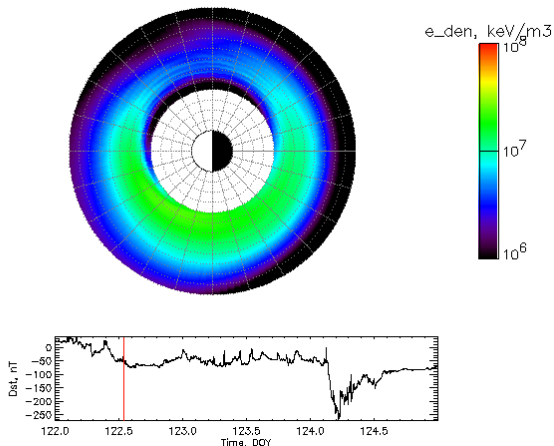
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Energy density,
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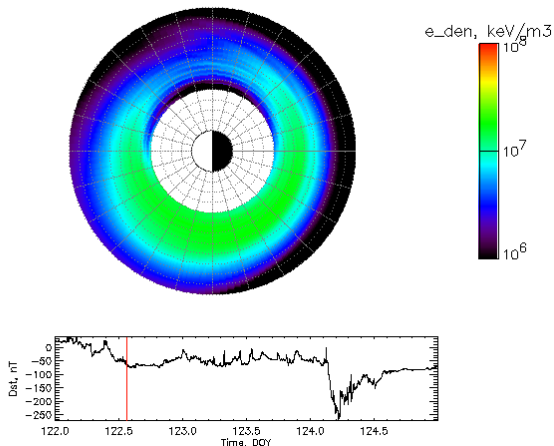
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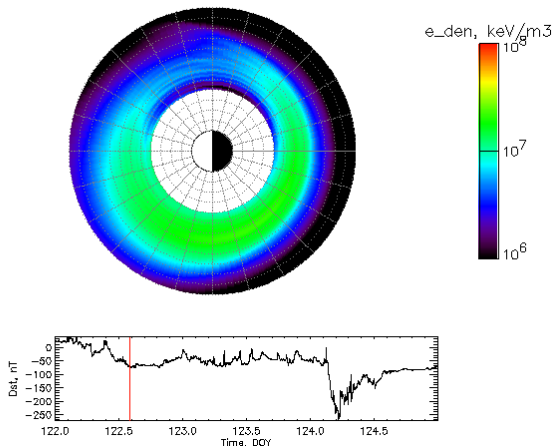
Ring Current Protons



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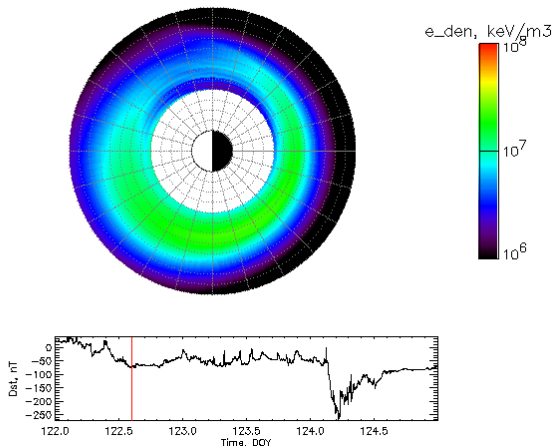
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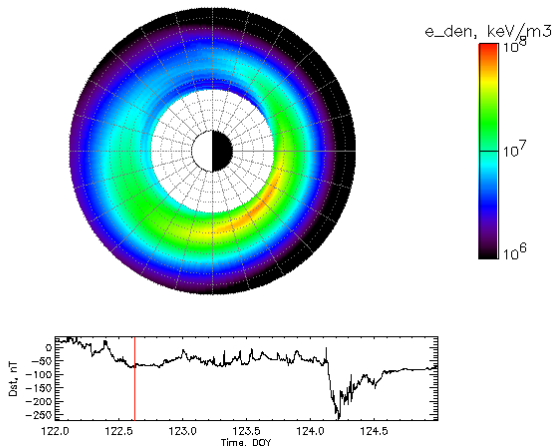
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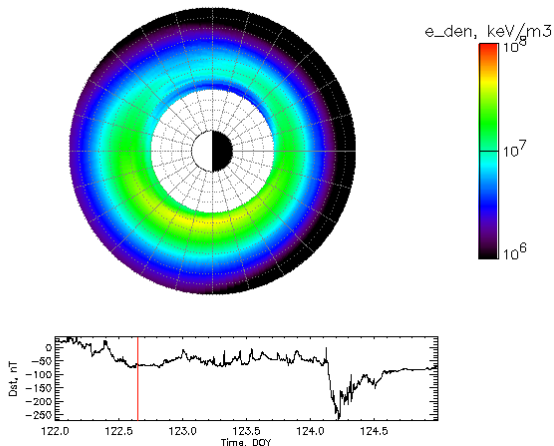
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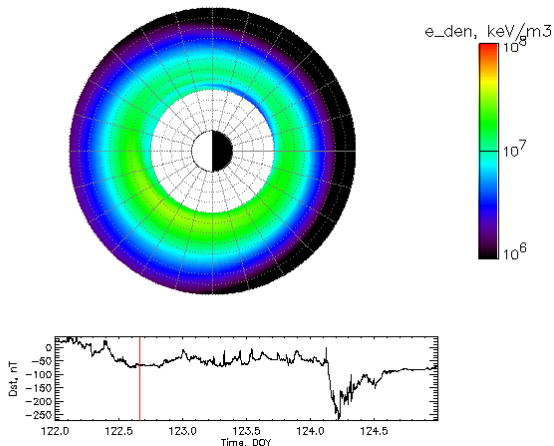
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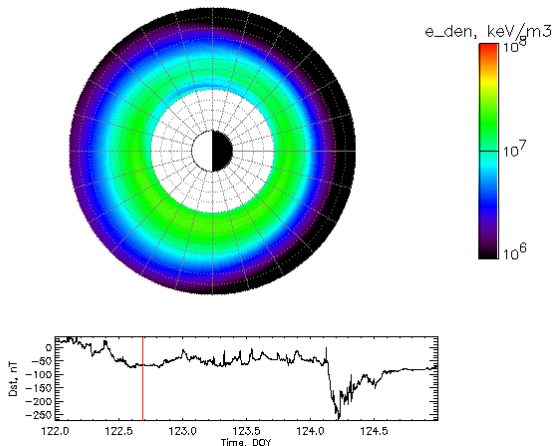
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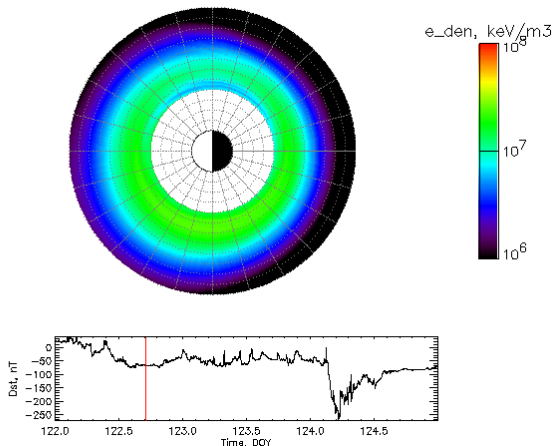
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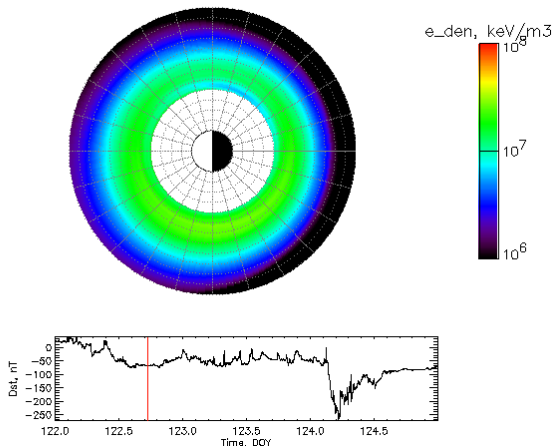
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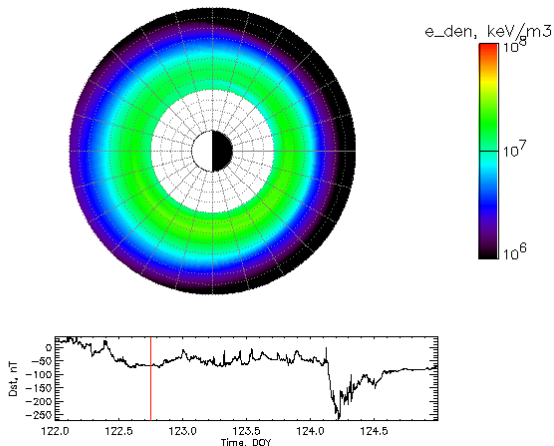
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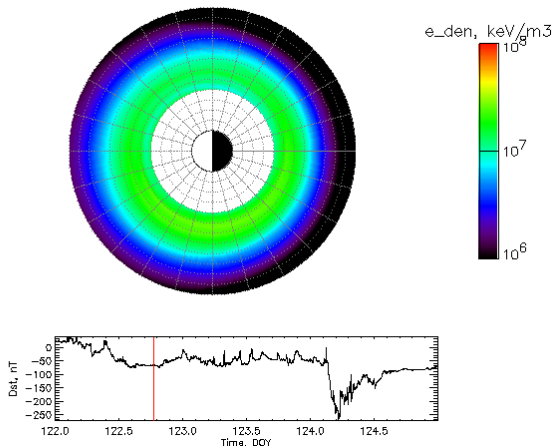
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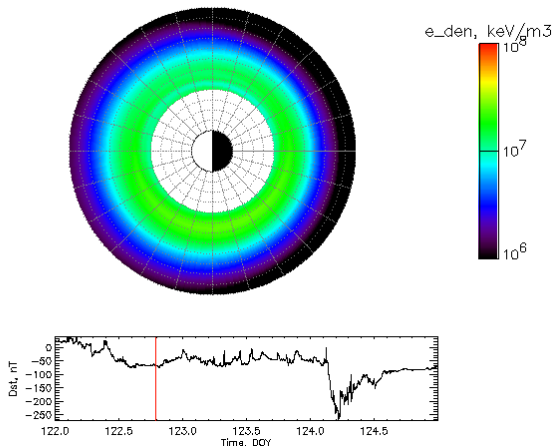
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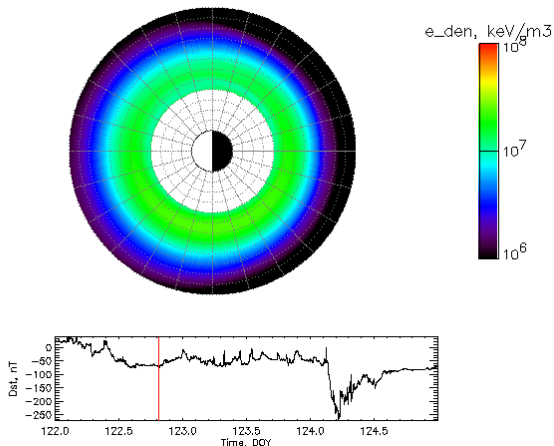
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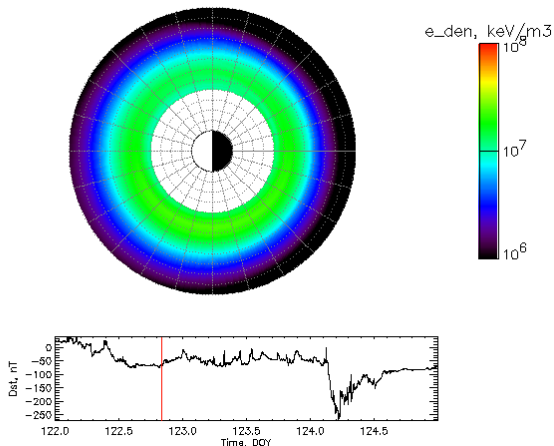
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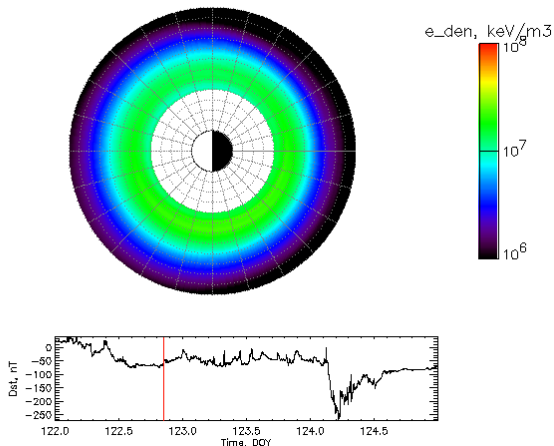
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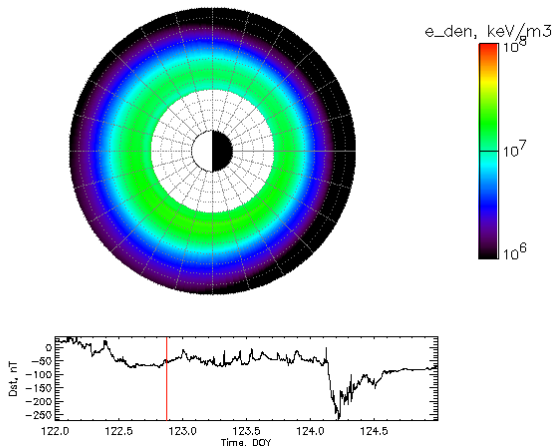
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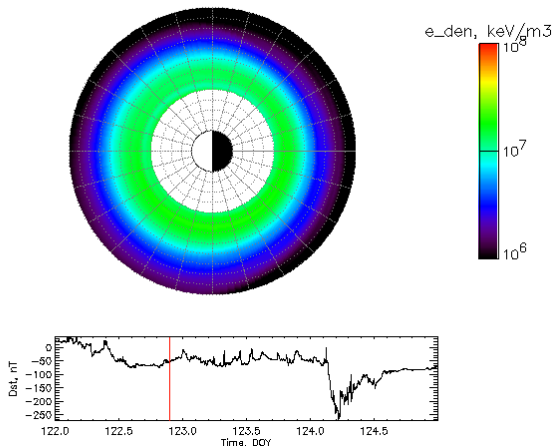
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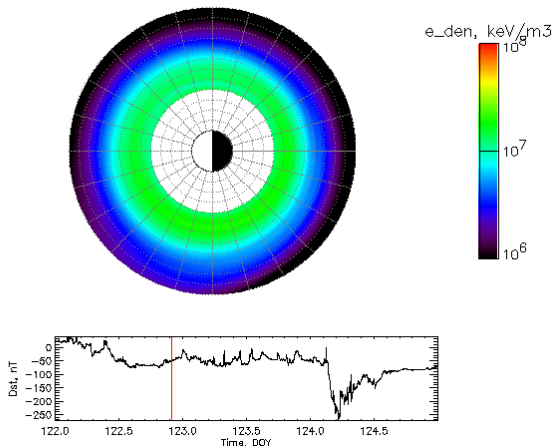
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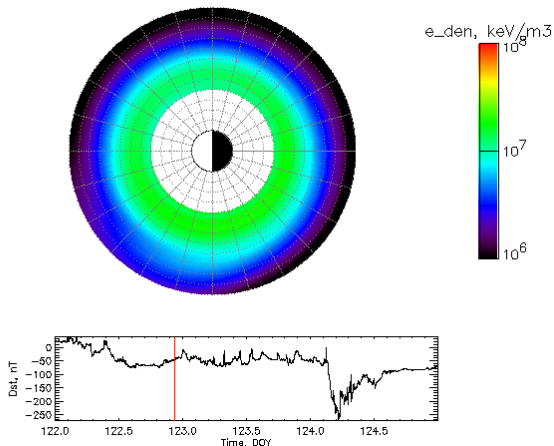
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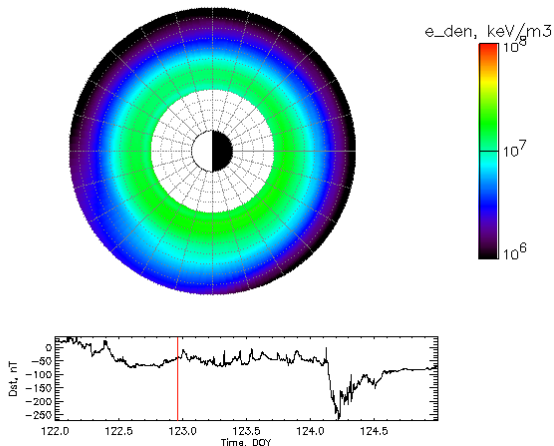
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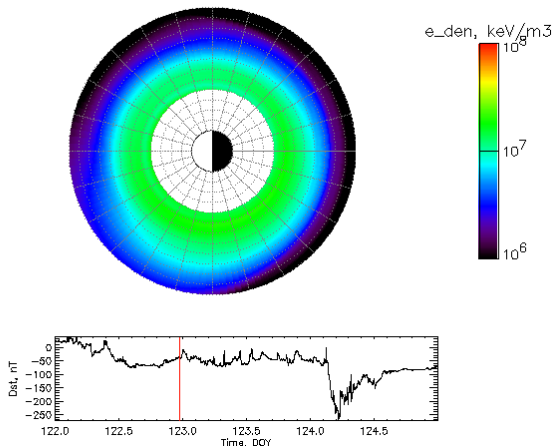
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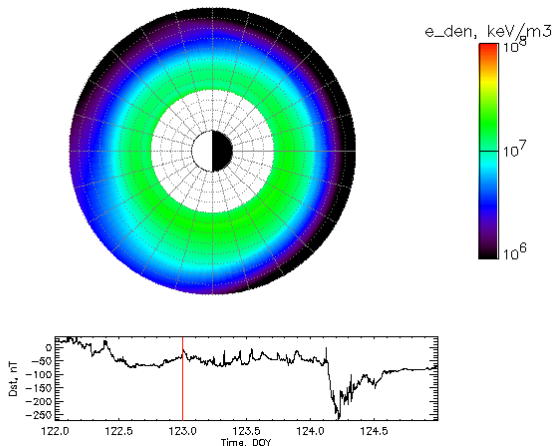
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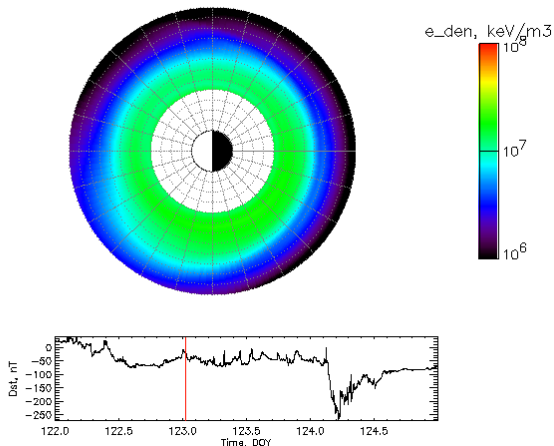
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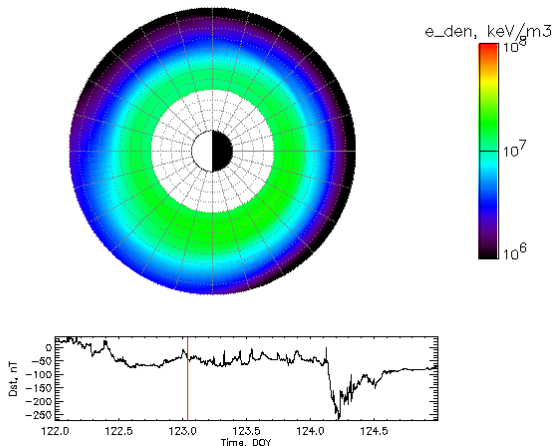
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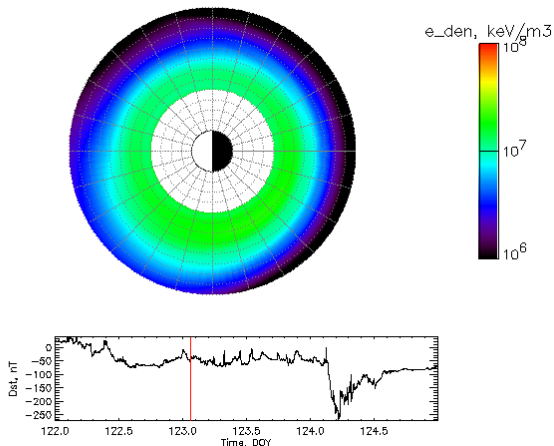
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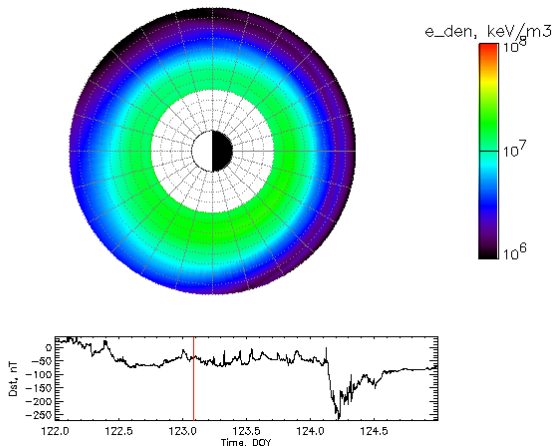
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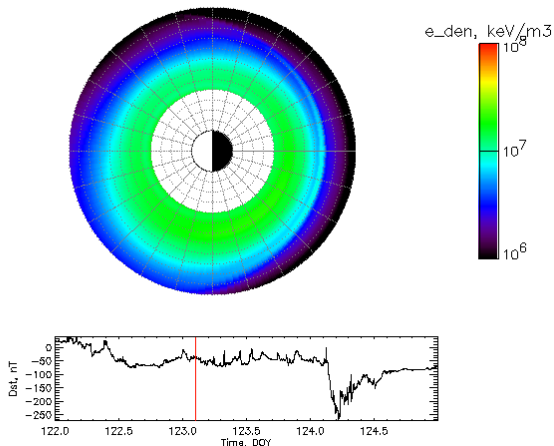
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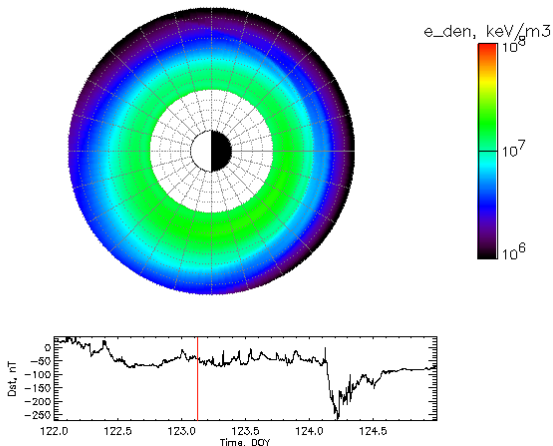
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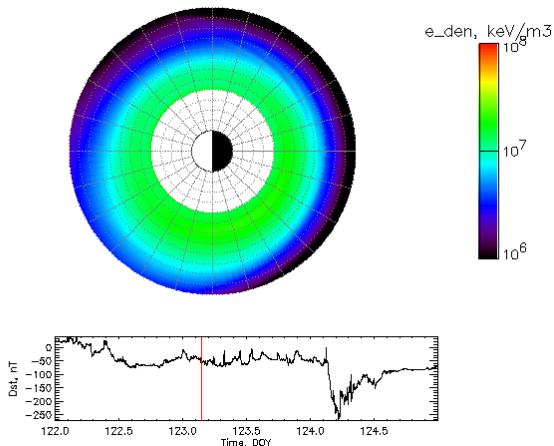
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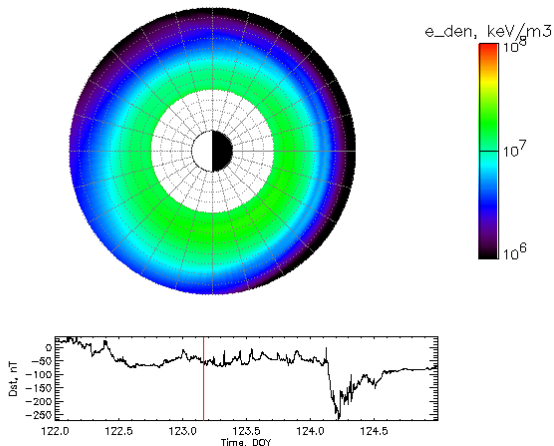
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Inner Magnetosphere
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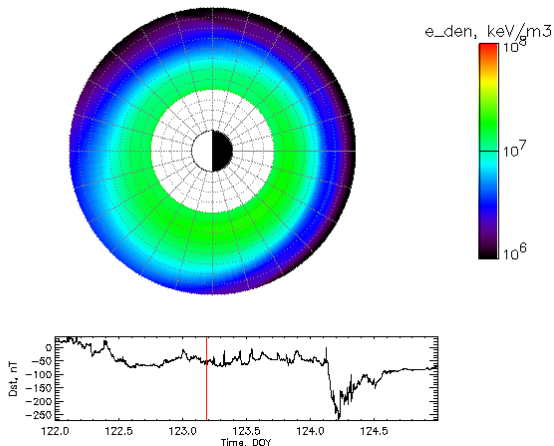
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Inner Magnetosphere
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Energy density,
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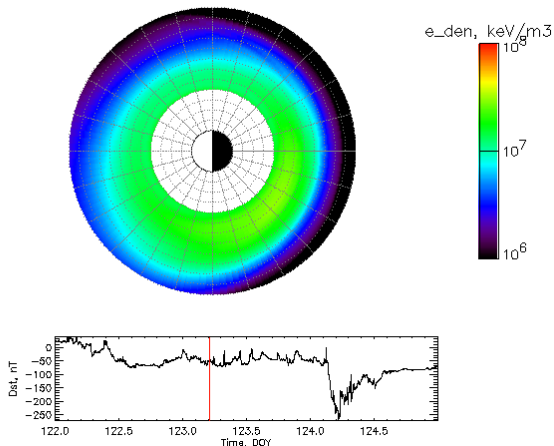
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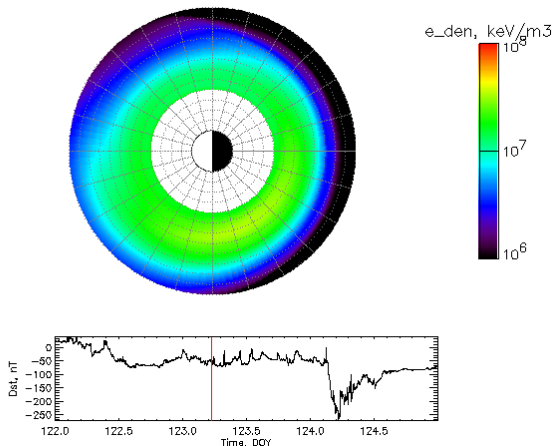
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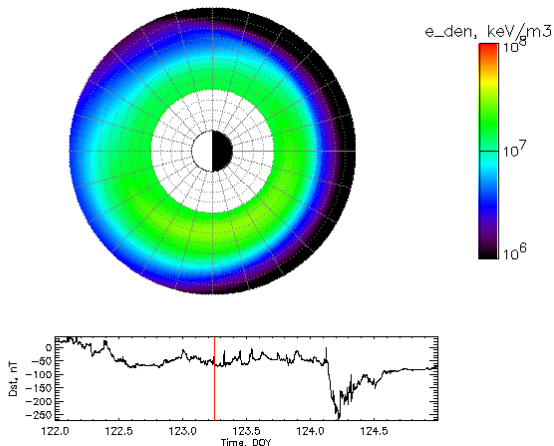
Ring Current Protons



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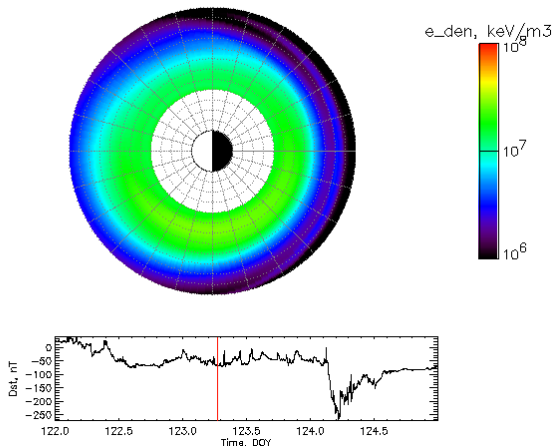
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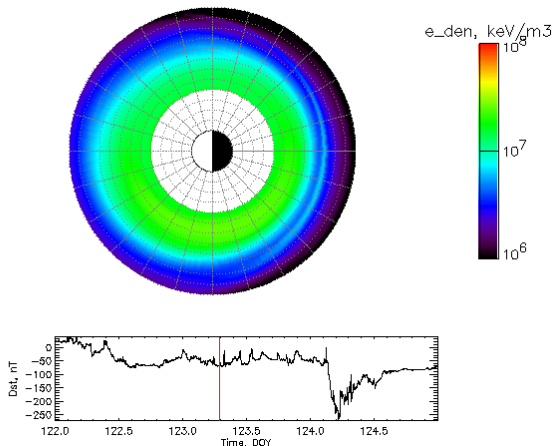
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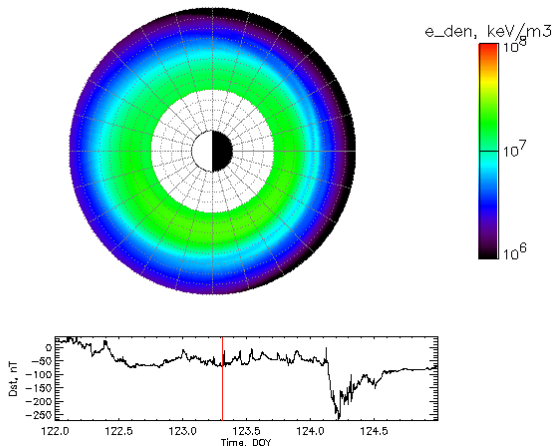
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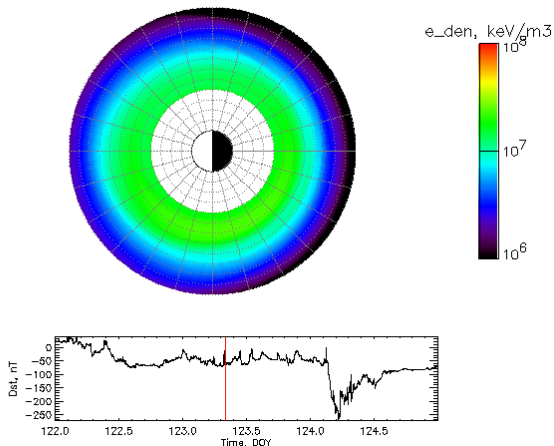
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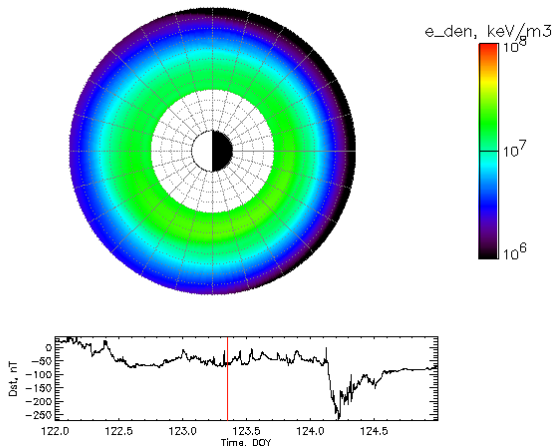
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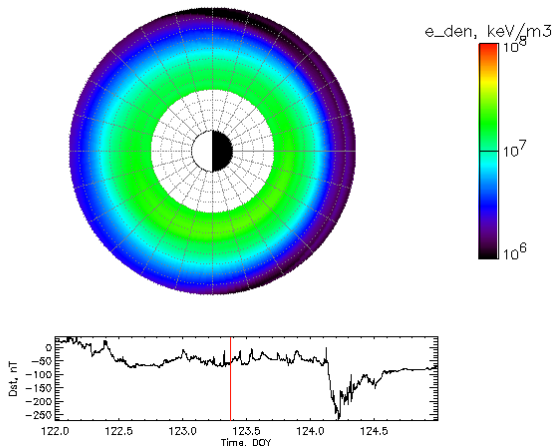
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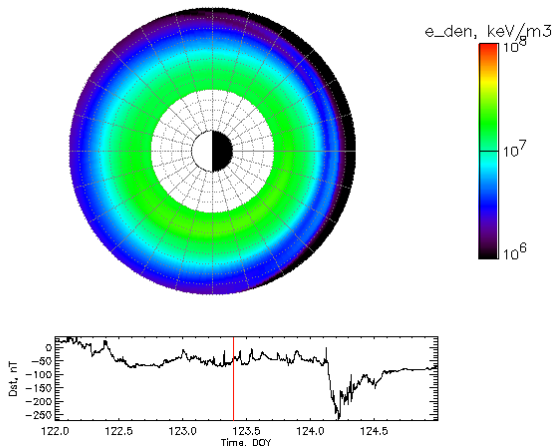
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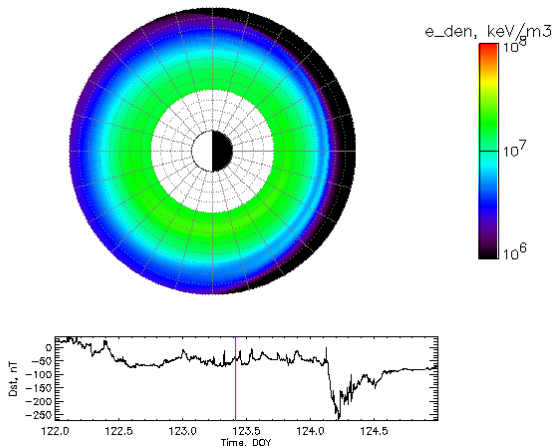
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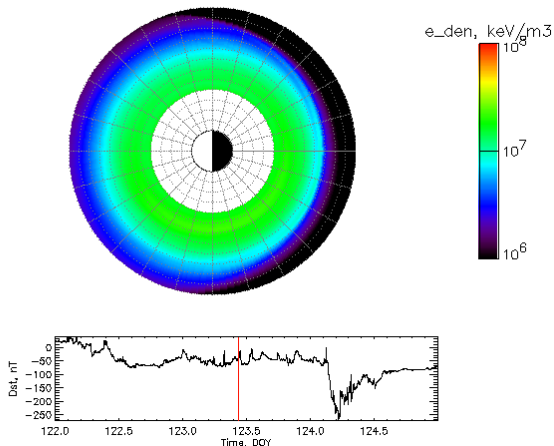
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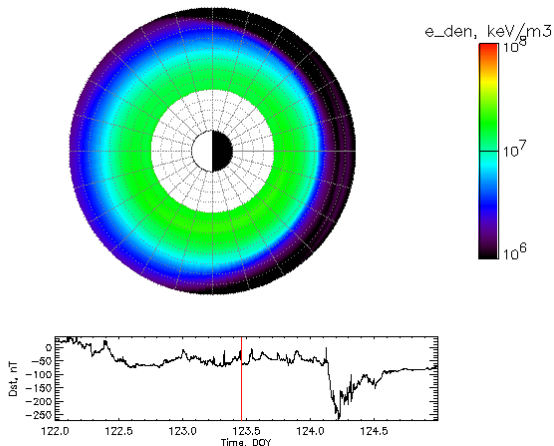
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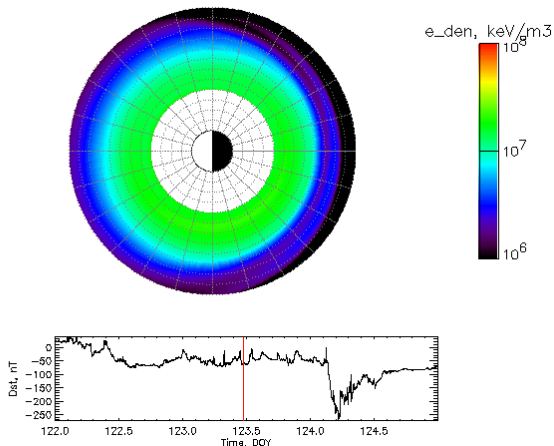
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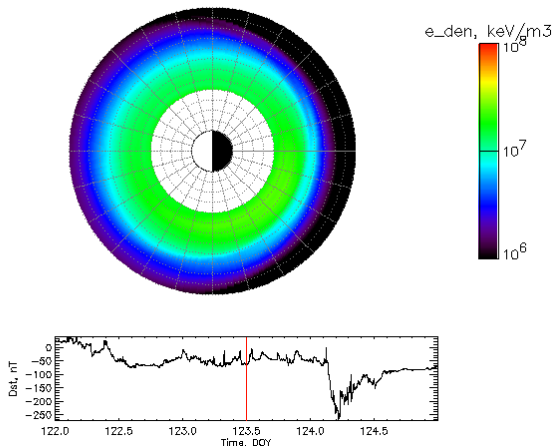
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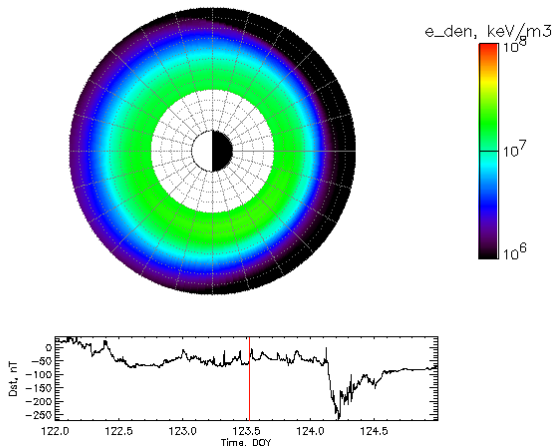
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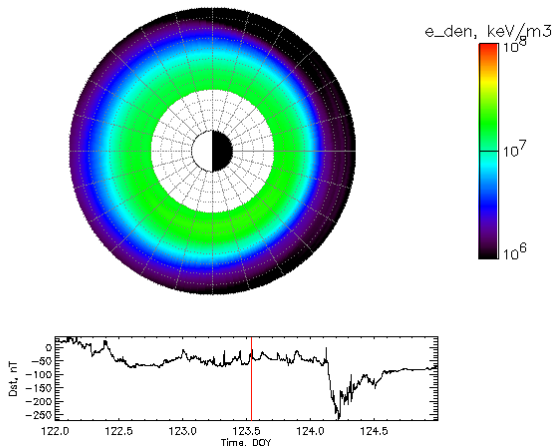
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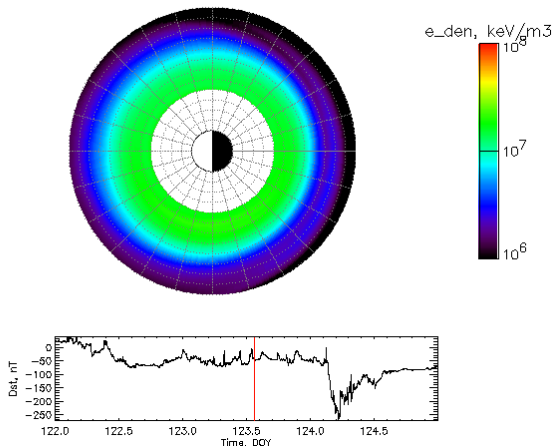
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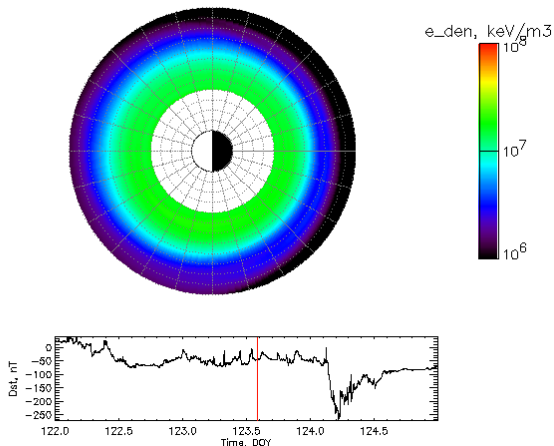
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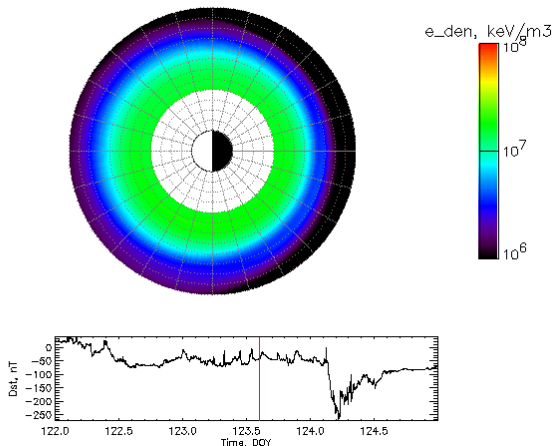
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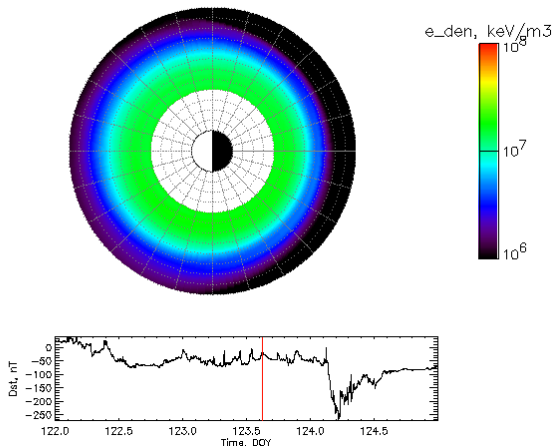
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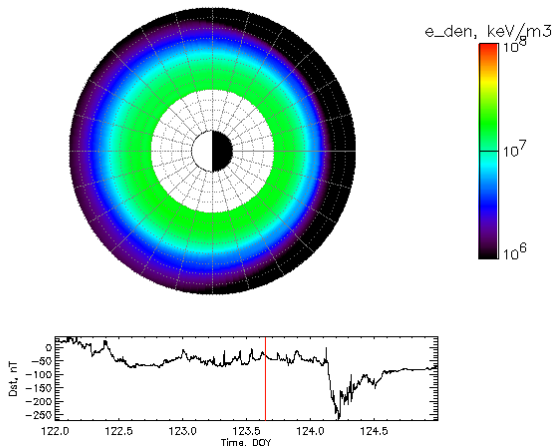
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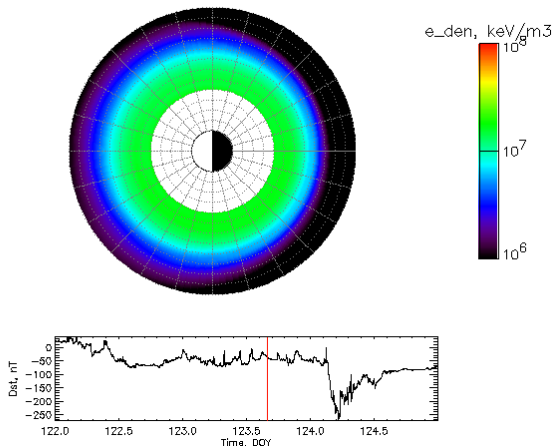
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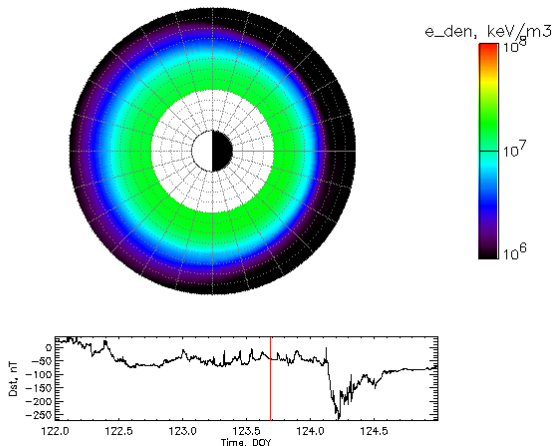
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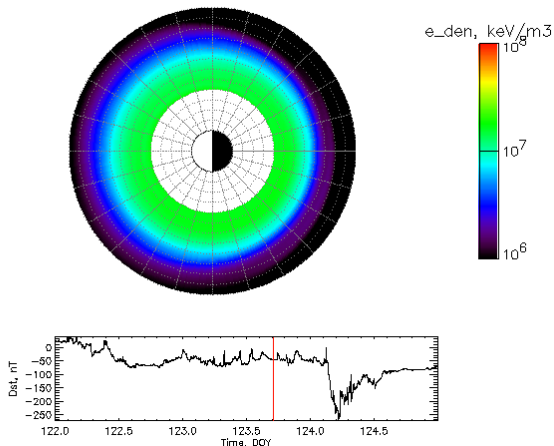
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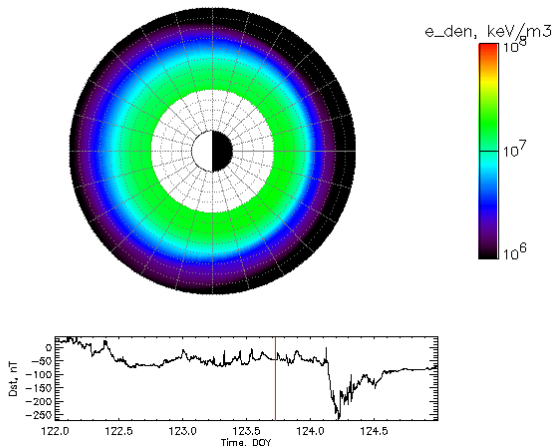
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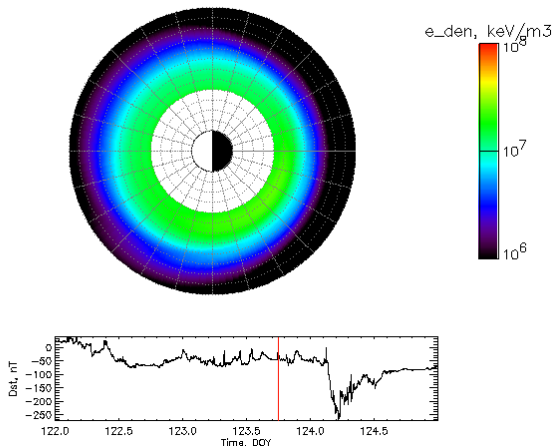
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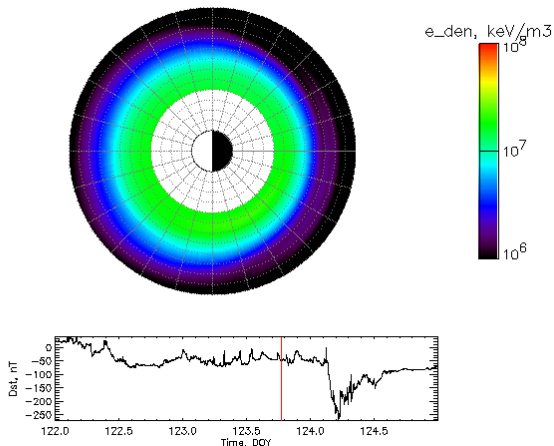
Ring Current Protons



Inner Magnetosphere
Particle Transport and
Acceleration Model
(IMPTAM)

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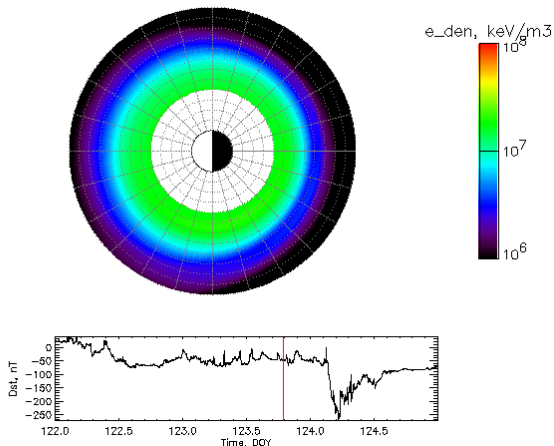
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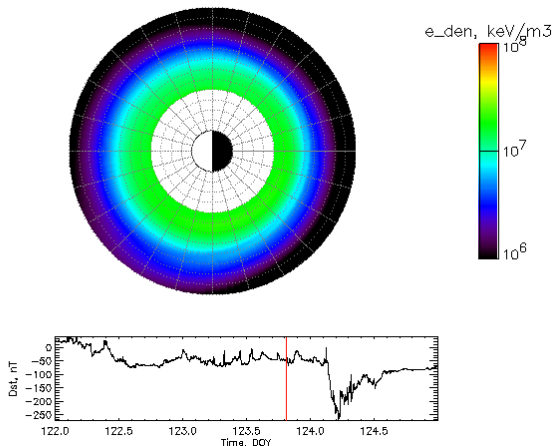
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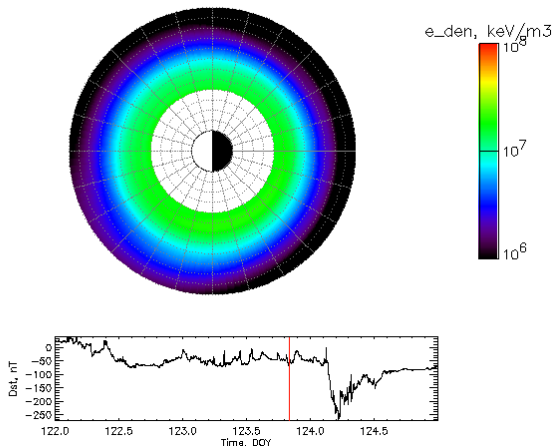
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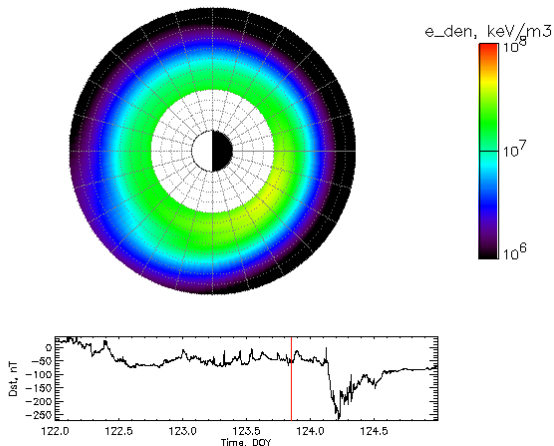
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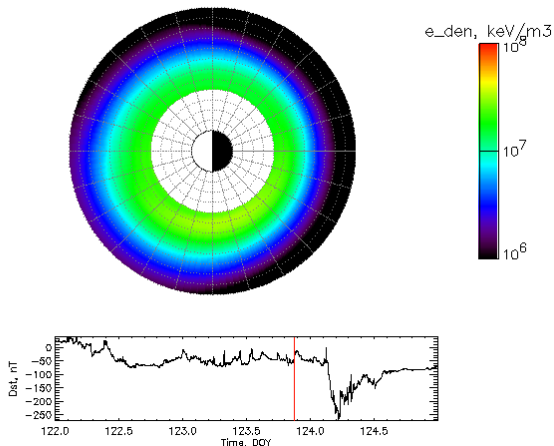
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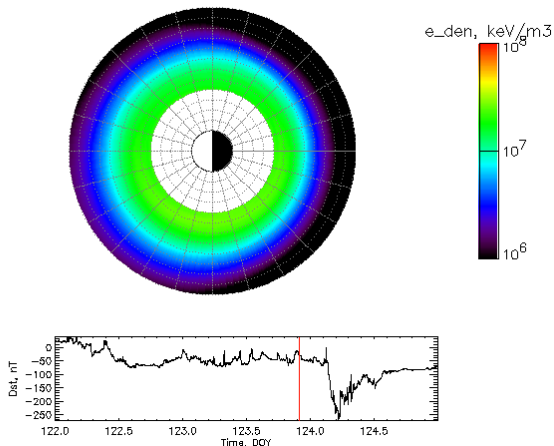
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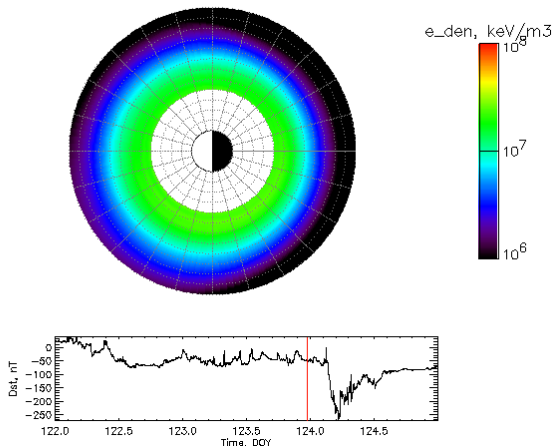
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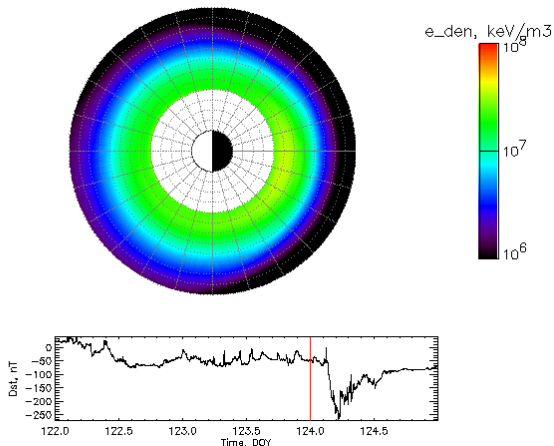
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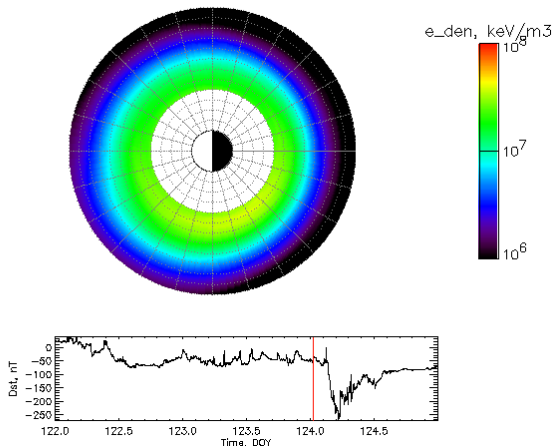
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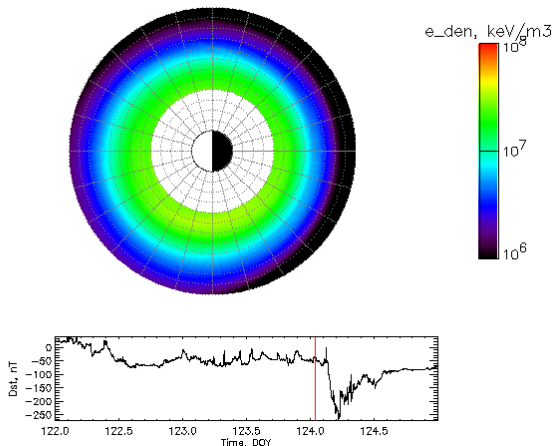
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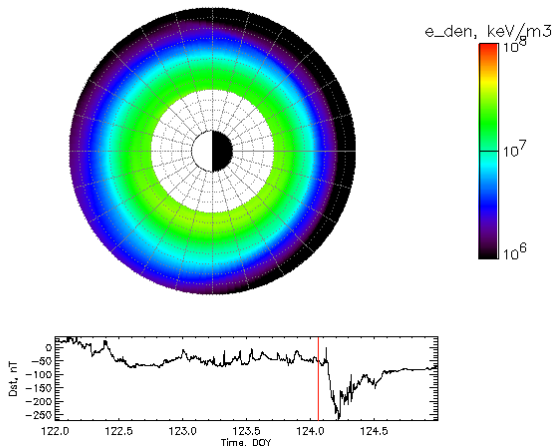
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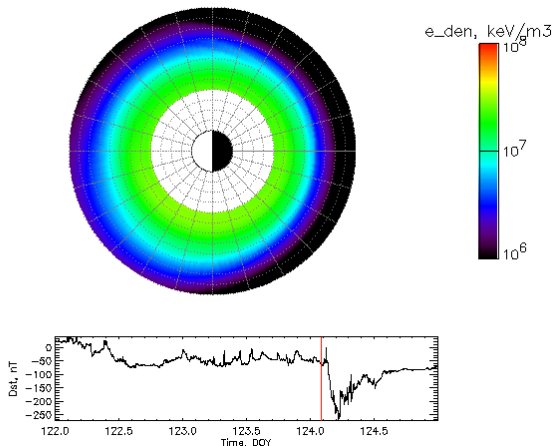
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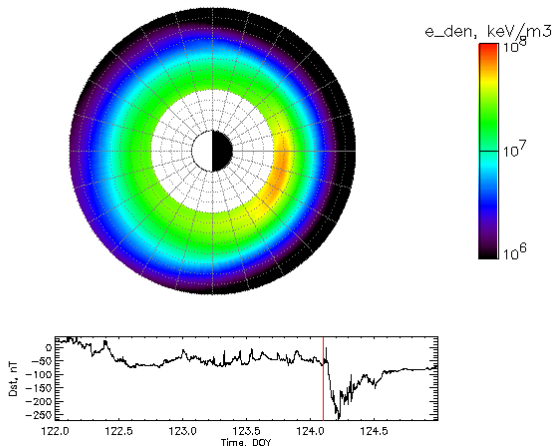
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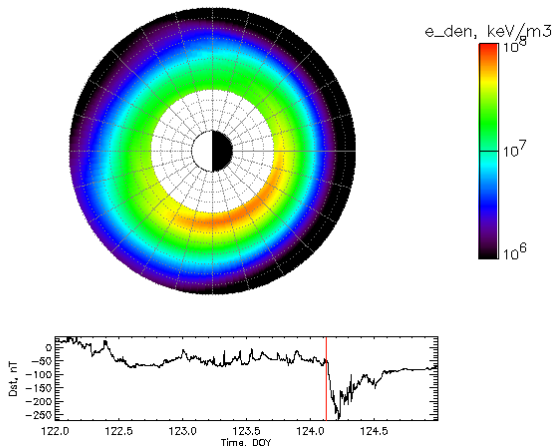
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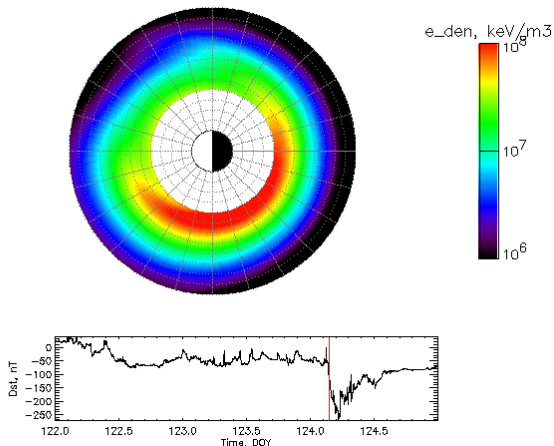
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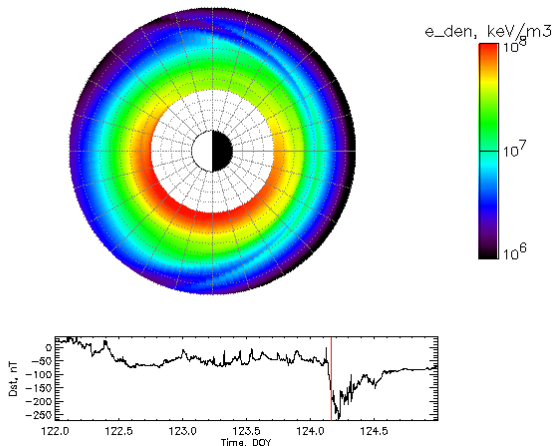
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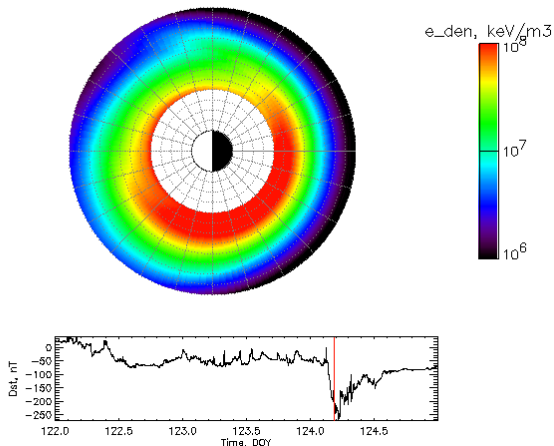
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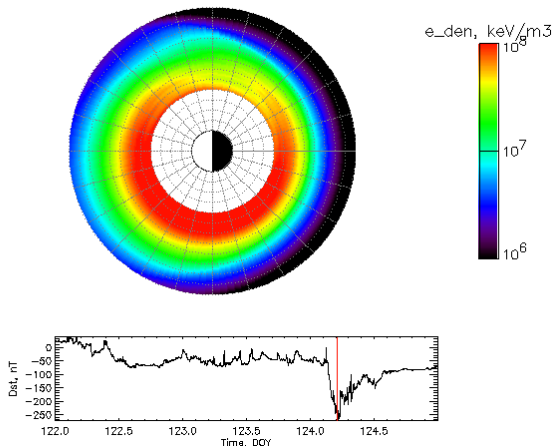
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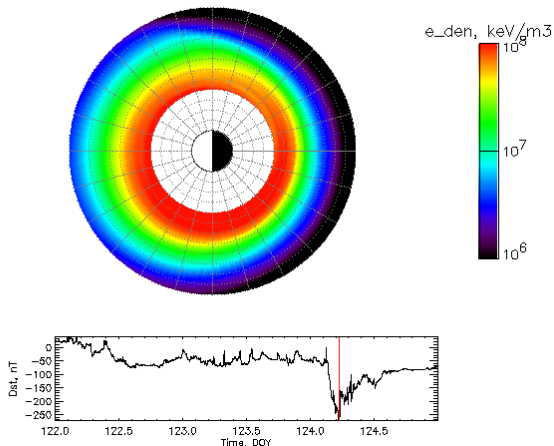
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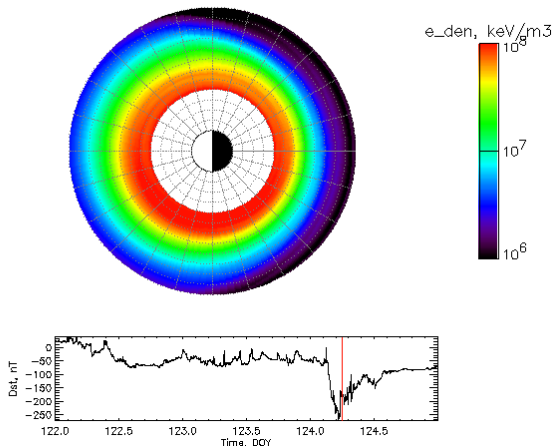
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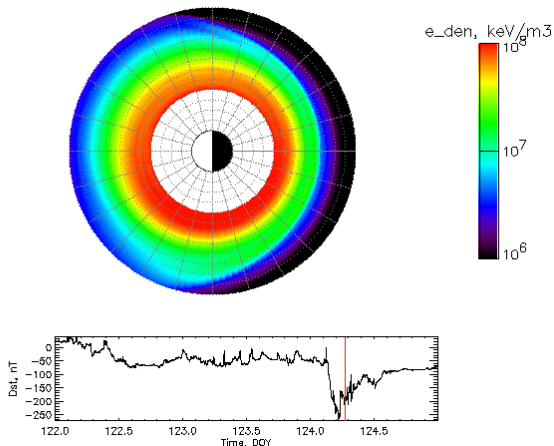
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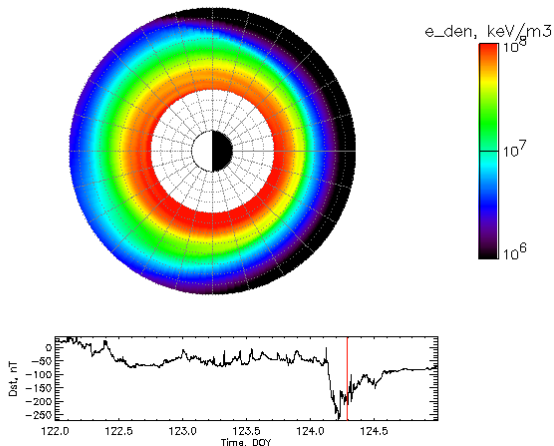
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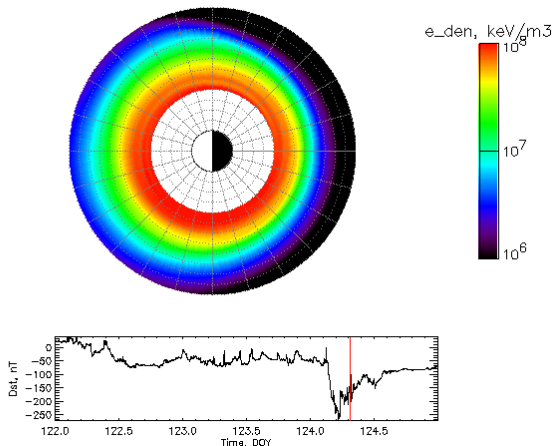
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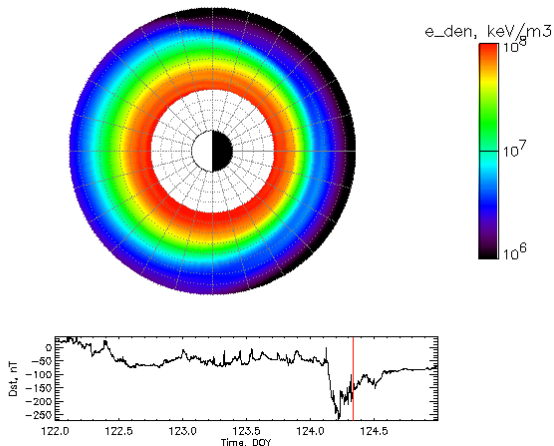
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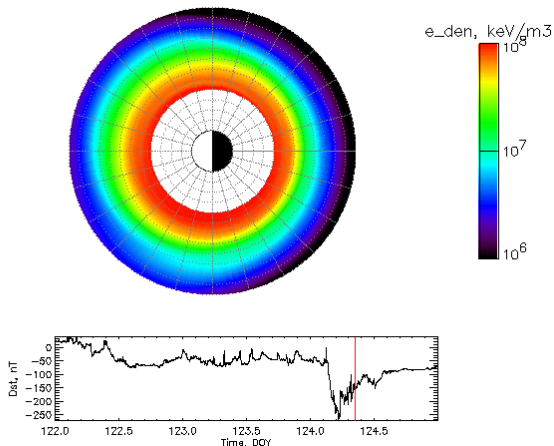
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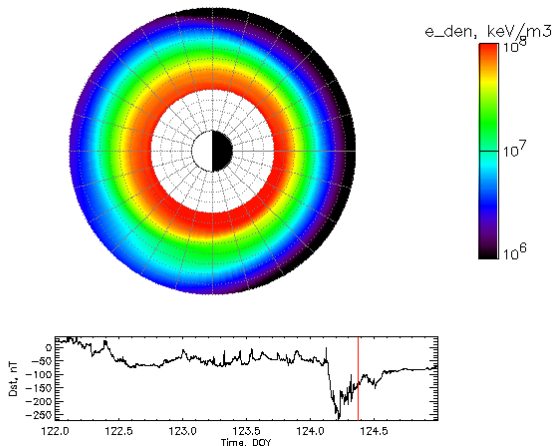
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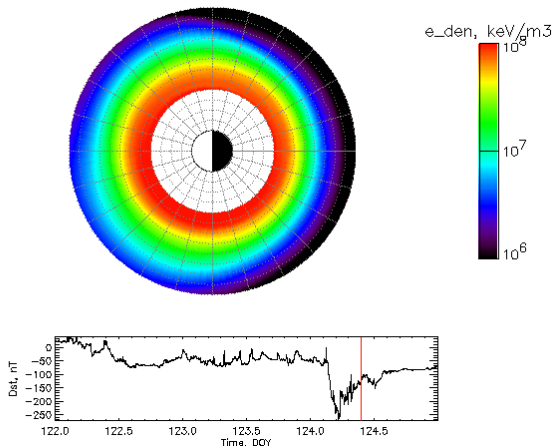
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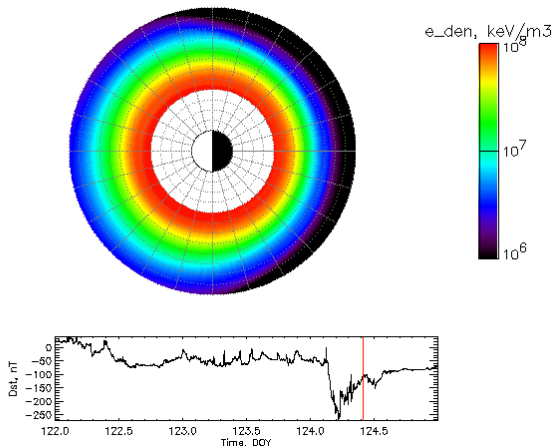
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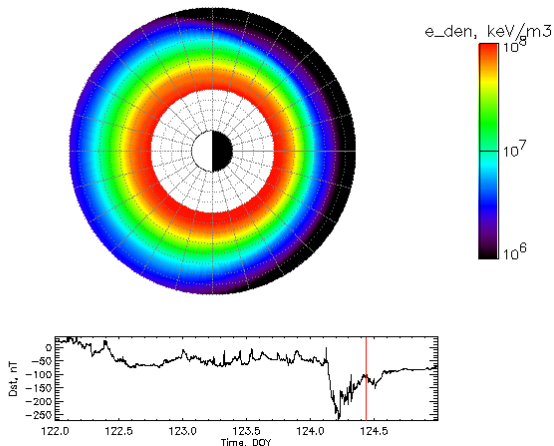
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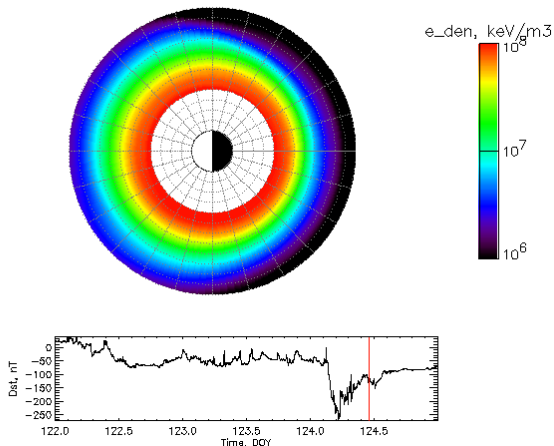
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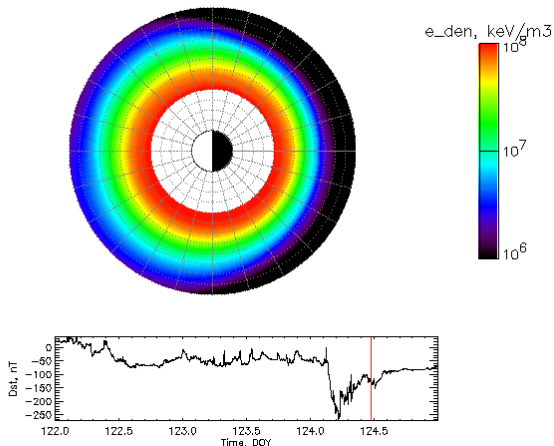
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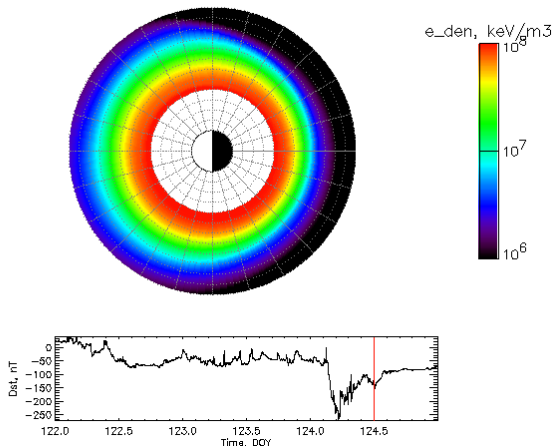
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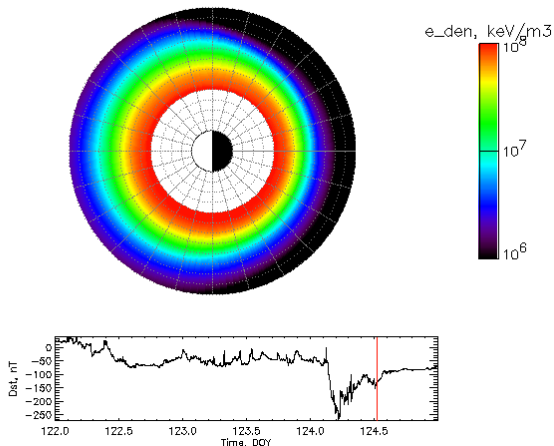
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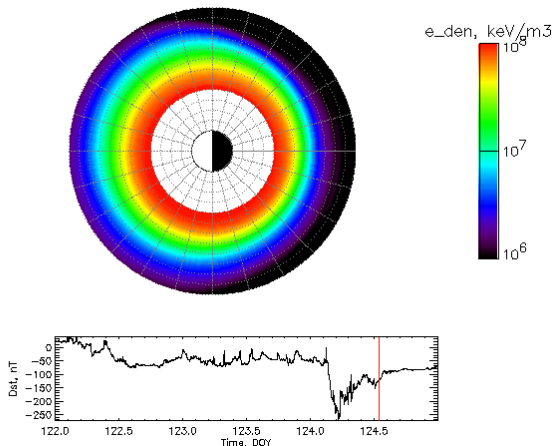
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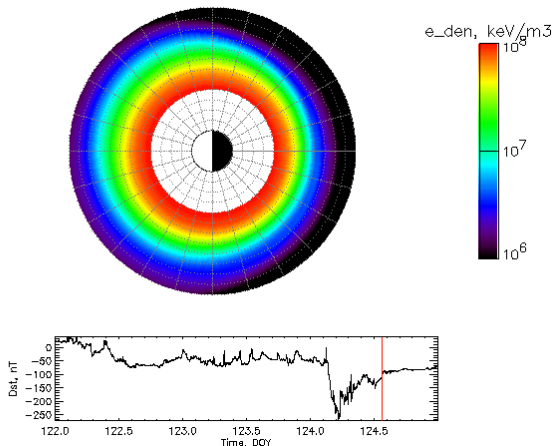
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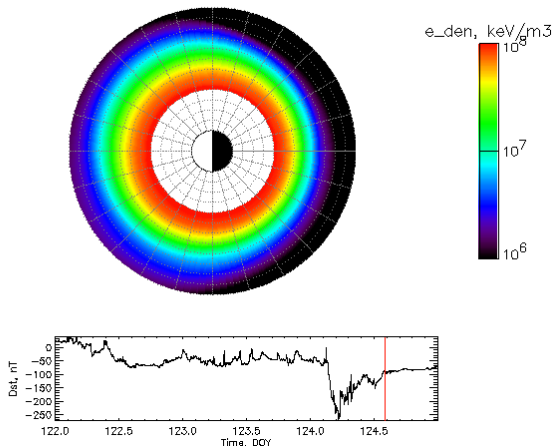
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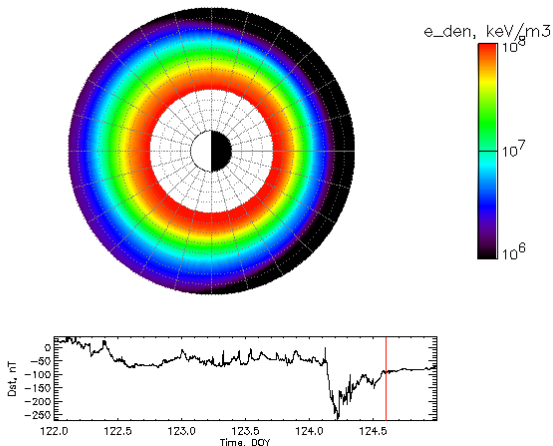
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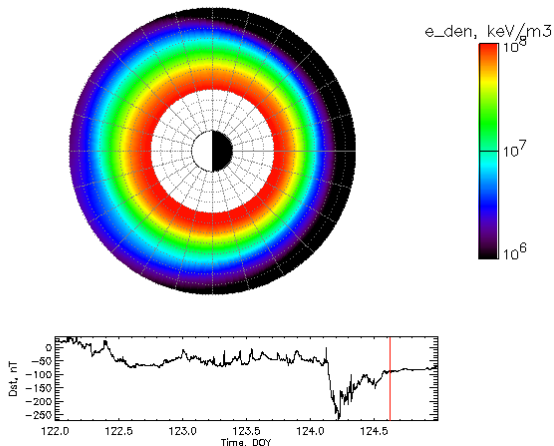
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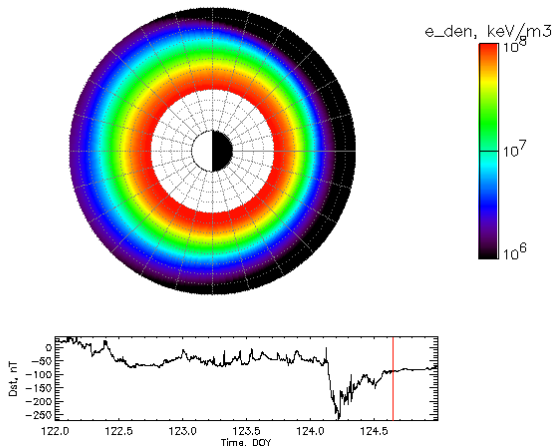
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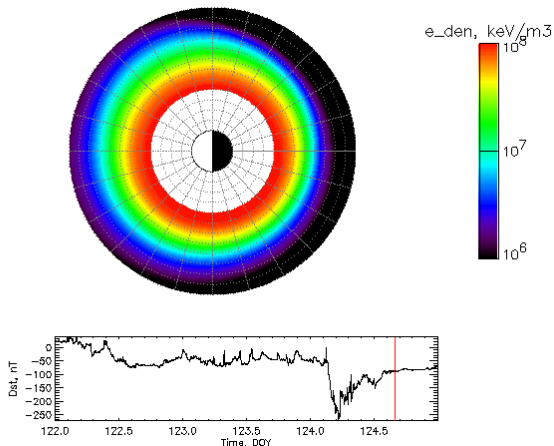
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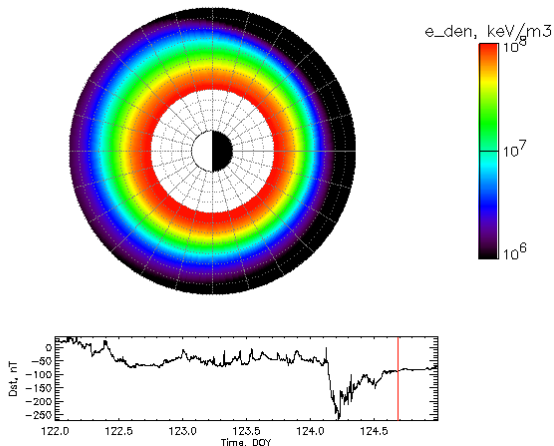
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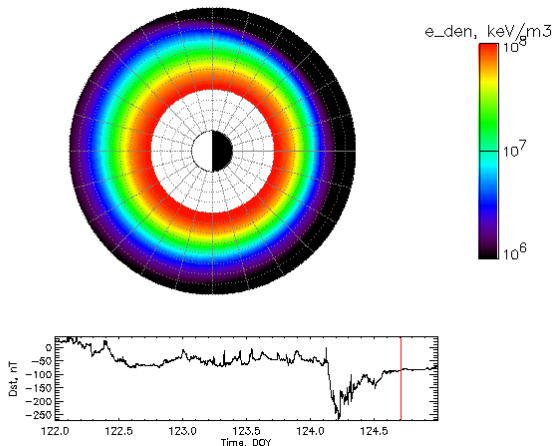
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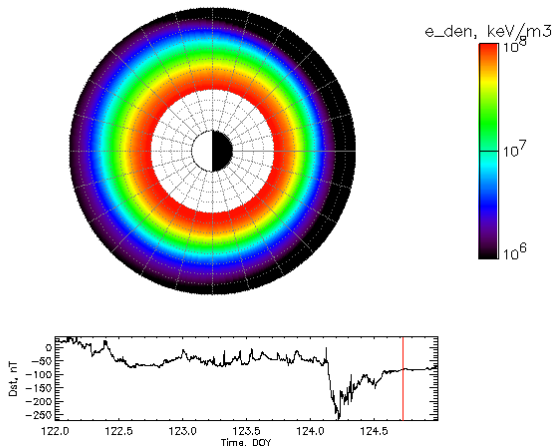
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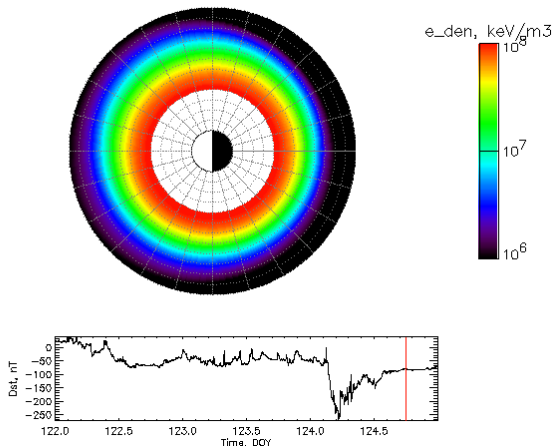
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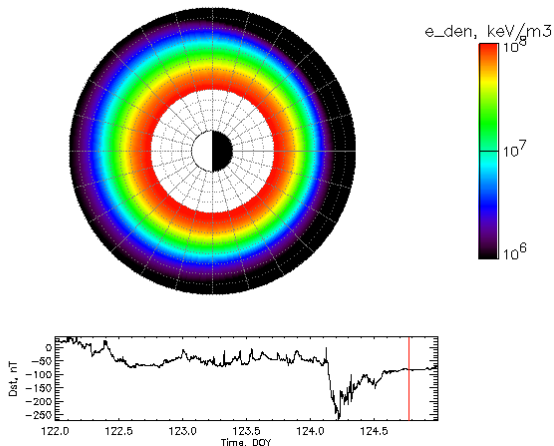
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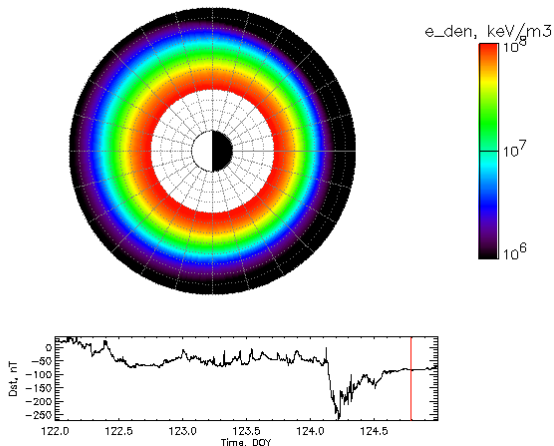
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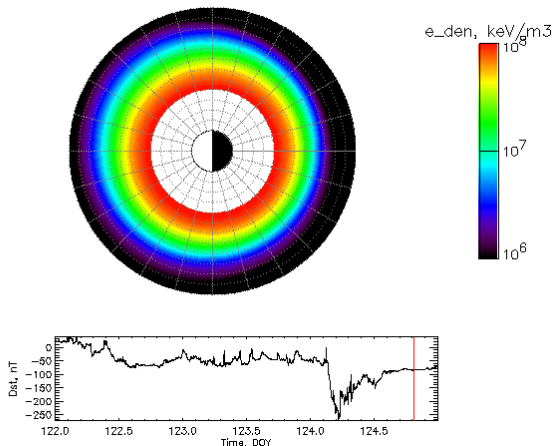
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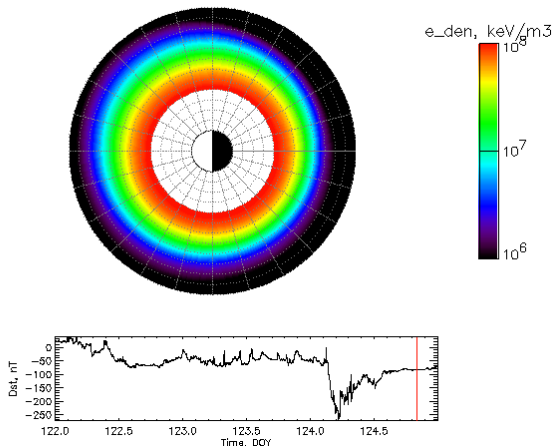
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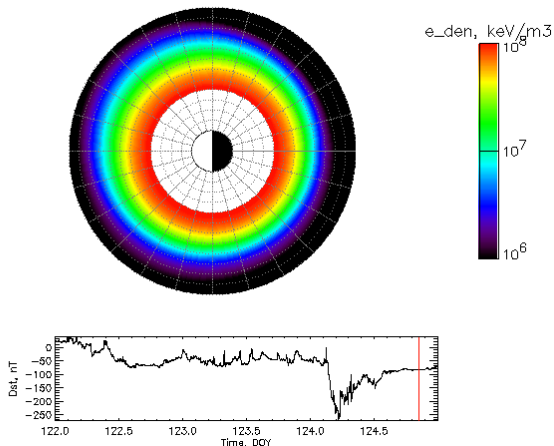
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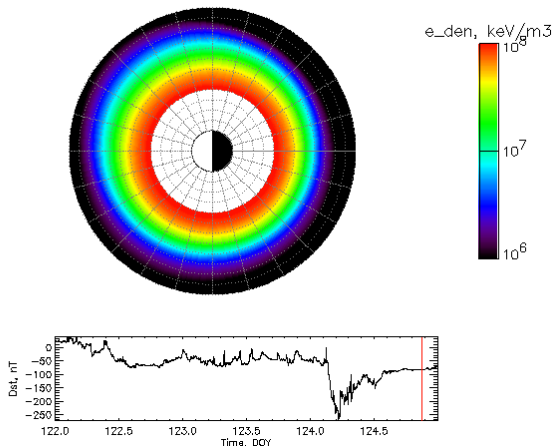
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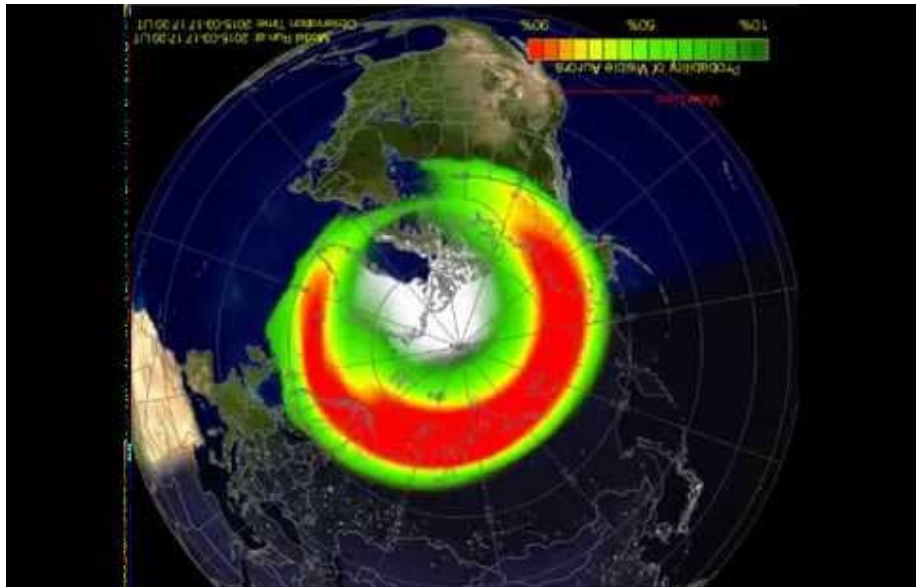
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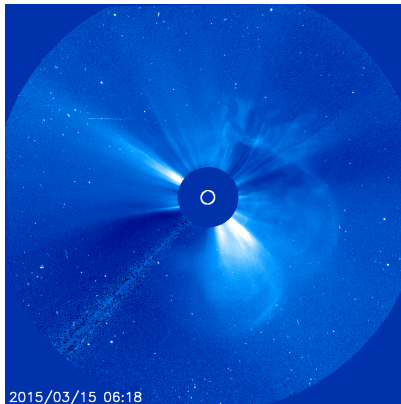
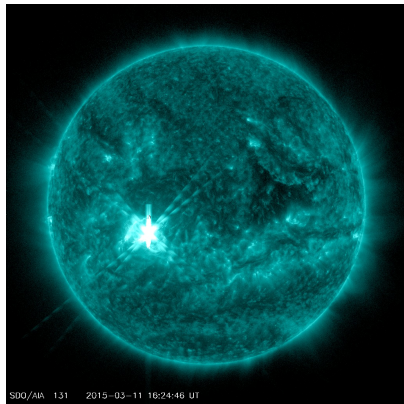
Aurora during magnetic storm



Magnetic storm: space weather preconditions

St. Patrick's Day magnetic storm: 17/03/2015

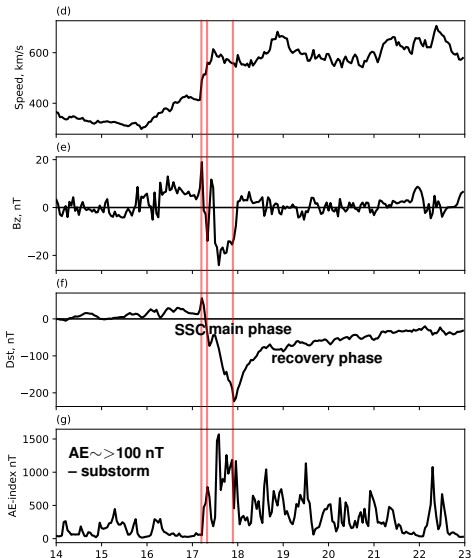
- The solar flare is followed by the CME
- (left) AIA 131 Å SDO image of the flaring regions; (right) SOHO LASCO C3 image of the inner heliosphere.



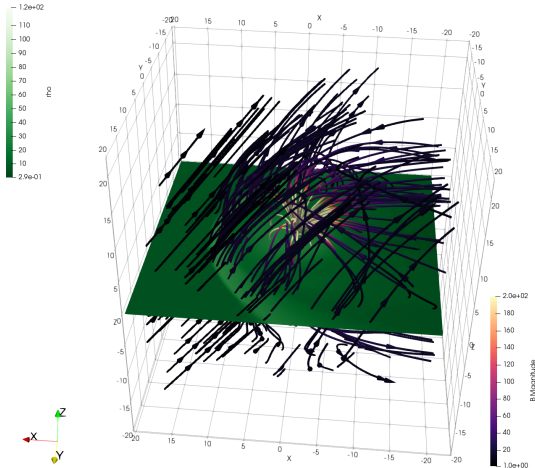
Magnetic storm: observations

St. Patrick's Day magnetic storm: 17/03/2015

- **sudden storm commencement (SSC):** the CME arrives on 17/03/2015 at 04:45 UT (increase in the solar wind speed (d), northward turn of the Interplanetary Magnetic Field (IMF) (e); Dst index increases (f))
- **main phase:** the vertical component of the IMF, B_z turns southward; Dst index decreases
- **recovery phase:** Dst index recovers

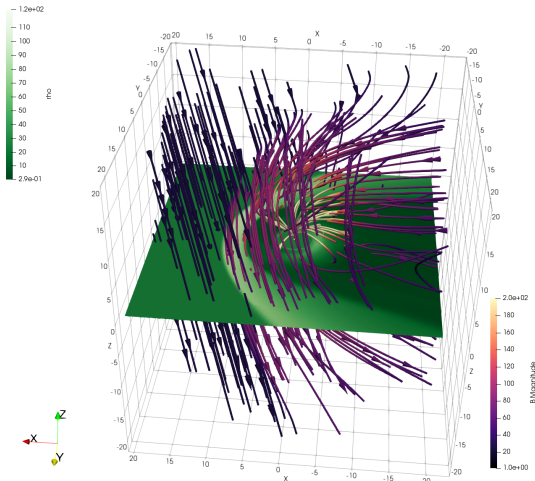


Magnetosphere: during northward IMF, 02:00 UT



Space Weather Modeling
Framework, data from R. Ilie

Magnetosphere: during southward IMF, 16:00 UT



Space Weather Modeling
Framework, data from R. Ilie

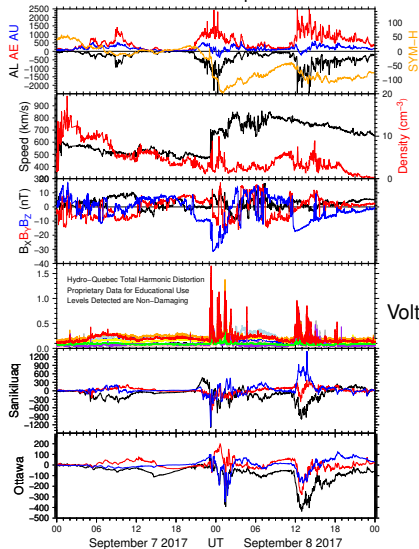
- During a prolonged southward IMF (associated with CMEs) many particles penetrate the dipolar region of the magnetosphere and form the ring current: a flow of trapped charged particles (typically 10–100 keV).
- Accelerated ring current particles form hazardous radiation belts.

Space Weather application: Hydroelectrostation

Credit: Martin Connors

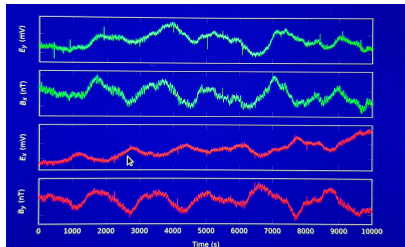


Storm and GIC Sep 7–8 2017



Voltage variation

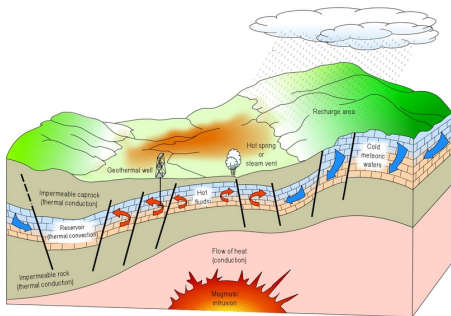
Space Weather application: Investigation of conductivity



The changing magnetic field creates currents within the Earth.



Credit: Max Moorkamp



Taken from www.geothermal-energy.org

Measuring in New Mexico

Summary

- The magnetosphere is a highly dynamical system that undergoes a more or less predictable sequence of changes in response to an energy loading.
- This sequence called a *magnetospheric substorm*.
- When the energy loading remains for an extended interval, auroral currents become continually disturbed and the ring current grows with time.
- The ring current causes a strong decrease in the equatorial magnetic field, a signature that is known as a *magnetic storm*.

- W. Baumjohann and R. Treumann, Basic Space Plasma Physics, 1996
- A. Keiling et al., Substorm current wedge driven by plasma flow vortices: THEMIS observations, JGR, 2009
- E. Kronberg et al., Comparing and contrasting dispersionless injections at geosynchronous orbit during a substorm event, JGR, 2017
- E. Kronberg et al., Contribution of energetic and heavy ions to the plasma pressure: The 27 September to 3 October 2002 storm, JGR, 2017