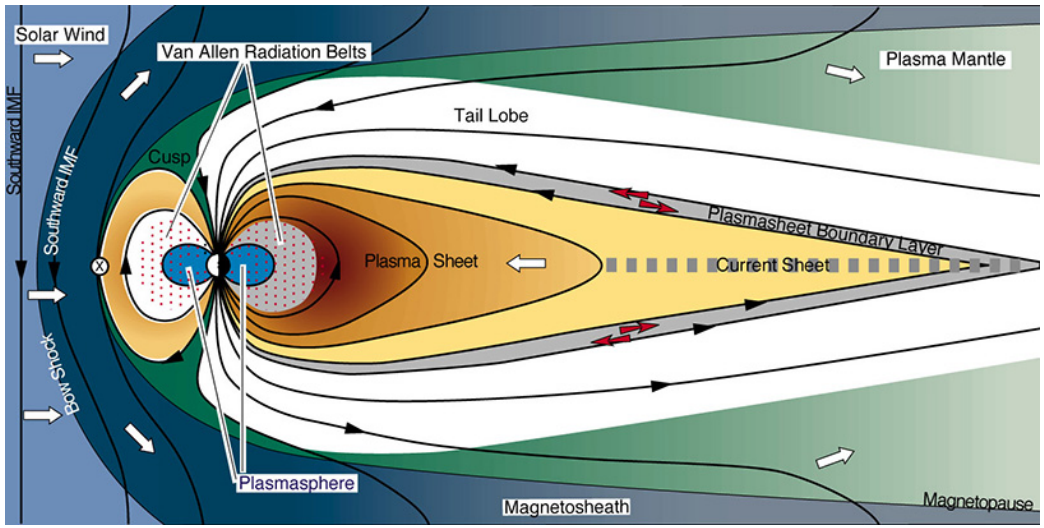
Space Weather
Lecture 7: Magnetospheric Substorms and Storms



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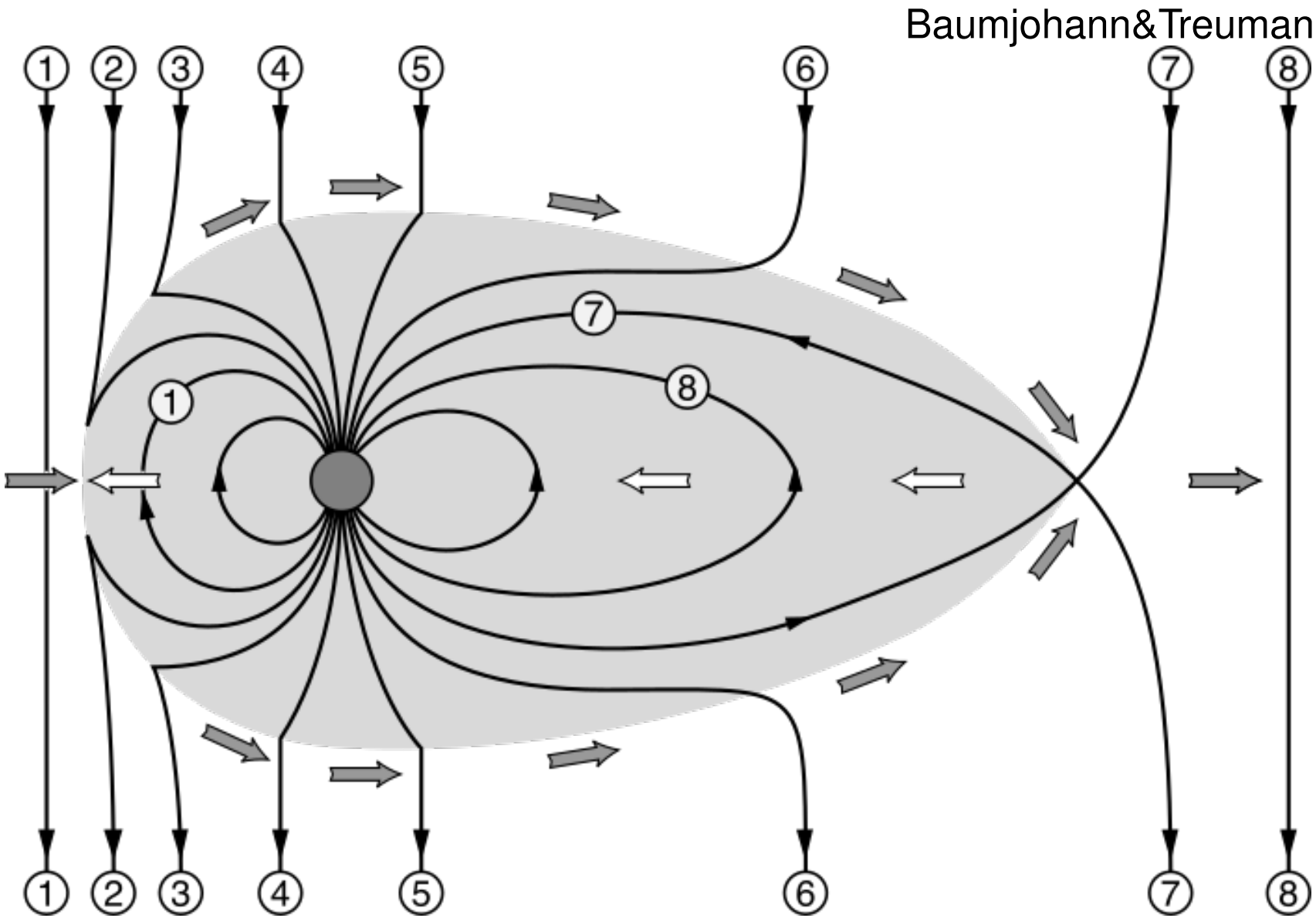
Definition

Source: Wikipedia

- 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



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

1st Difference: cause

substorms: regular southward turning of IMF

vs

storms: prolongated southward turning of IMF (during CME)

2nd Difference: duration

substorms: $\sim$3 hours

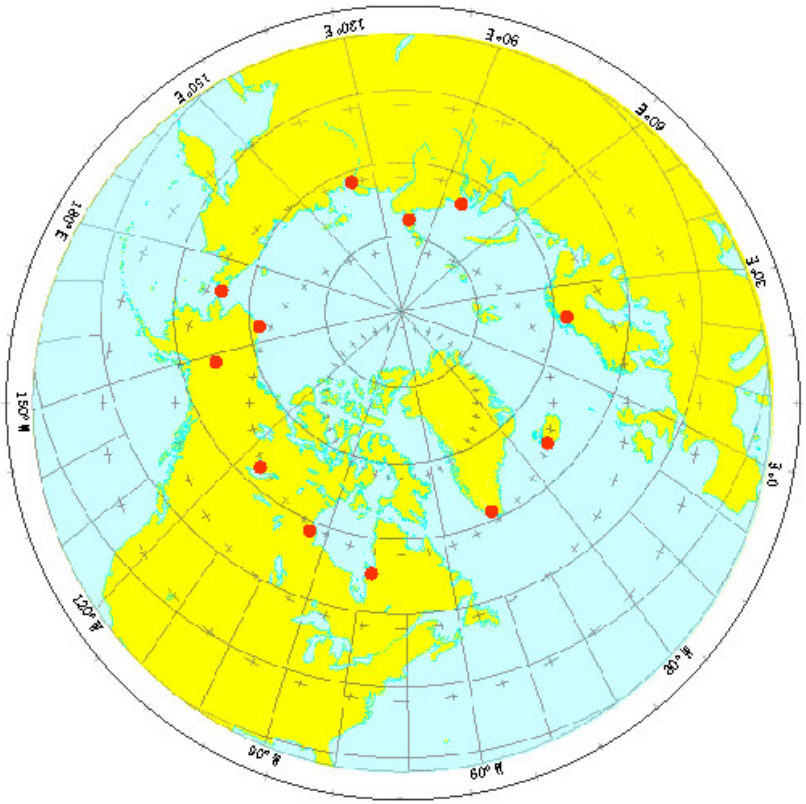
vs

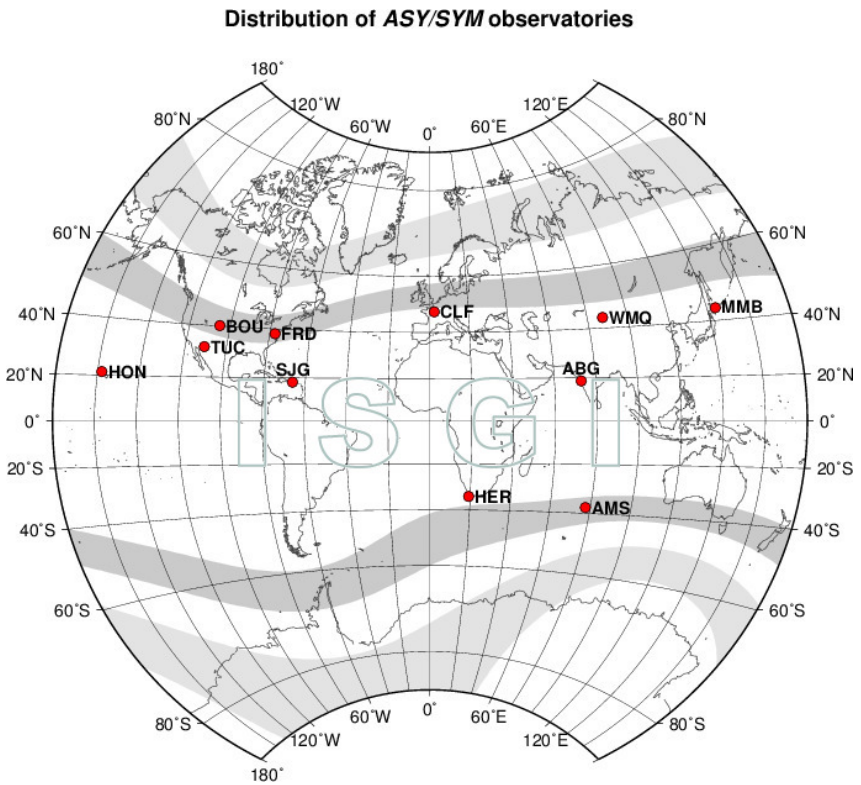
storms: several days

3rd Difference: location of magnetic disturbances at the ground

Polar region: Substorms and Storms

Equatorial: Storms





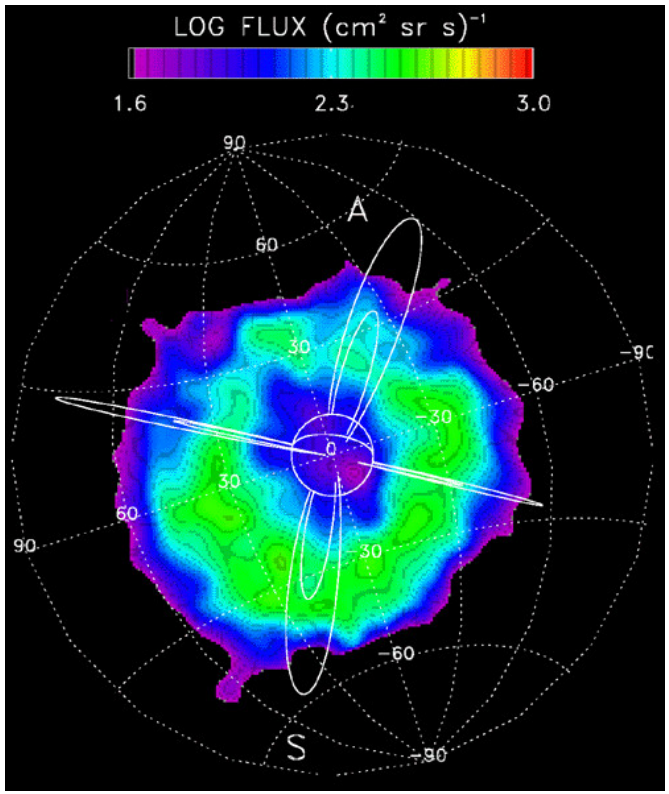
Location of magnetic field observatories

Source: World Data Center for Geomagnetism, Kyoto and ISGI (left)

4th Difference: associated physical phenomena

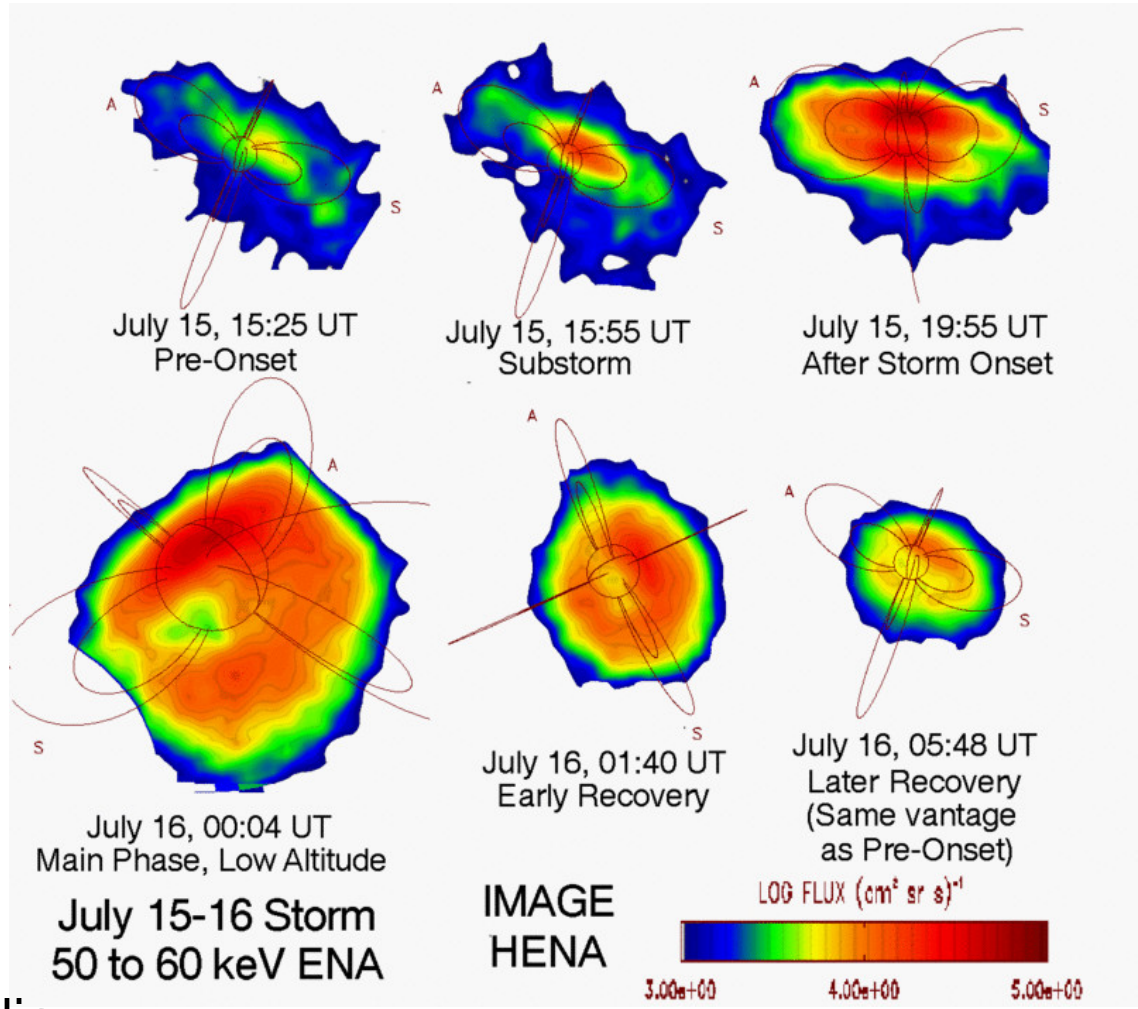
Aurora: Substorms and Storms

Ring Current: Storms



5th Difference: size of the disturbance

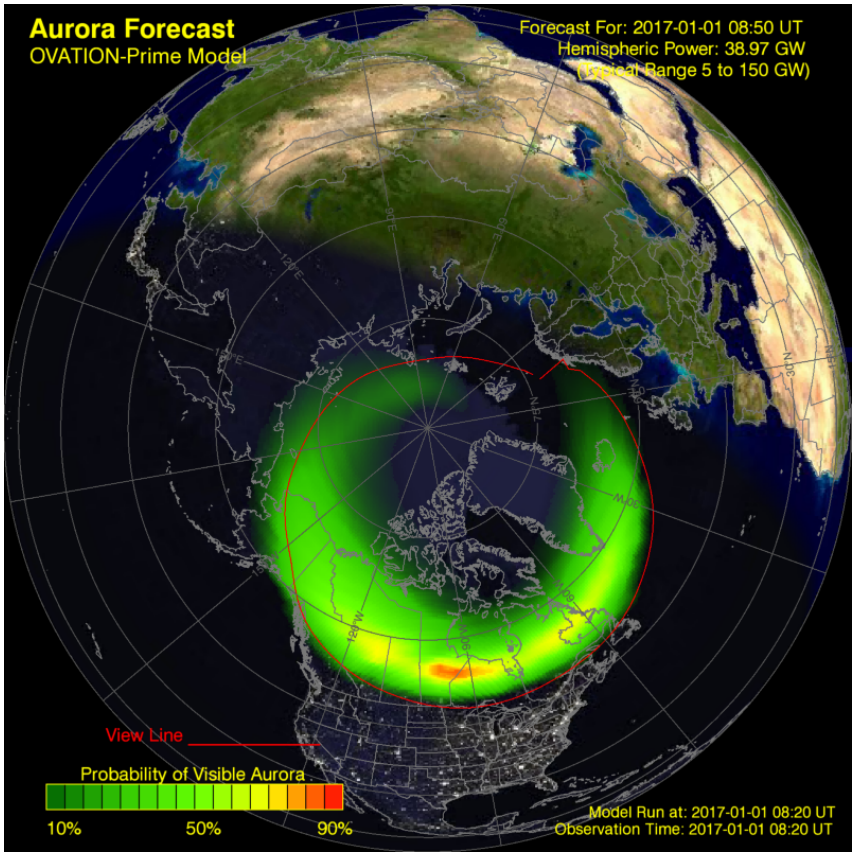
ENA images of the fluctuation of Earth's ring current during July 15–16, 2000 geomagnetic storm made by the IMAGE HENA Instrument



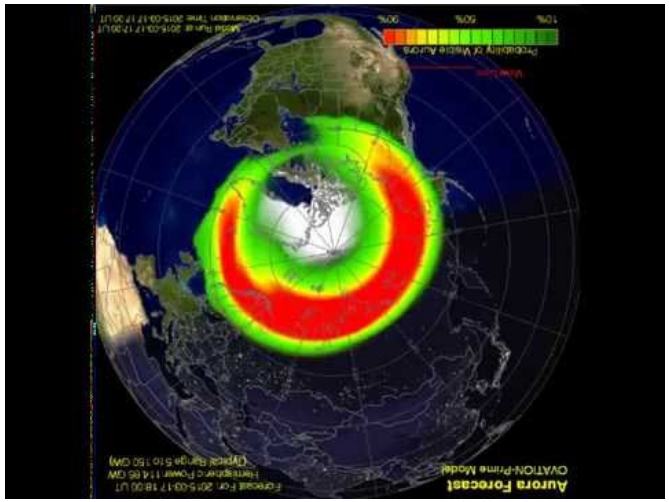
Source: Wikipedia

6th Difference: location and size of the aurora

Nightside: Substorms



Almost all auroral oval: Storms



Credit:

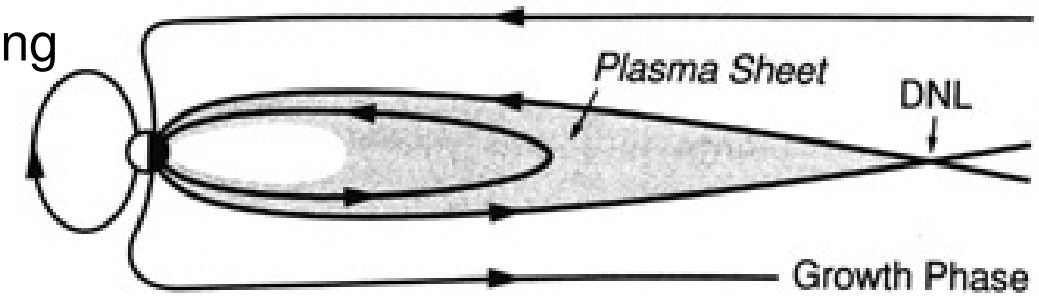
`http://www.swpc.noaa.gov/products/aurora-30-minute-forecast`

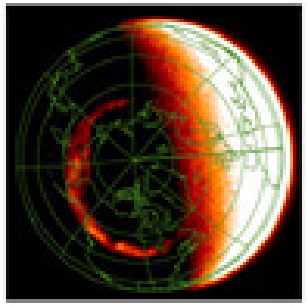
Substorm phases

Baumjohann&Treumann

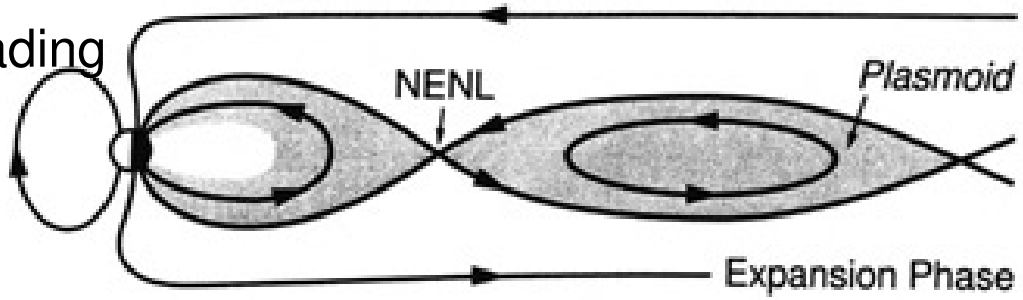
Duration $\simeq$ 3 hours

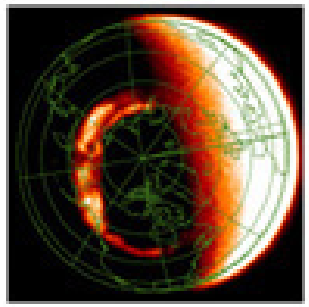
energy loading

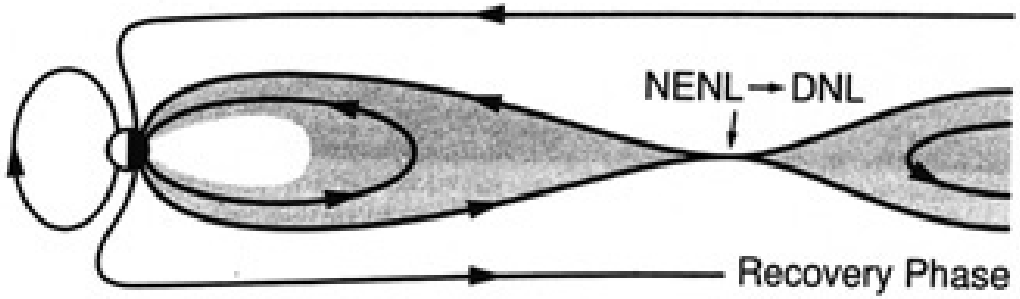


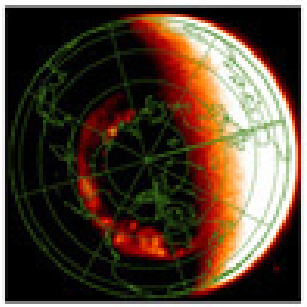


energy unloading

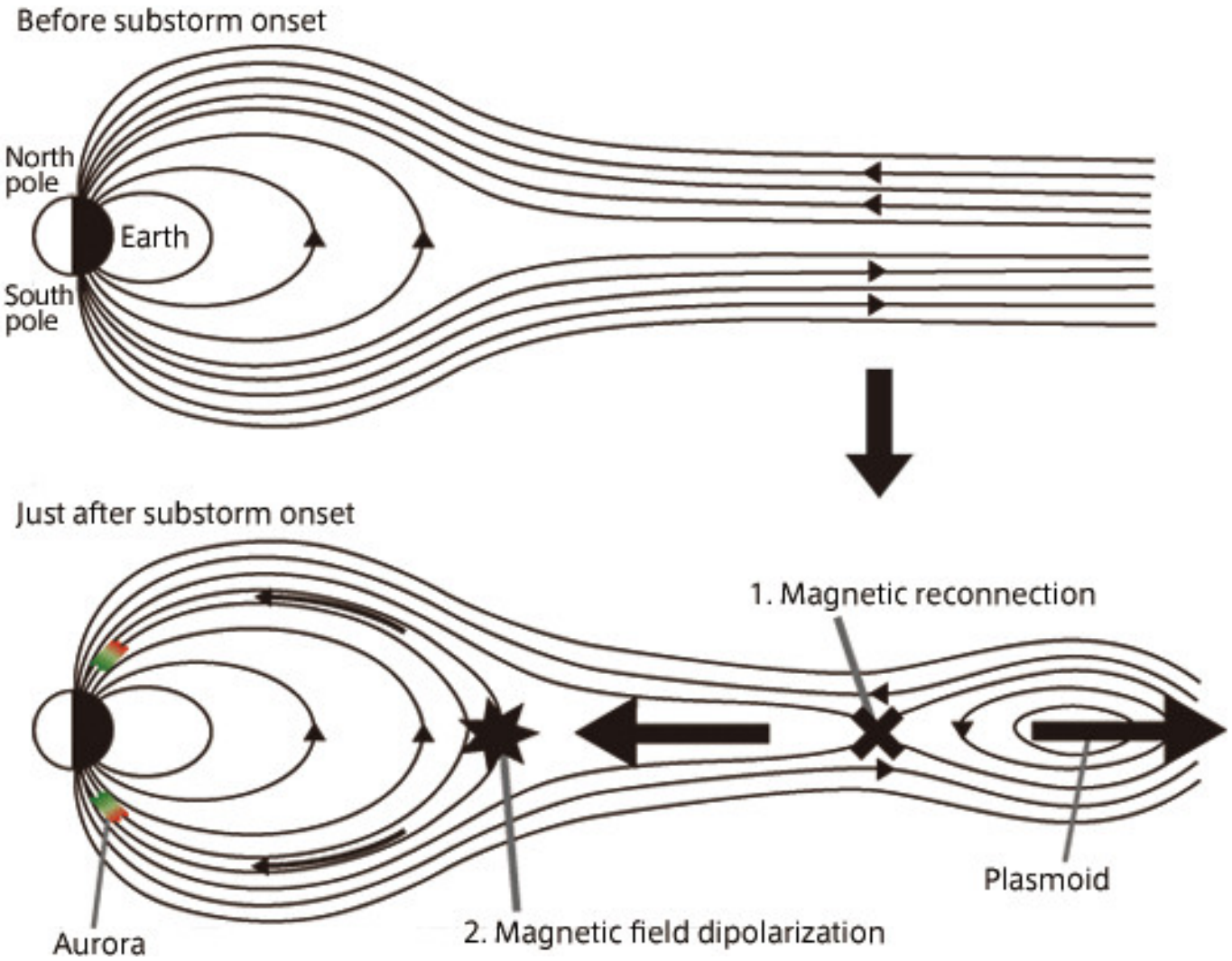






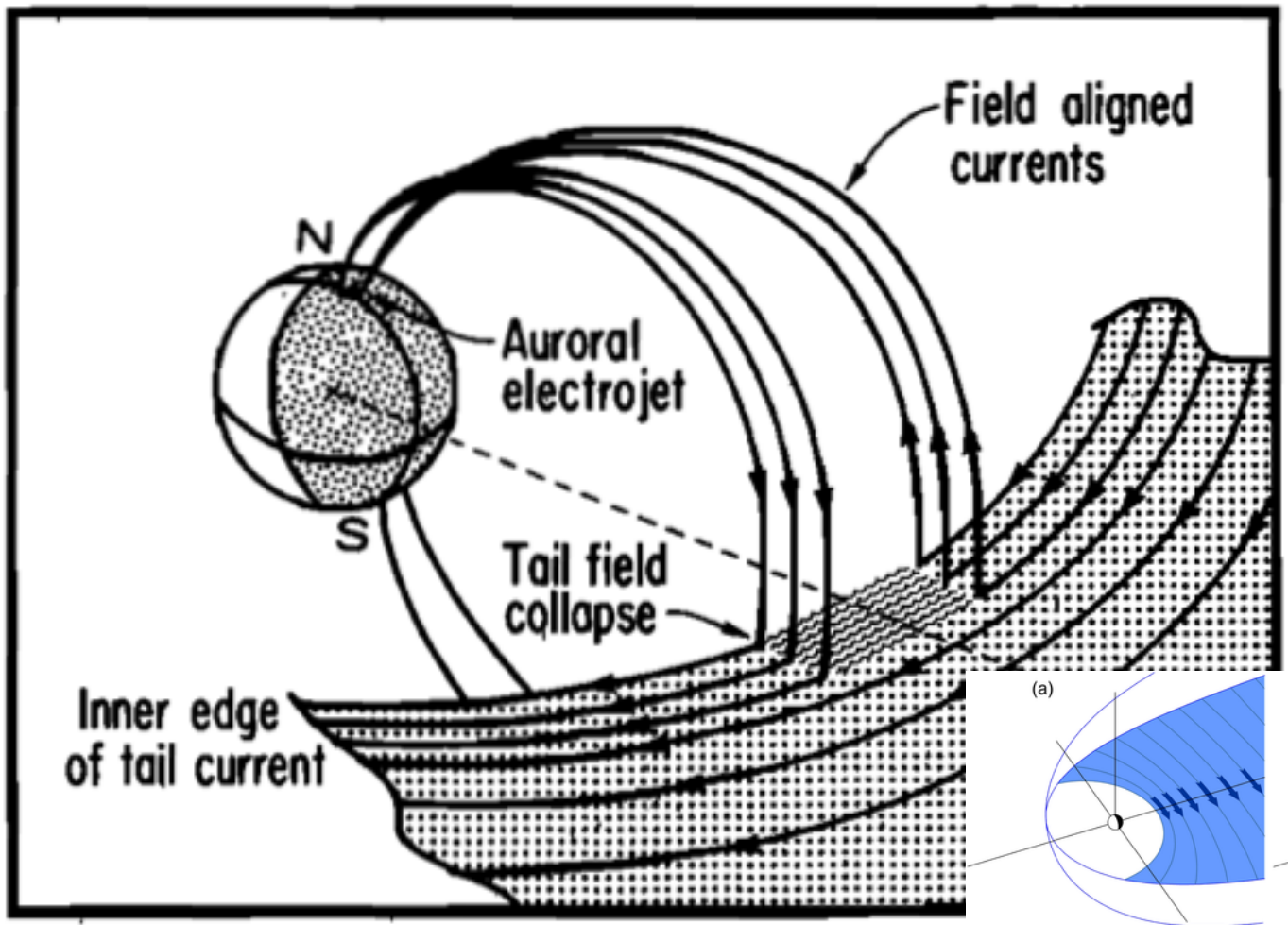


Substorm phases: before and after the onset



Current Wedge: underlying physics

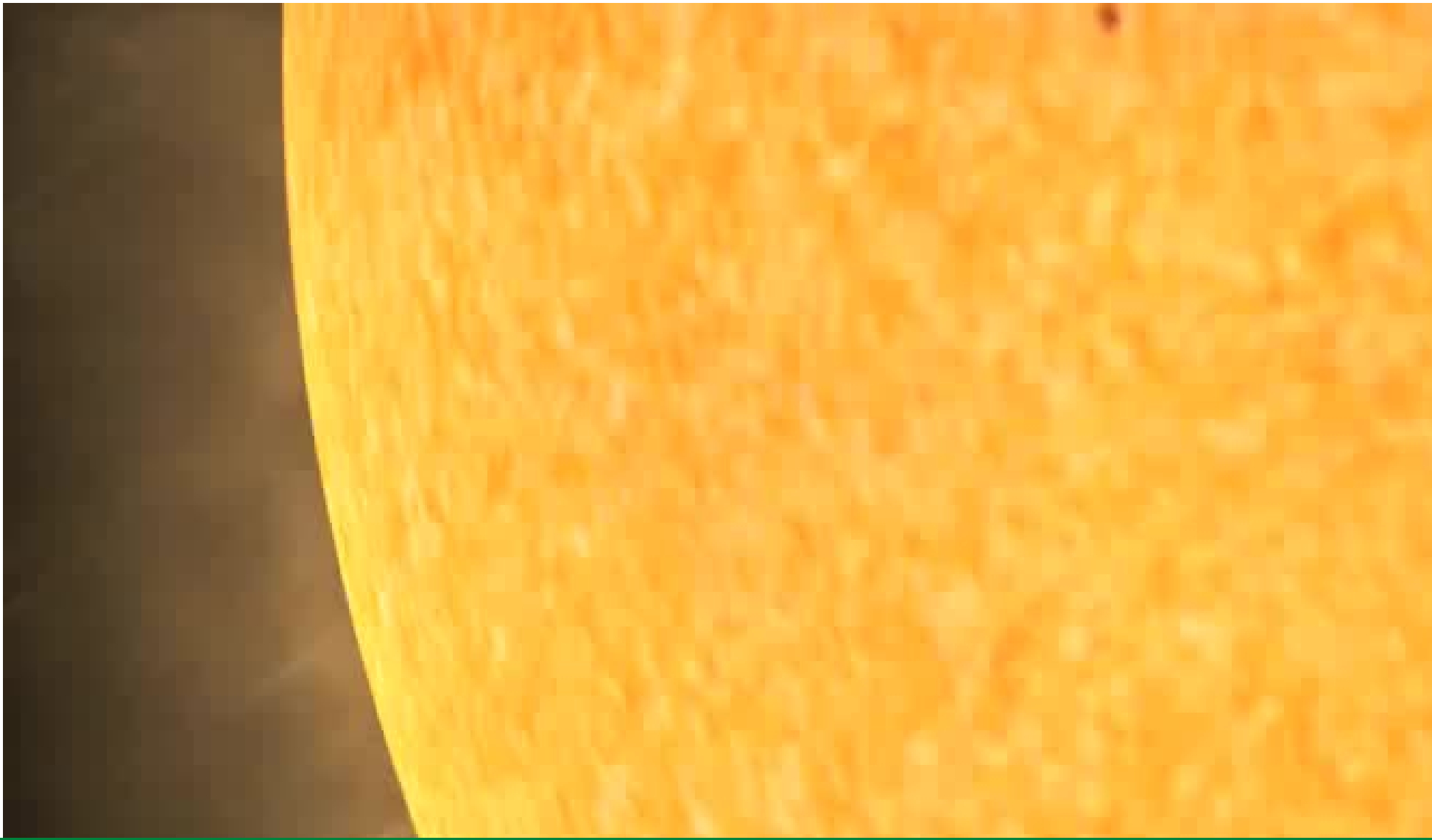
- The substorm current wedge diverts part of the neutral sheet current along magnetic field lines through the ionosphere



McPherron&Chu 16

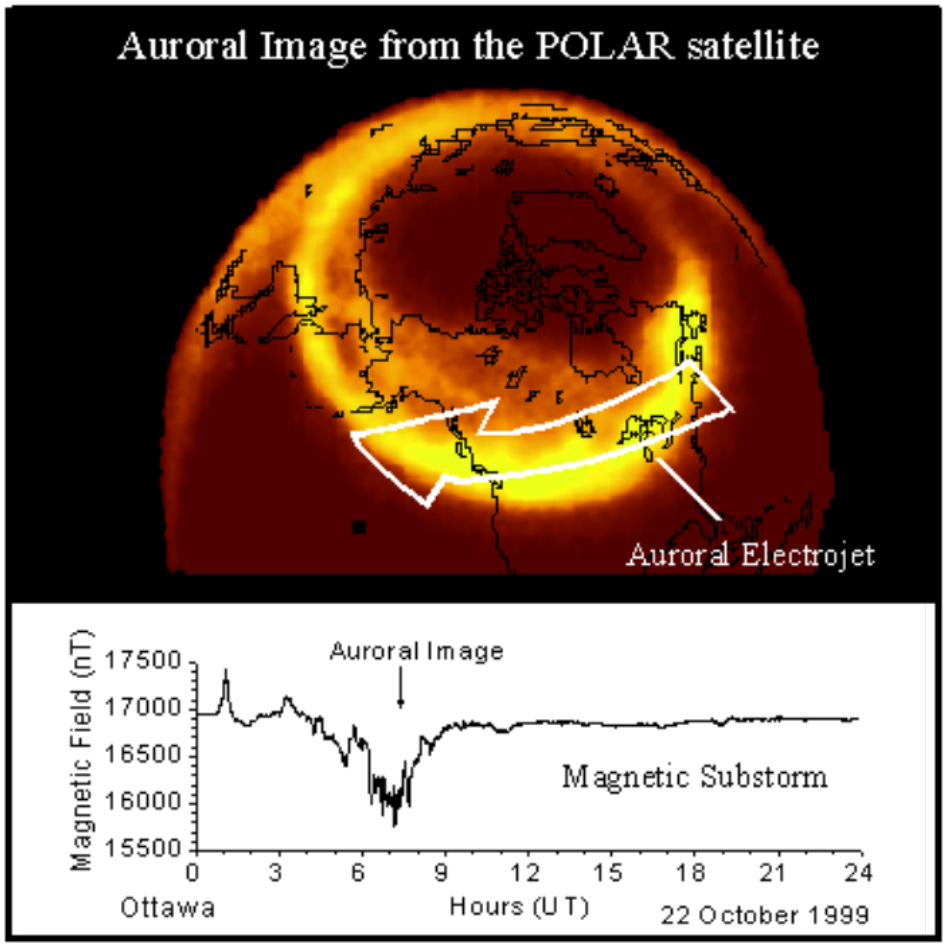
Ganushkina+18

Substorm: visualization



Auroral Elecrojet

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



AE, AU, AL indeces

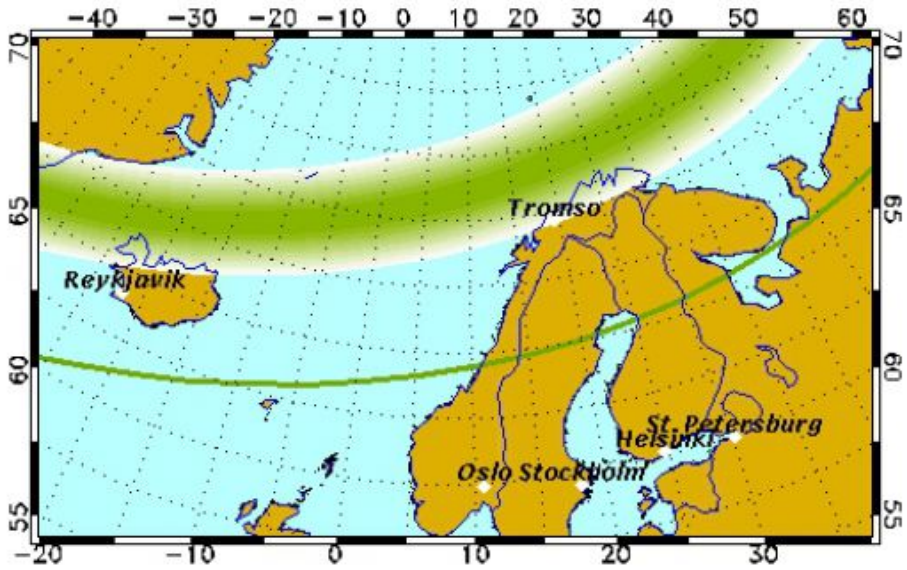
- Measure of global auroral electrojet activity (Northern Hemisphere)
- 12 observatories between $\lambda \simeq 65^\circ$ and 70°

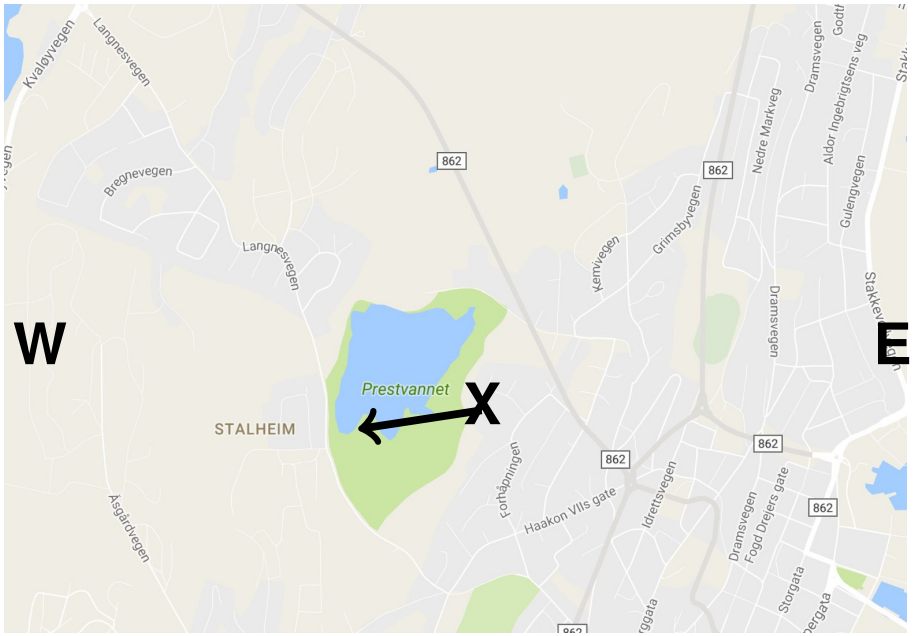
$$AU(t) = \max_{i=1,12} \{H(t) - H_0\}_i$$
$$AL(t) = \min_{i=1,12} \{H(t) - H_0\}_i$$
$$AE(t) = AU(t) - AL(t)$$

- H – horizontal component
- AU – maximum eastward electrojet current
- AL – maximum westward electrojet current
- AE – the total maximum electrojet current
- H_0 – base average value for 5 most quiet days of previous month
- Now SuperMAG Electrojet Index (SME) index is used (N-component is taken for calculations)

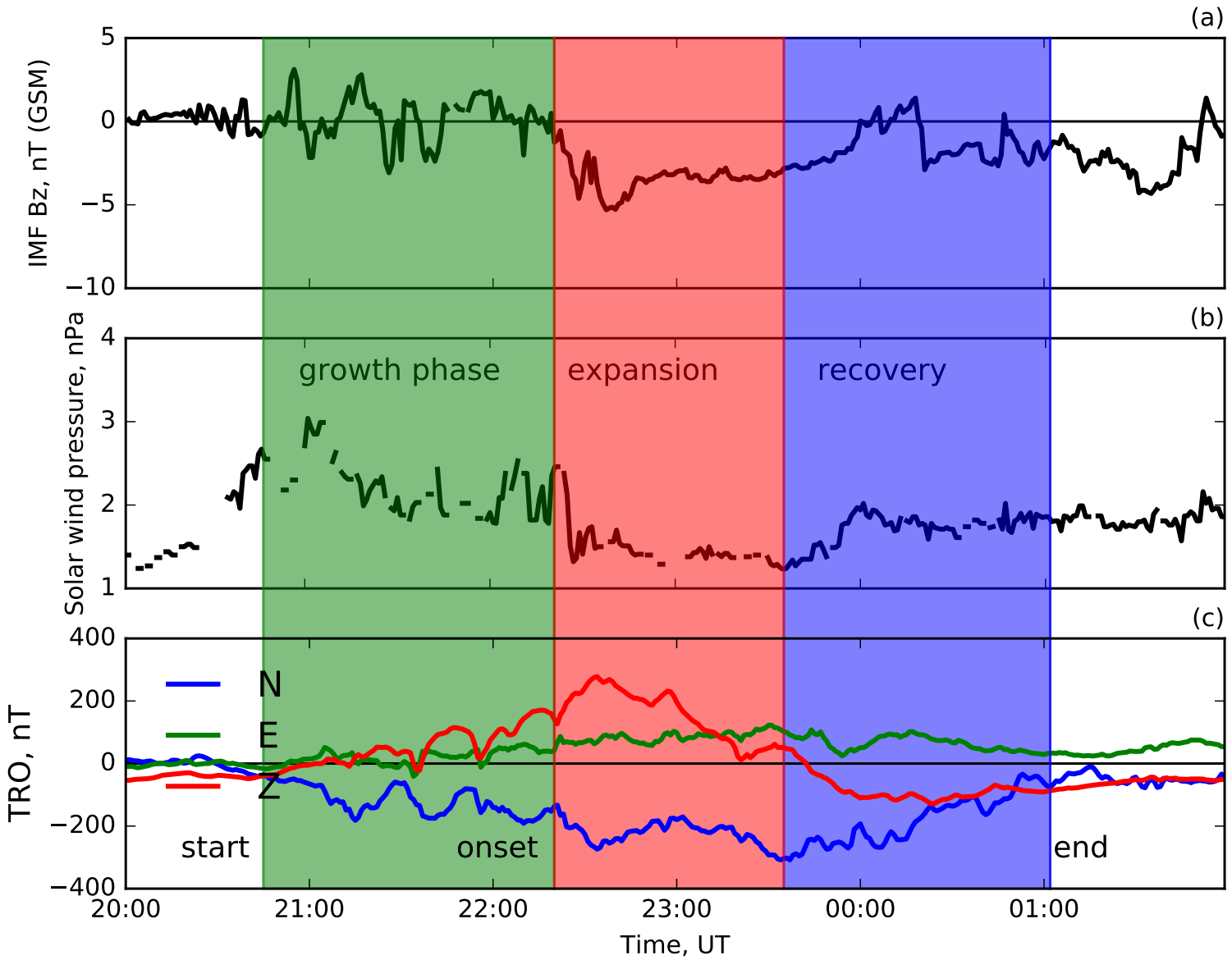
My experience: Tromsø, Norway

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

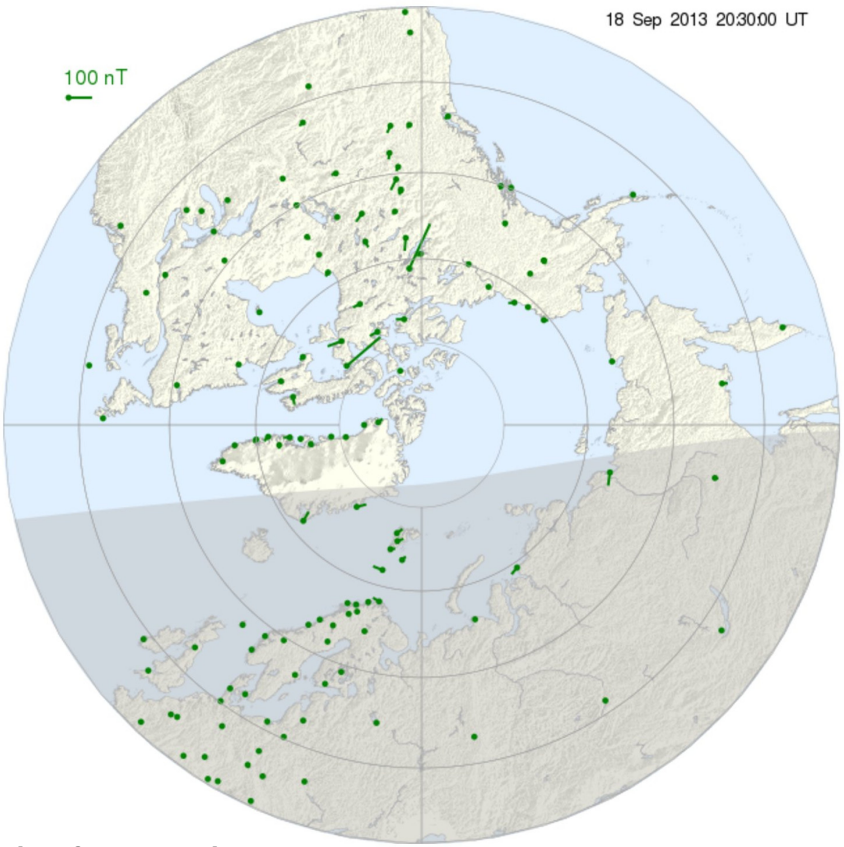




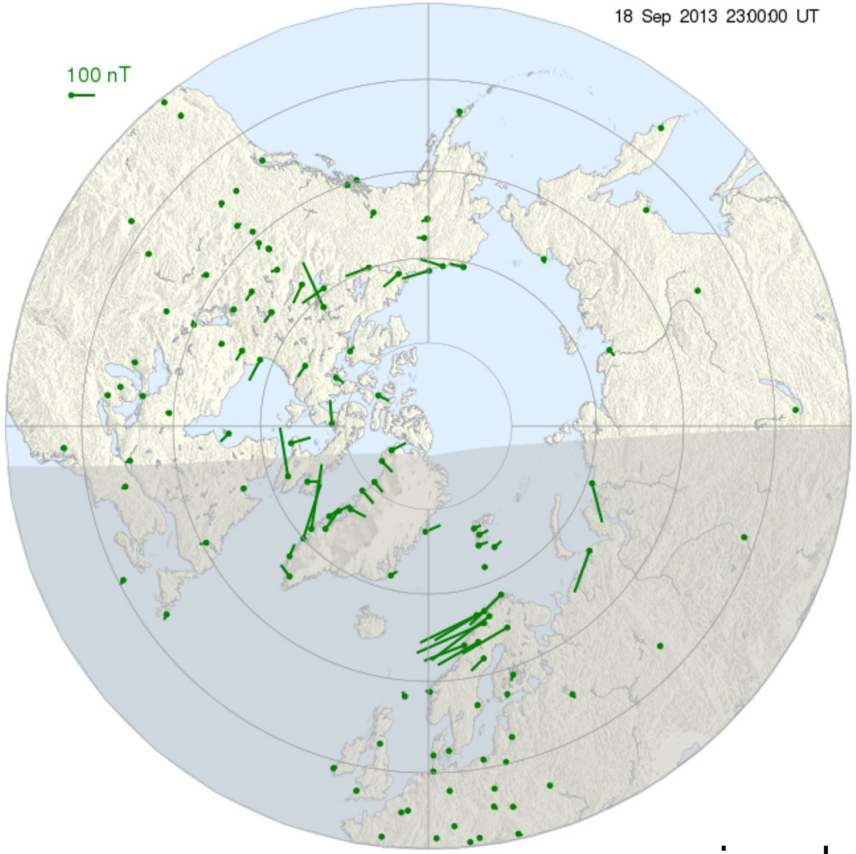
Observations by ACE and magnetic field at TRO



Ground-based observations: polar plots of SUPERMAG data

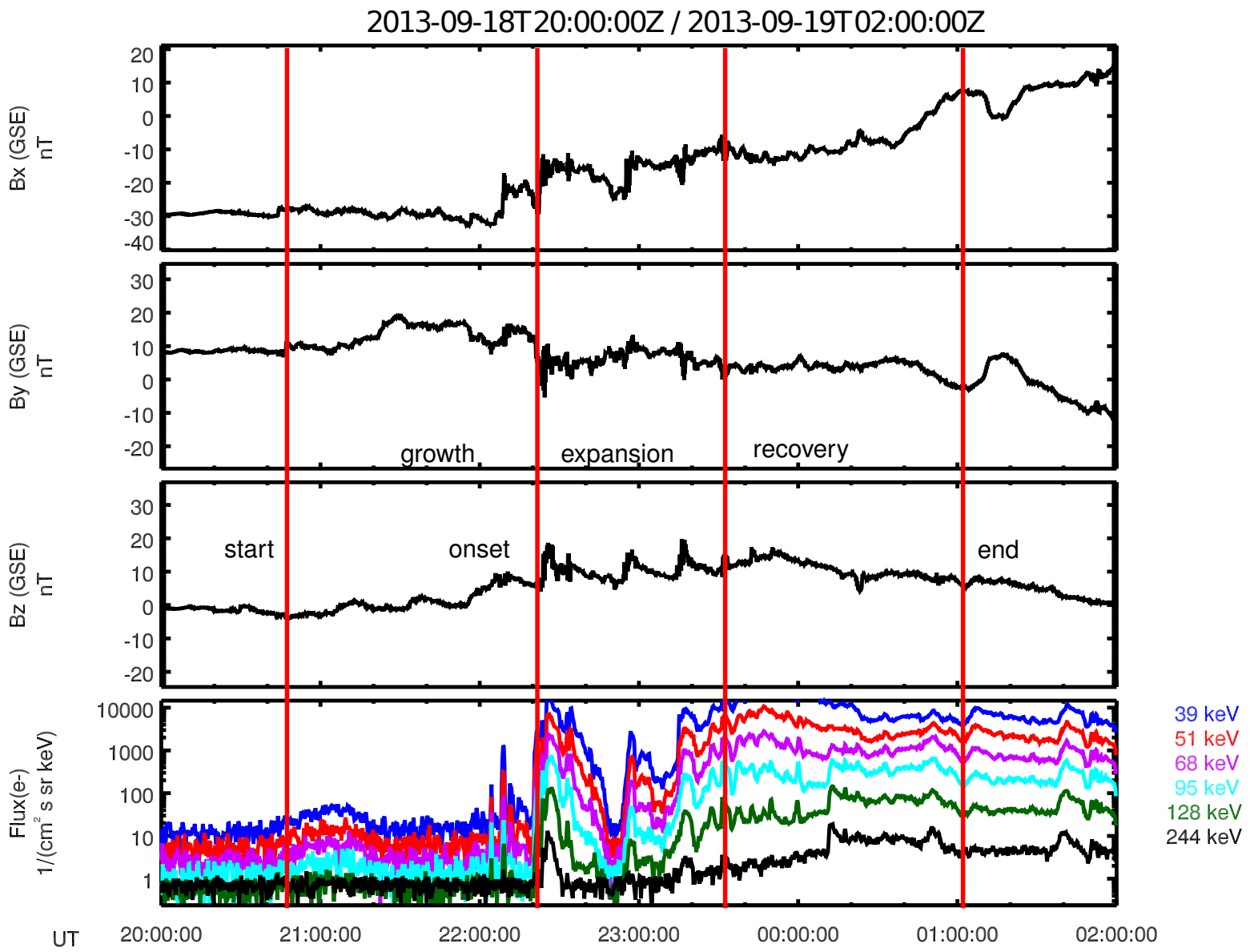


before substorm

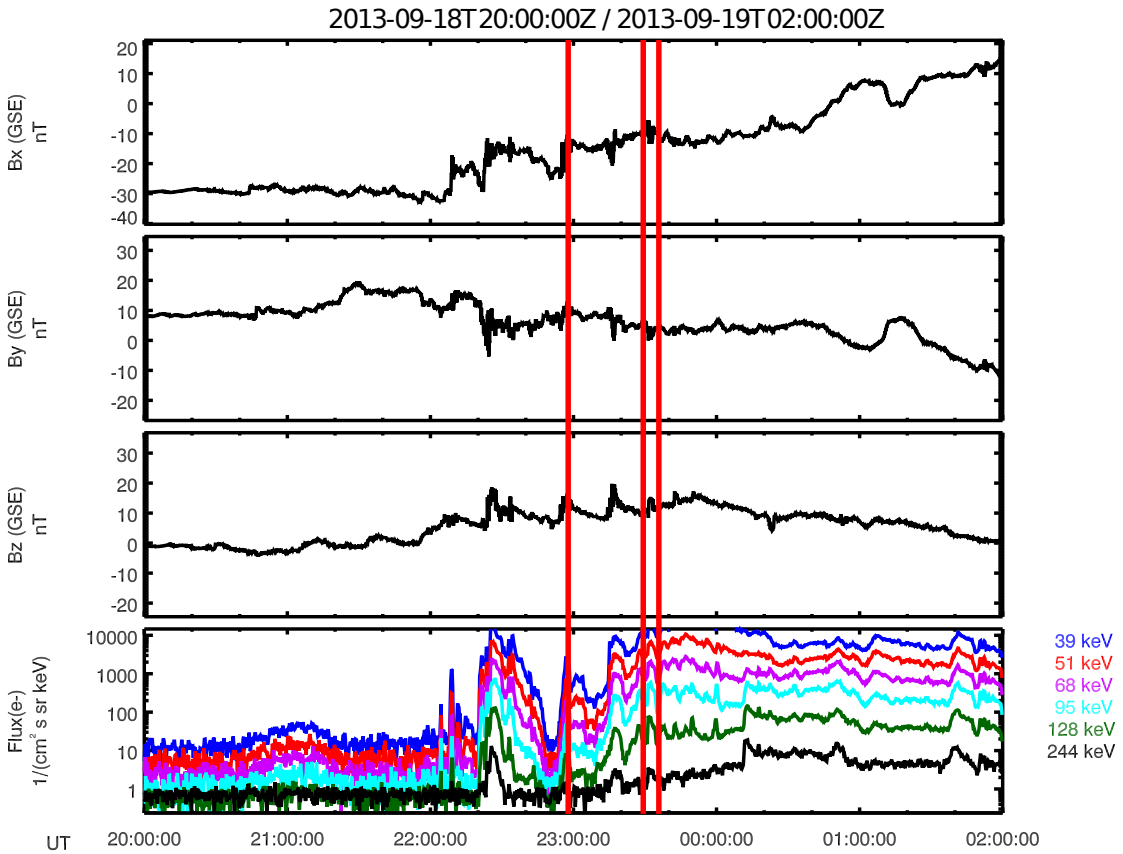


expansion phase

CLUSTER observations



CLUSTER and aurora observations



22:58 UT

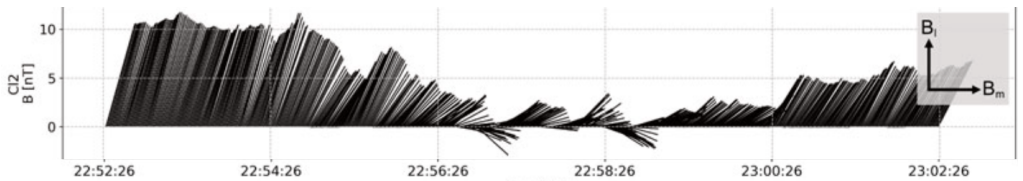
23:27 UT

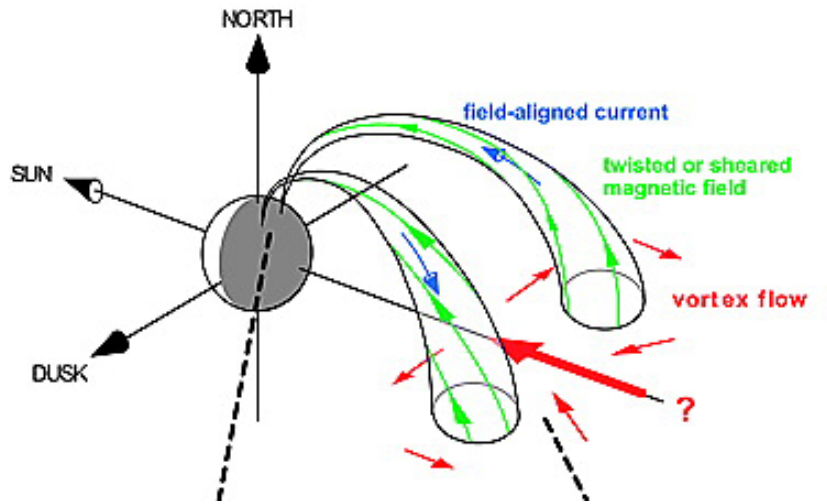
23:34 UT

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



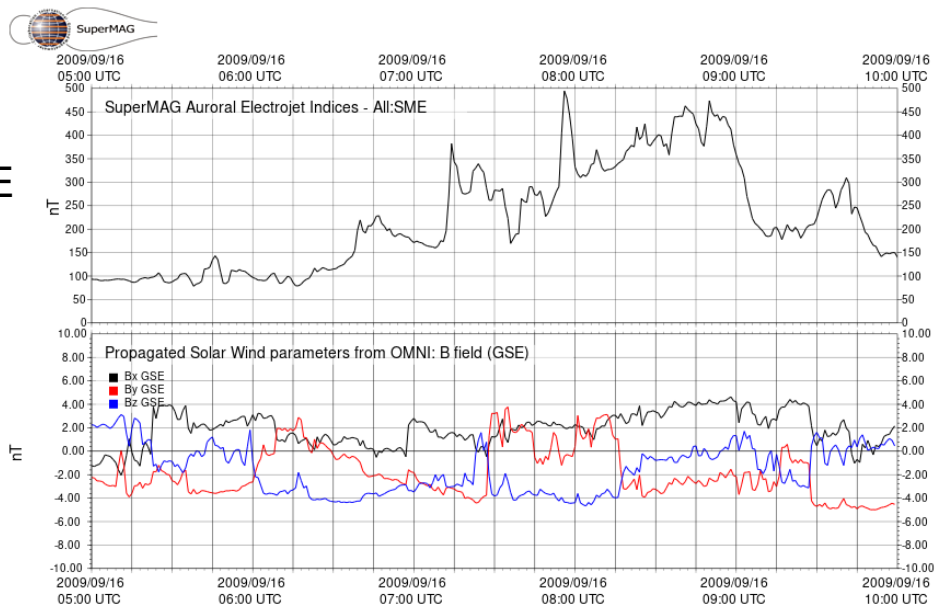


Keiling et al, 2009

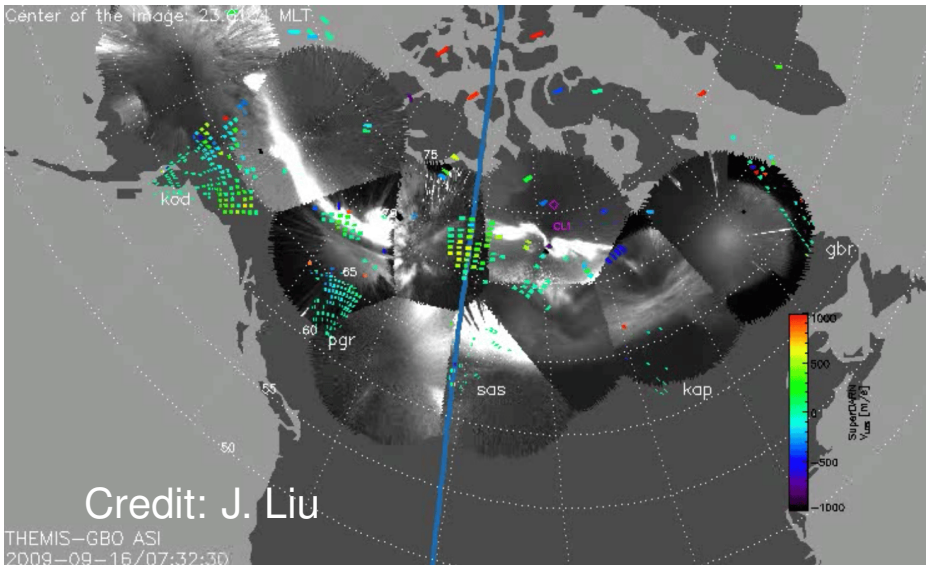
All Sky Imagers observations of a substorm

SME

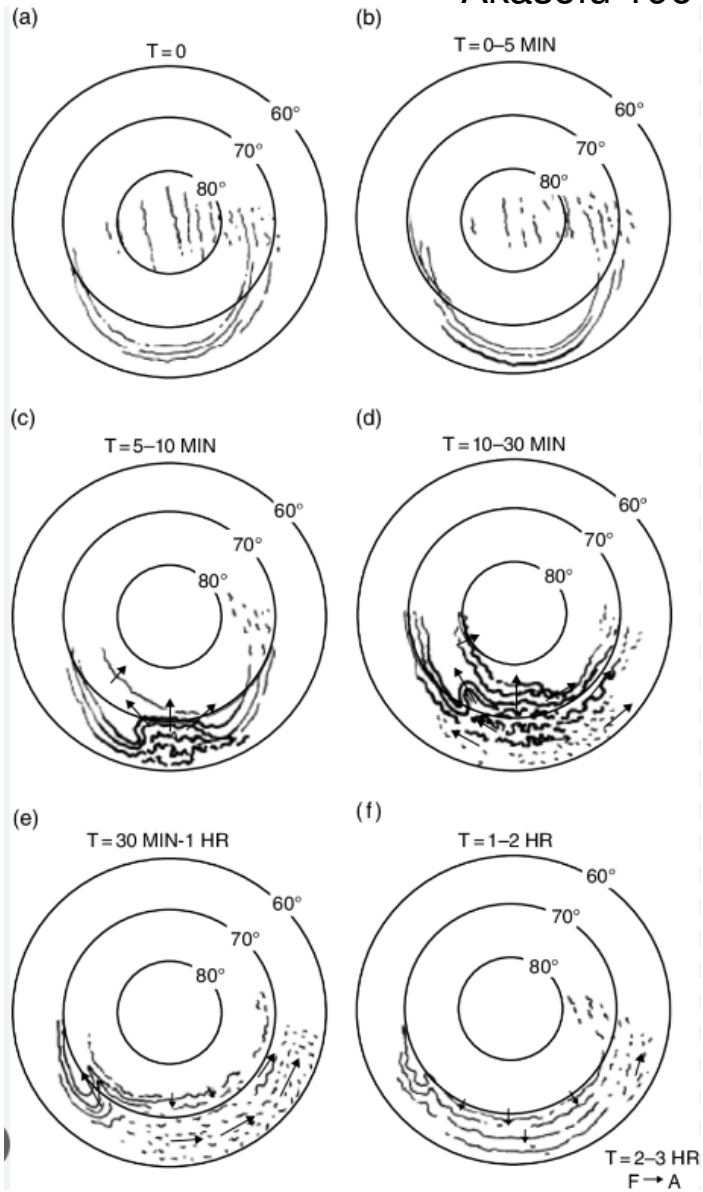
IMF



Onset at 06:36 UT

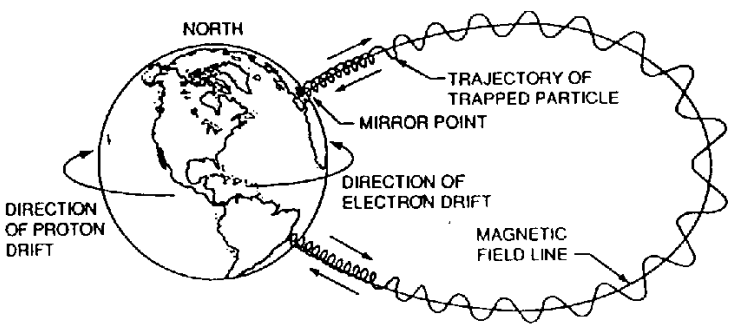


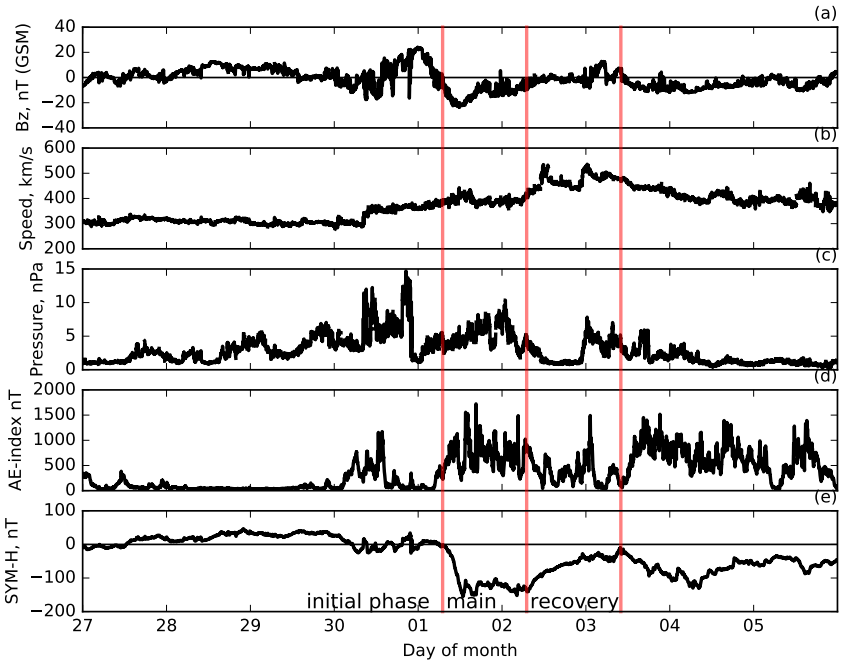
Akasofu 1964



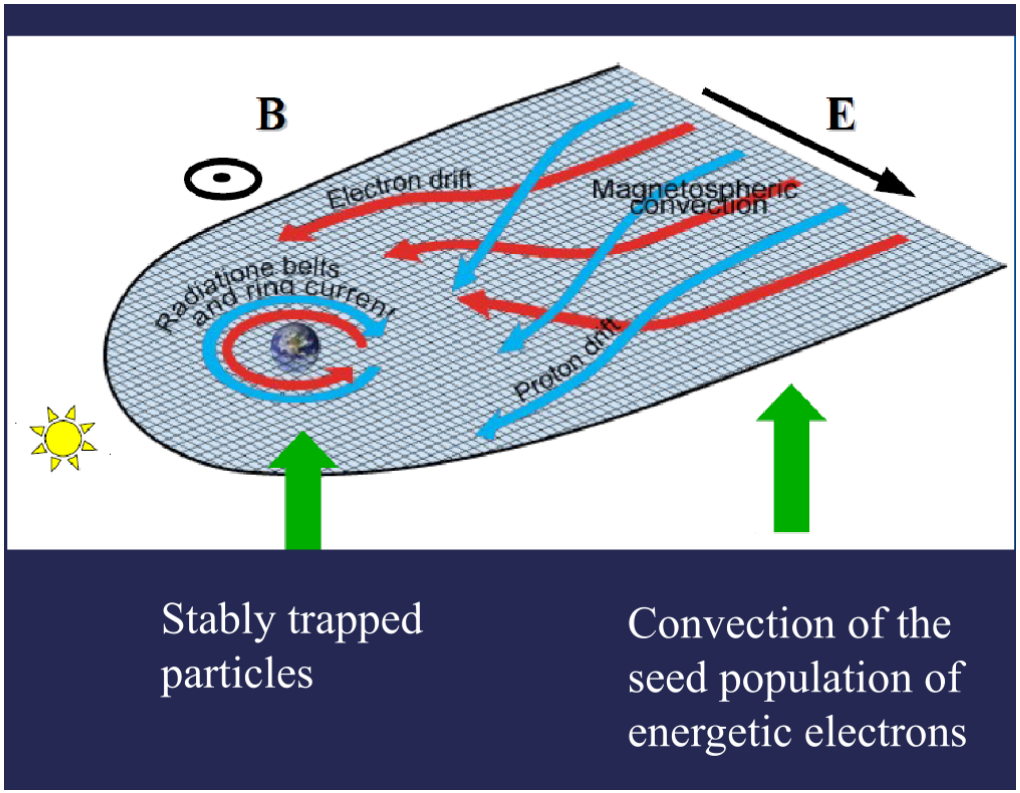
Magnetic Storms: Ring Current

- During a prolongated southward IMF (associated with CMEs) many particles penetrate the dipolar region of the magnetosphere.
- A particle in a dipole field gyrates, while bouncing and drifting.
- 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 move around the Earth
- Electrons –eastward, ions – westward

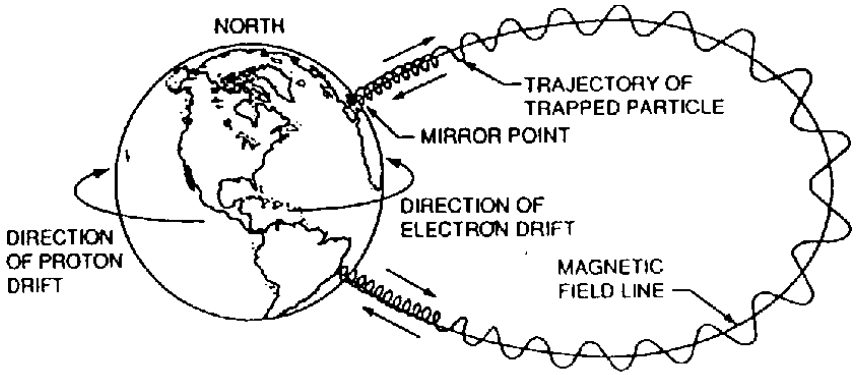
Subbotin+2011

Magnetic Storms: Ring Current

- The average equatorial drift velocity (approximate solution) is

$$v_{\mathrm{d}} \simeq \frac{6L^2W}{qB_{\mathrm{E}}R_{\mathrm{E}}}(0.35 + 0.15\sin\alpha_{\mathrm{eq}}) \tag{1}$$

v_{d} ... the average drift velocity, W ... energy of particle, q ... particle charge, R_{E} ... Earth's radii, α_{eq} ... equatorial pitch angle, L ... L-shell



Baumjohann&Treumann

Ring Current

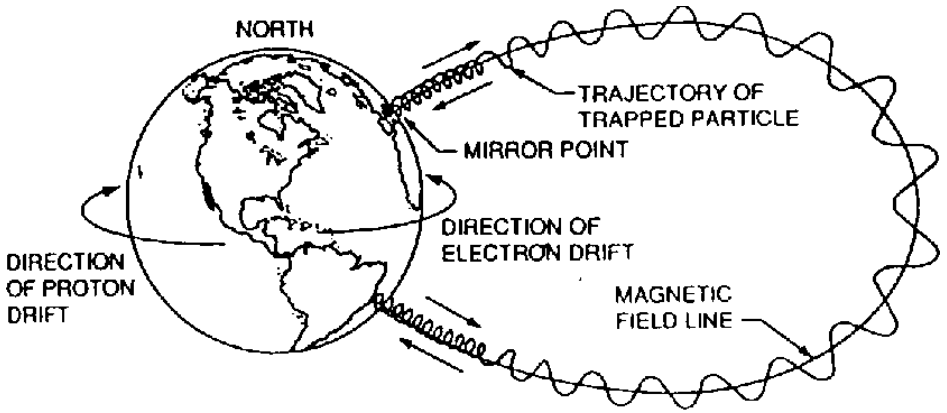
- From Eq. (1) azimuthal current in westward direction is

$$j_{\mathrm{d}} \simeq \frac{3L^2 nW}{B_{\mathrm{E}} R_{\mathrm{E}}}$$

  n . . . ion density
- Then the total ring current is

$$I_L \simeq \frac{3U_L L}{2\pi B_{\mathrm{E}} R_{\mathrm{E}}^2}$$

  where $I_L \mathrm{d}l = j_{\mathrm{d}} \mathrm{d}V$, $U_L = \int nW \mathrm{d}V$ . . . energy of all ions and electrons, $\int \mathrm{d}l = 2\pi L R_{\mathrm{E}}$ . . . total circumference



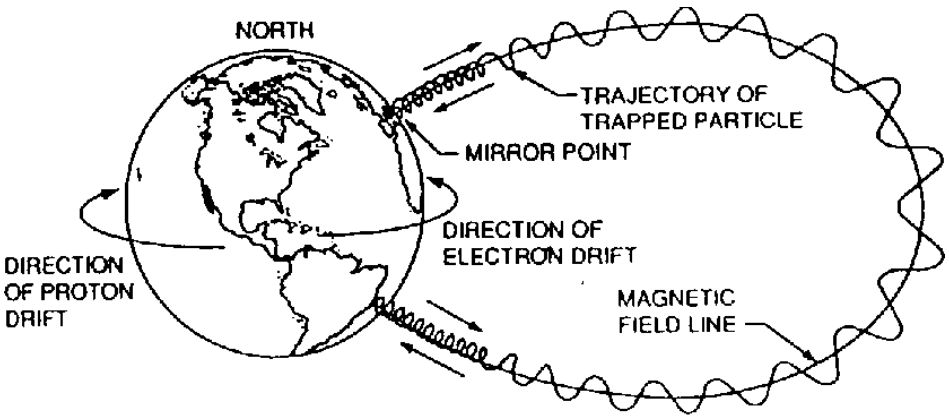
Magnetic field disturbance: contributor I – drifting particles

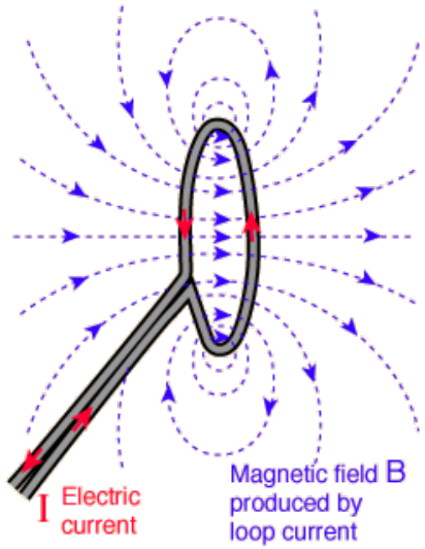
- From Biot-Savart's law of a circular current loop ,

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

- the magnetic field disturbance at the Earth's center is (southward)

$$\delta B_\mathrm{d} = -\frac{\mu_0 I_L}{2LR_\mathrm{E}} = -\frac{\mu_0 3U_L}{4\pi B_\mathrm{E} R_\mathrm{E}^3}.$$





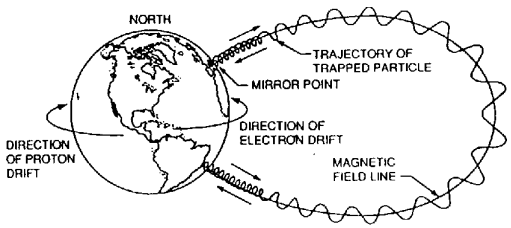
Magnetic field disturbance: contributor II – gyrating particles

- The diamagnetic field at the center of Earth induced by orbiting charged particles is

$$\delta B_\mu = \frac{\mu_0}{4\pi} \frac{\mu}{L^3 R_{\mathrm{E}}^3}.$$

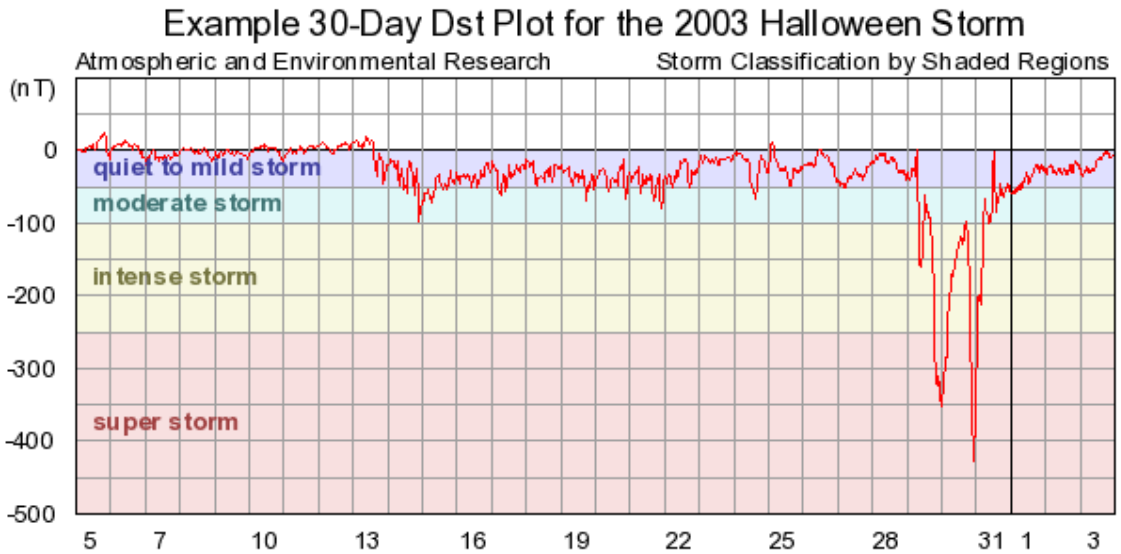
Here we used the particle's magnetic moment μ instead of Earth's moment M_{E} in the formula for Earth's dipole assuming $\alpha_{\mathrm{eq}} = 90°$. Using magnetic moment $\mu = \frac{W_\perp}{B}$ and definition of the dipolar field $B \simeq B_{\mathrm{E}}/L^3$, the diamagnetic field disturbance is (northward)

$$\delta B_\mu = \frac{\mu_0}{4\pi} \frac{W}{B_{\mathrm{E}} R_{\mathrm{E}}^3}$$



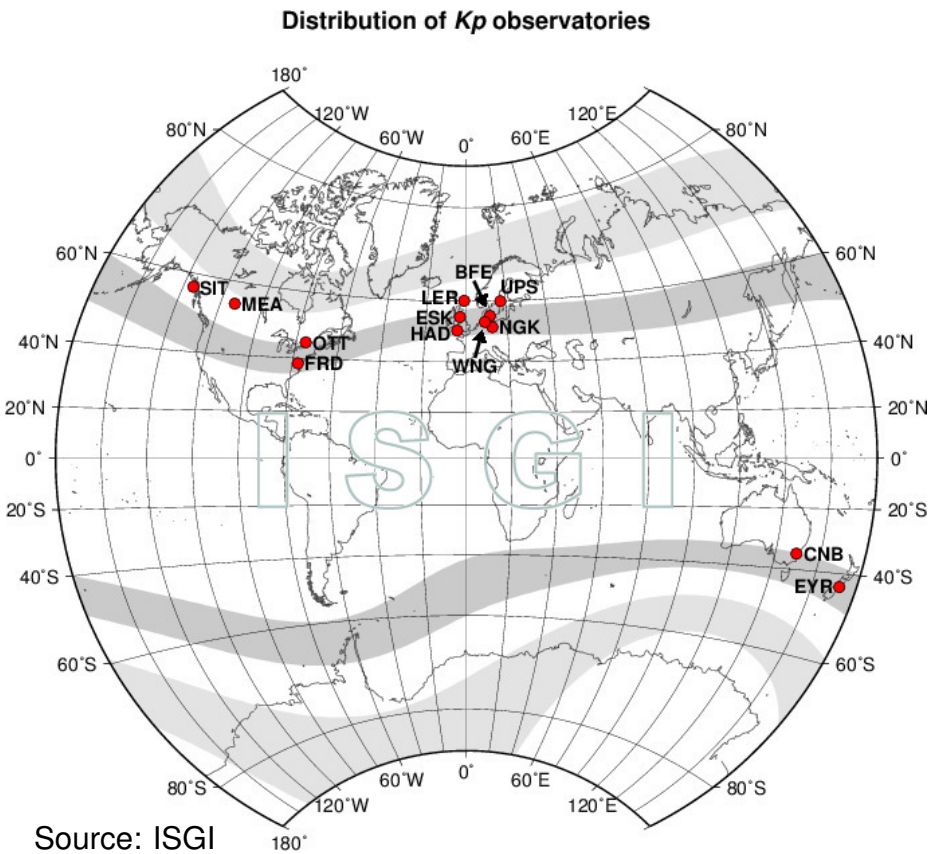
Ring current effect on the ground: magnetic storm

- Disturbance storm time (Dst) index is a measure of the ring current strength, $\Delta B_R = \Delta B_{\mathrm{d}} + \Delta B_{\mu} = -\frac{\mu_0}{2\pi}\frac{U_R}{B_{\mathrm{E}} R_{\mathrm{E}}^3} \simeq \frac{2}{3}\mathrm{Dst}$
- by 4 stations at $\lambda \simeq \pm 20^\circ \ldots 30^\circ$, 1-hour index
- $Dst(t) \sim \sum_{i=1}^{4}\{H(t) - H_0(t') - H_{Sq}(t')\}$
- Magnetic storm duration can be several days, Dst$<$-30 nT, total current $\sim 10^7$A
- The SYM-H index is the 1-min version of the Dst index, obtained from $\sim$6 stations.



Kp-index

- Kp is a 3-hour index that describes the global level of irregular disturbances of the H componets of the geomagnetic field caused by solar wind and used by space weather services in near-real time



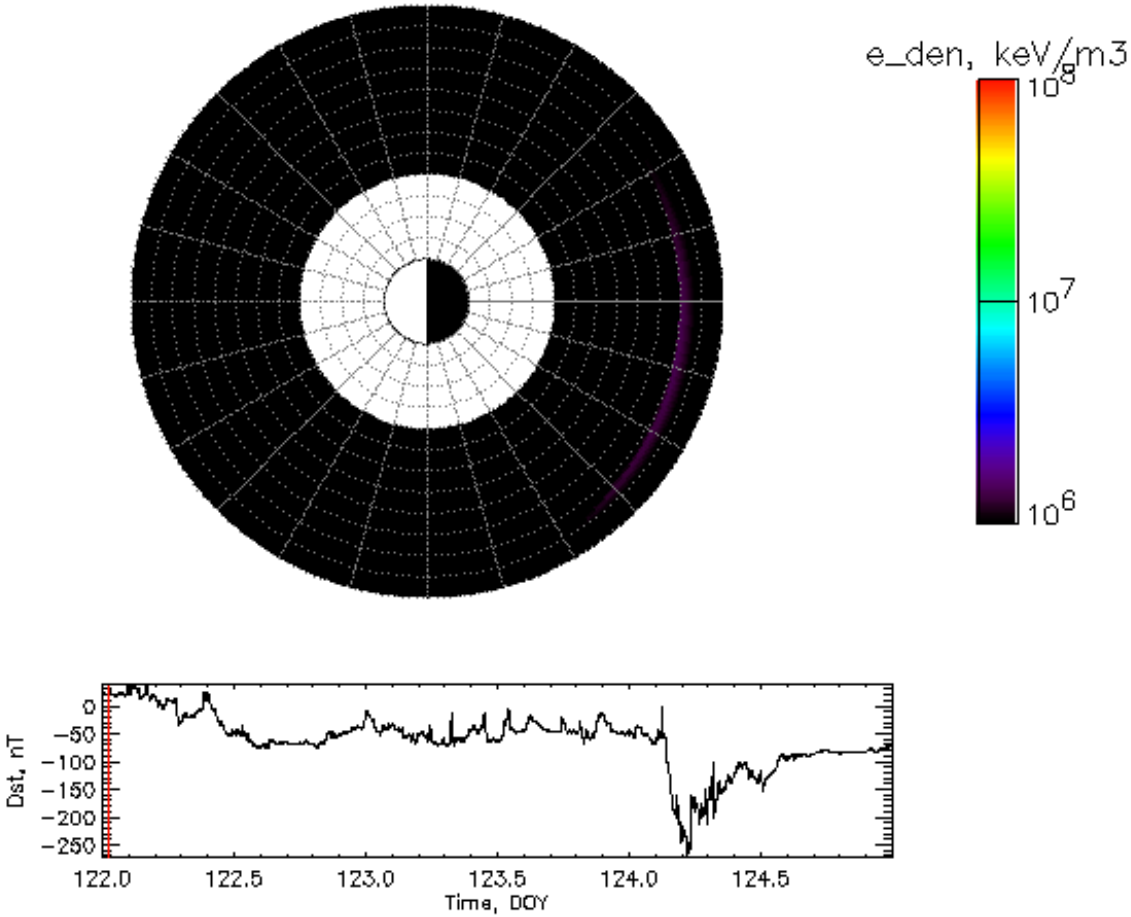
Source: ISGI

Hpo, apo indecies

- The geomagnetic Hpo index is a Kp-like index with a time resolution of half an hour, called Hp30, and one hour, called Hp60.
- The Hpo index is not capped at 9 like Kp, but is an open ended index that describes the strongest geomagnetic storms.
- Expressed in unites of thirds (0, 1/3, 2/3, 1, 4/3, 5/3, 2, ...)
- Kp with its underlying quasi-logarithmic scale does not lend itself for the calculation of arithmetic means. To this end, Kp is converted to the linear apo index (ap30 and ap60)

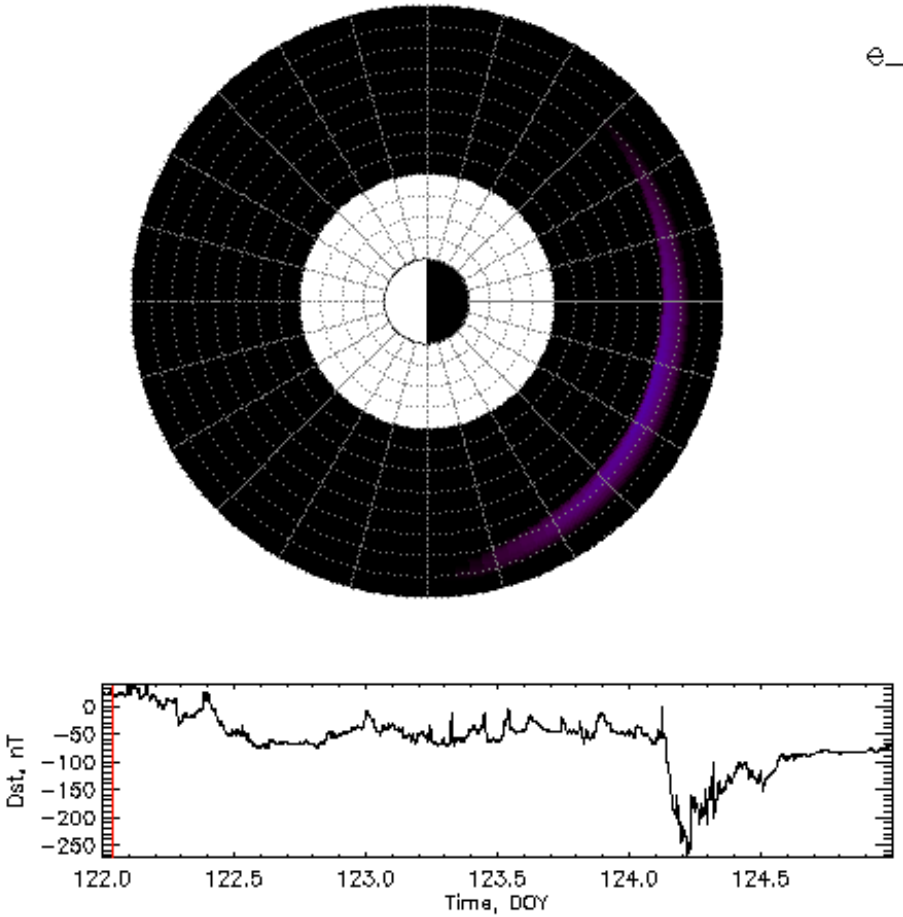
See Matzka et al., 2021 for Kp-indices

Ring Current Protons



Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



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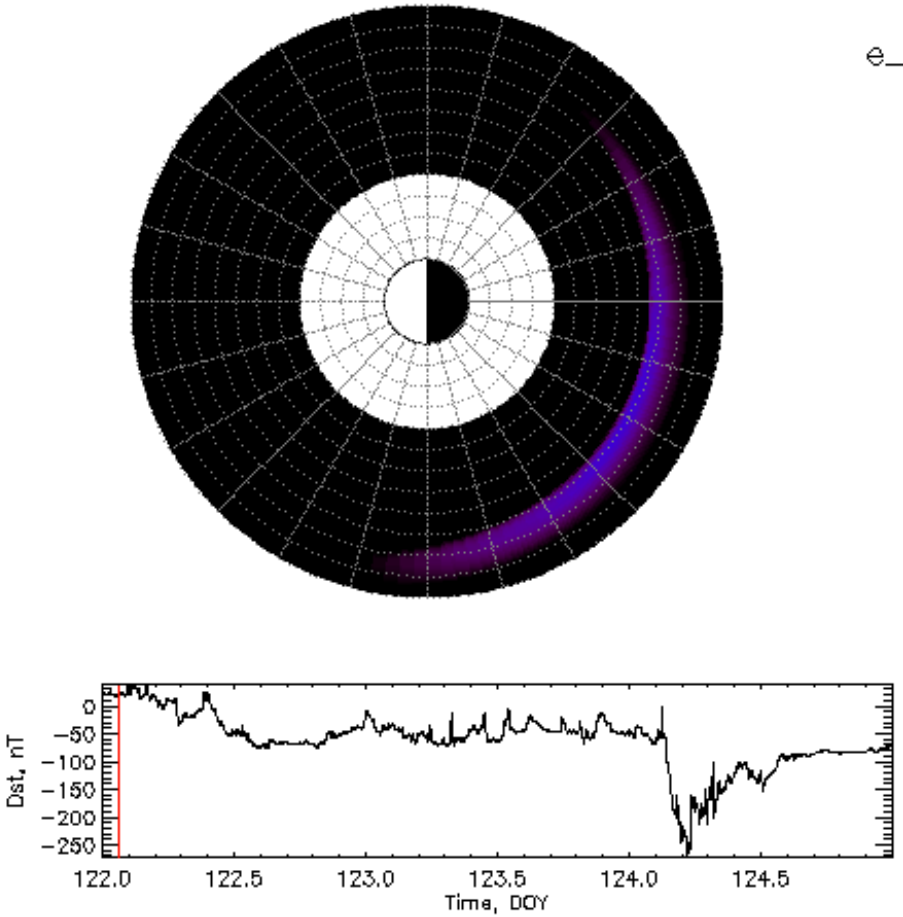
Ring Current Protons



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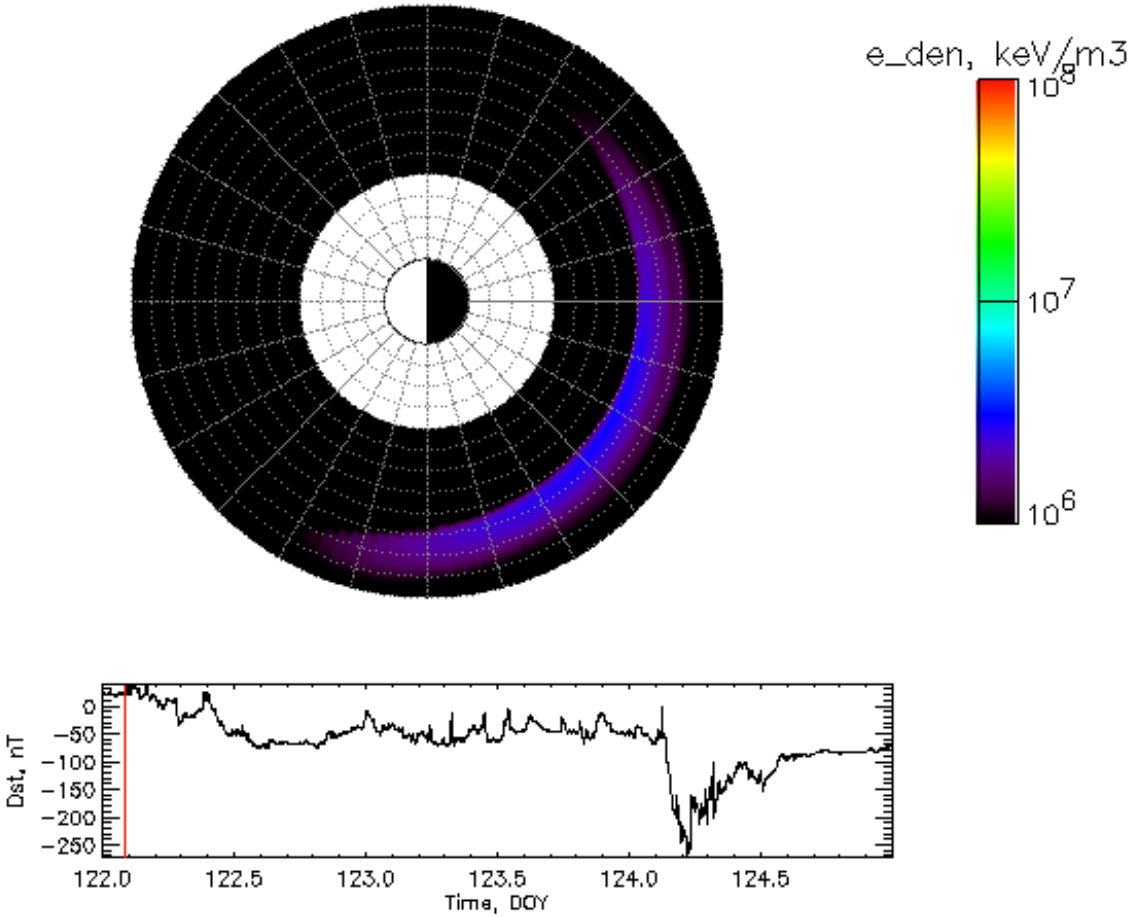
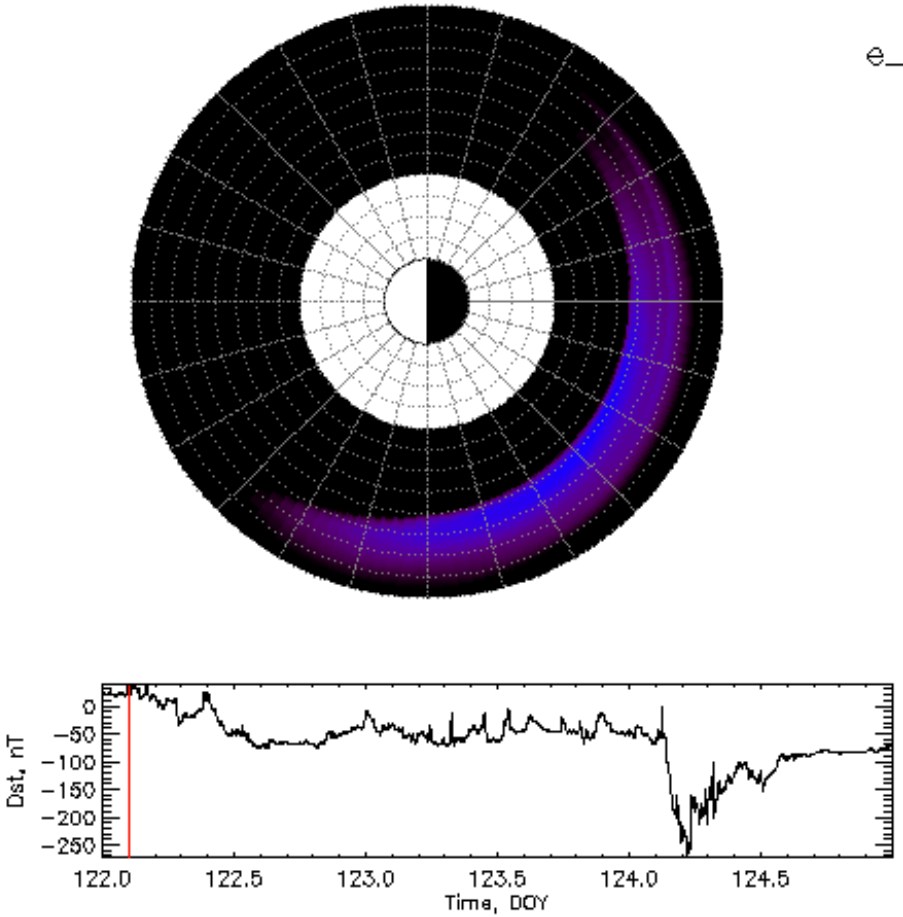
3 days, May 2–4, 1998

Ring Current Protons



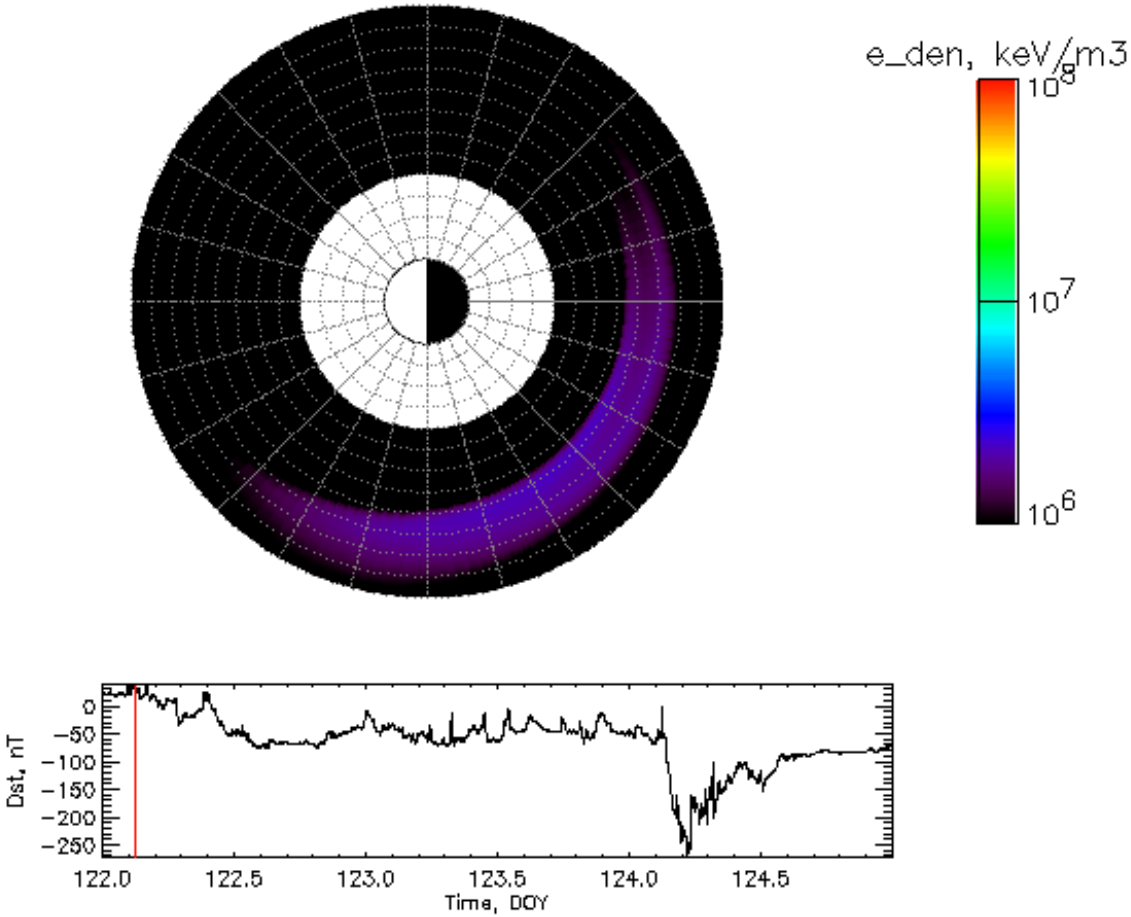
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



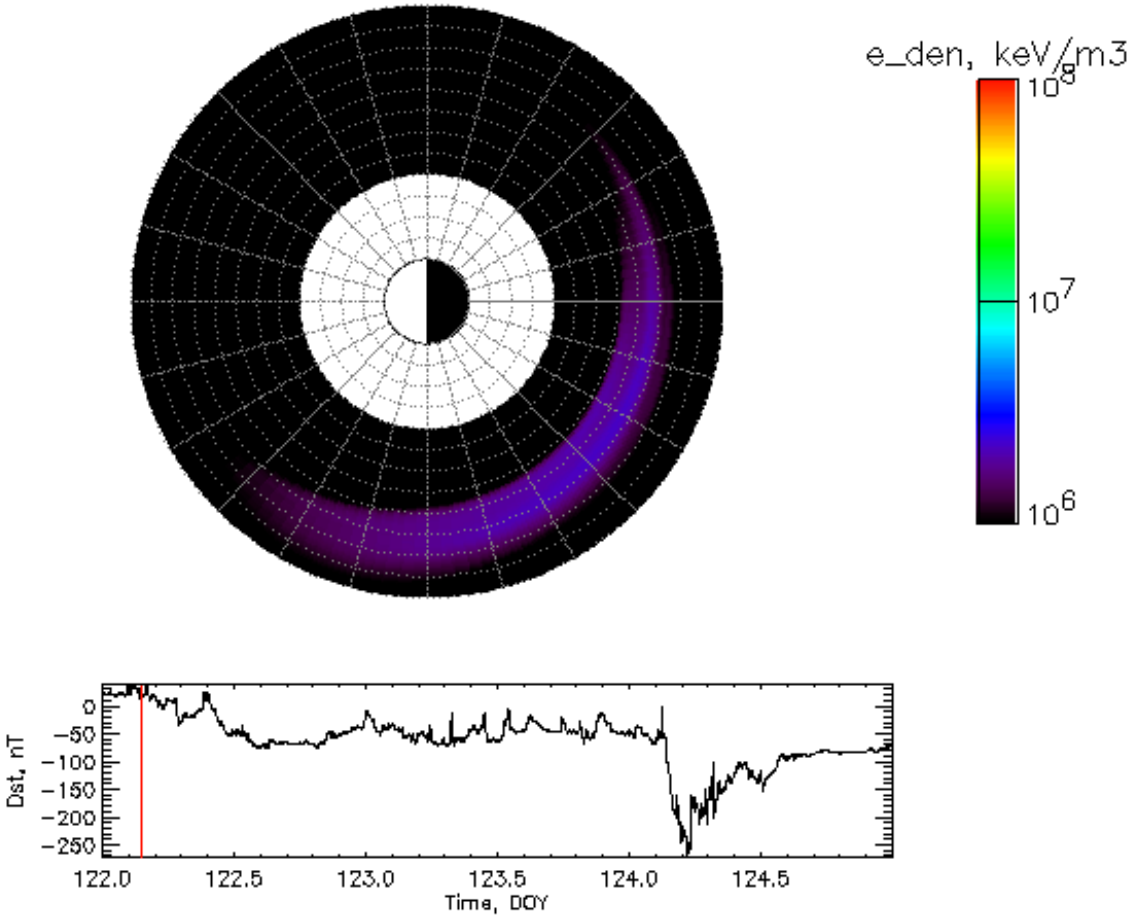
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



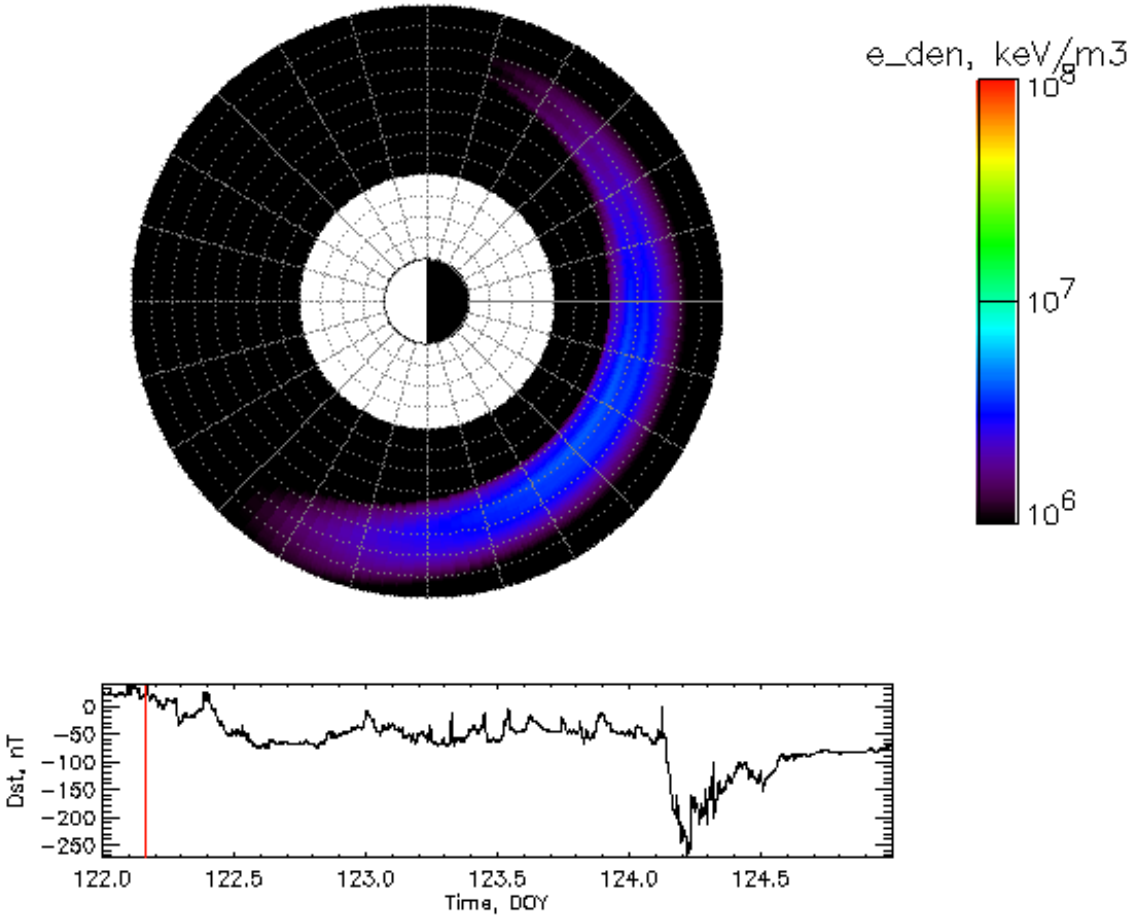
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



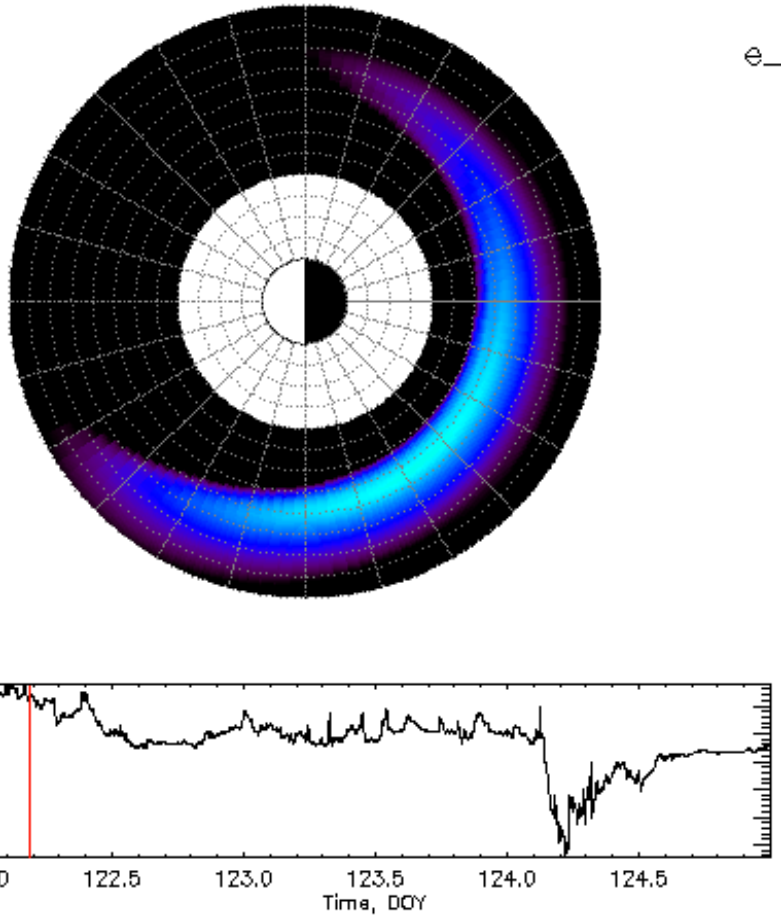
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



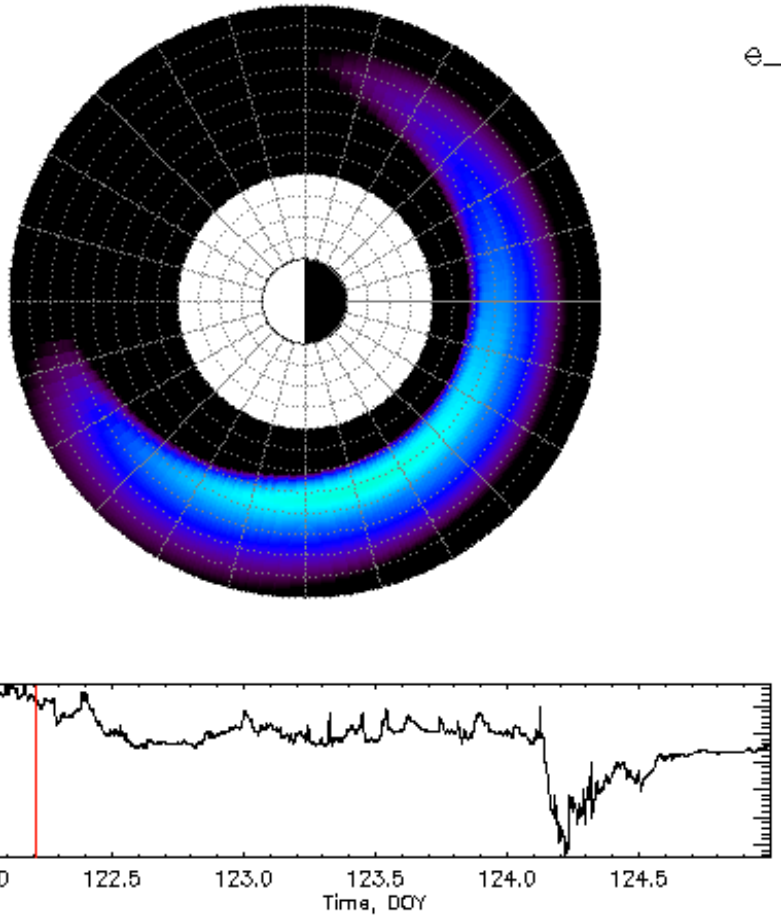
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



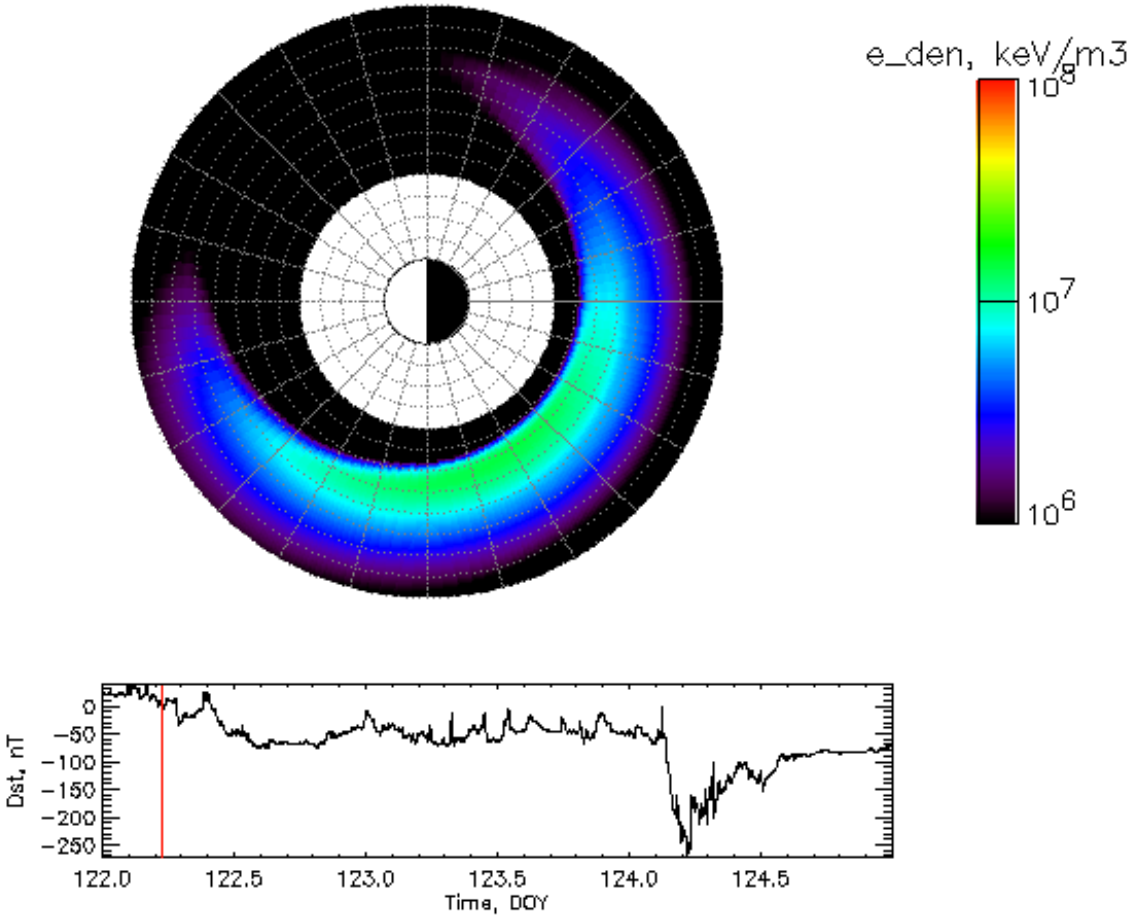
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



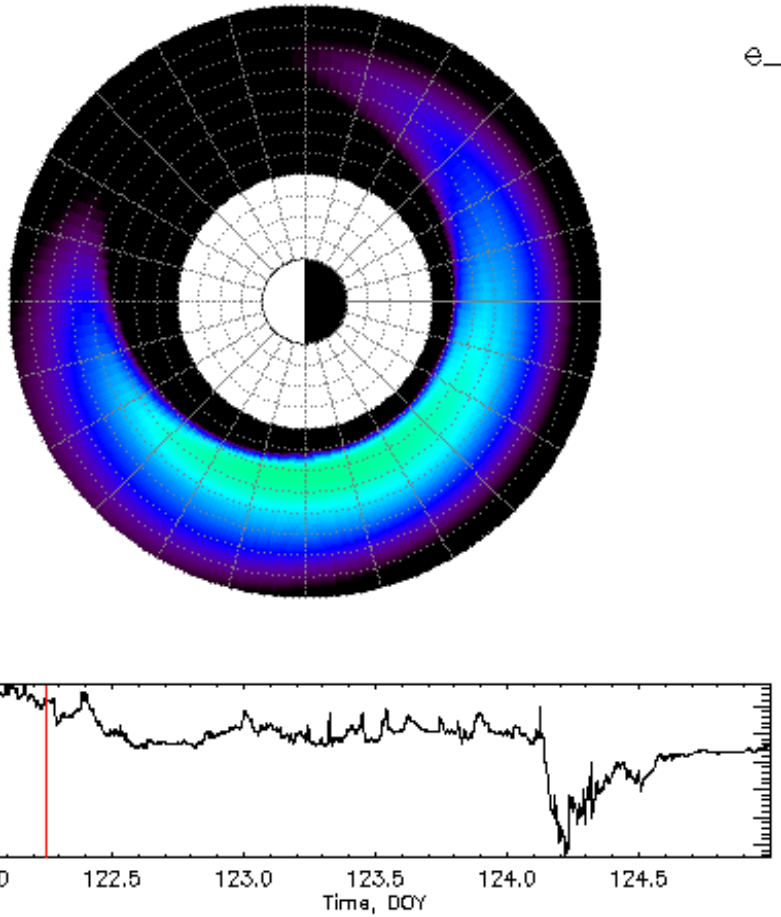
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



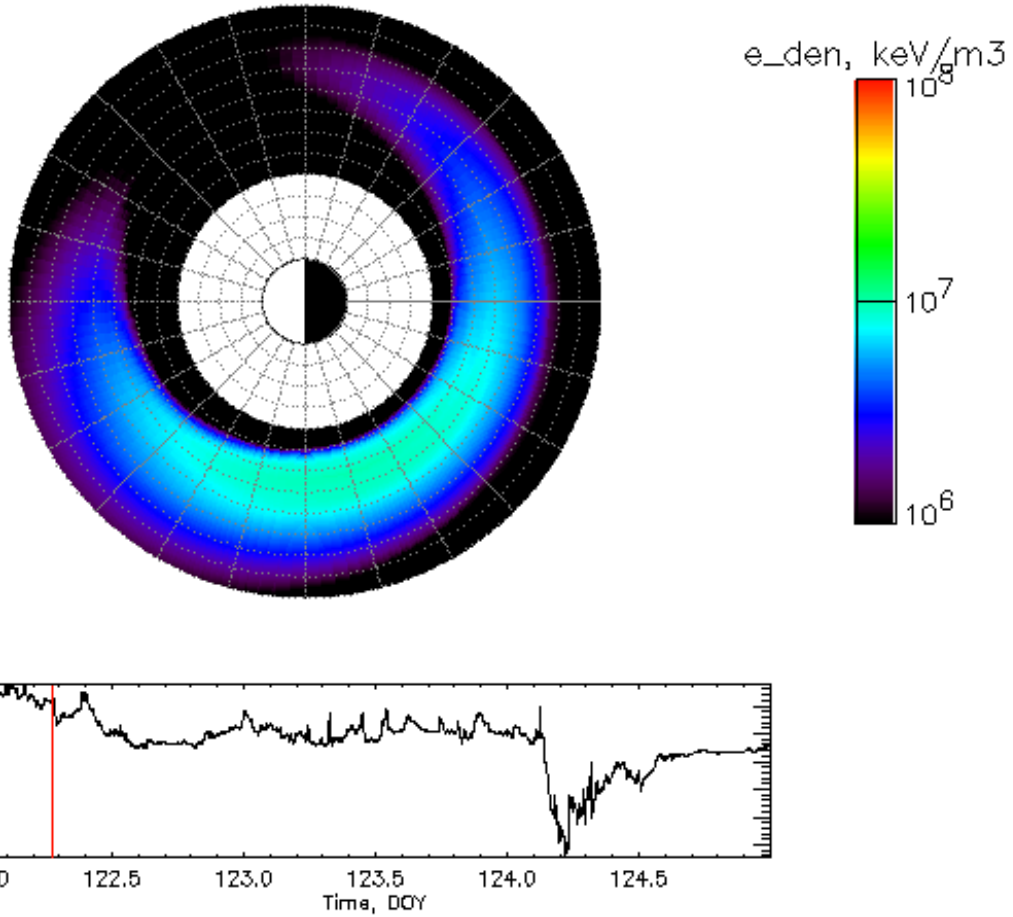
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



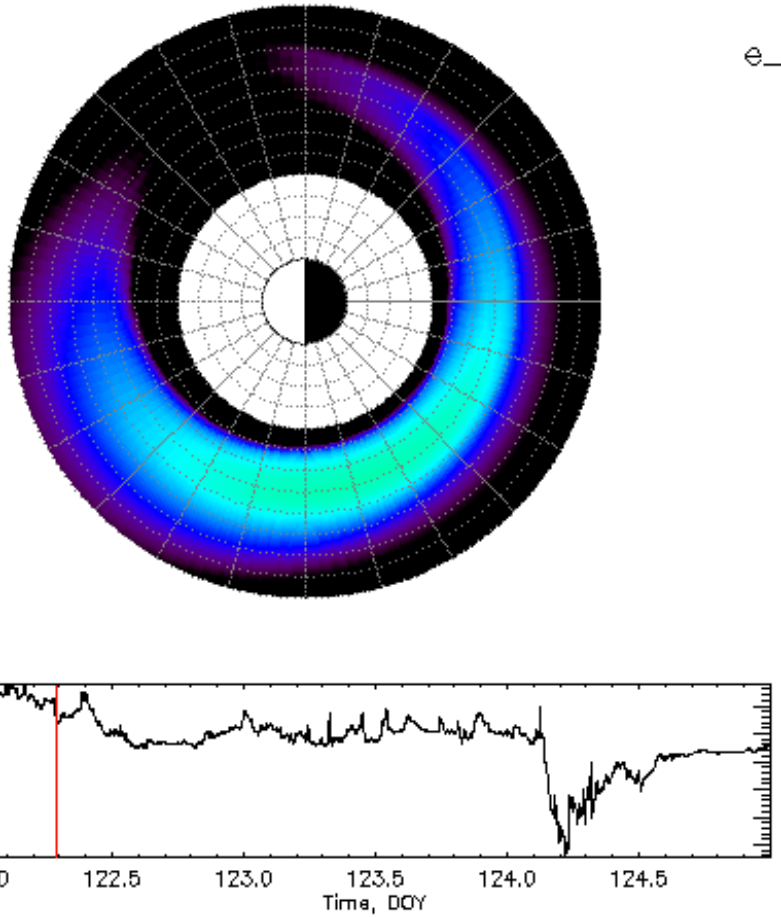
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



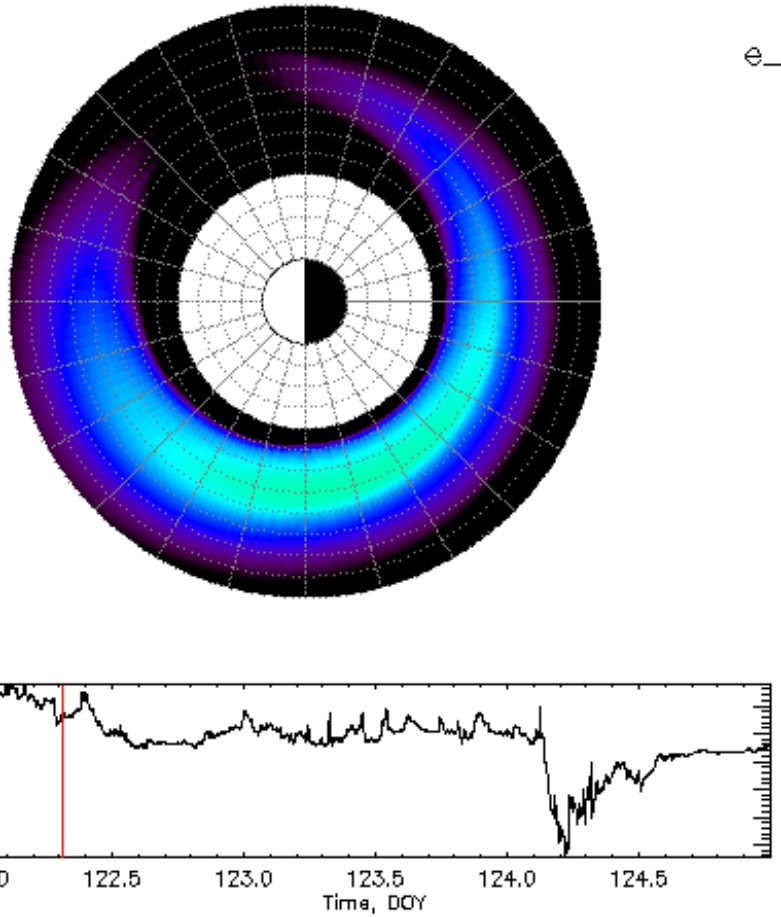
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



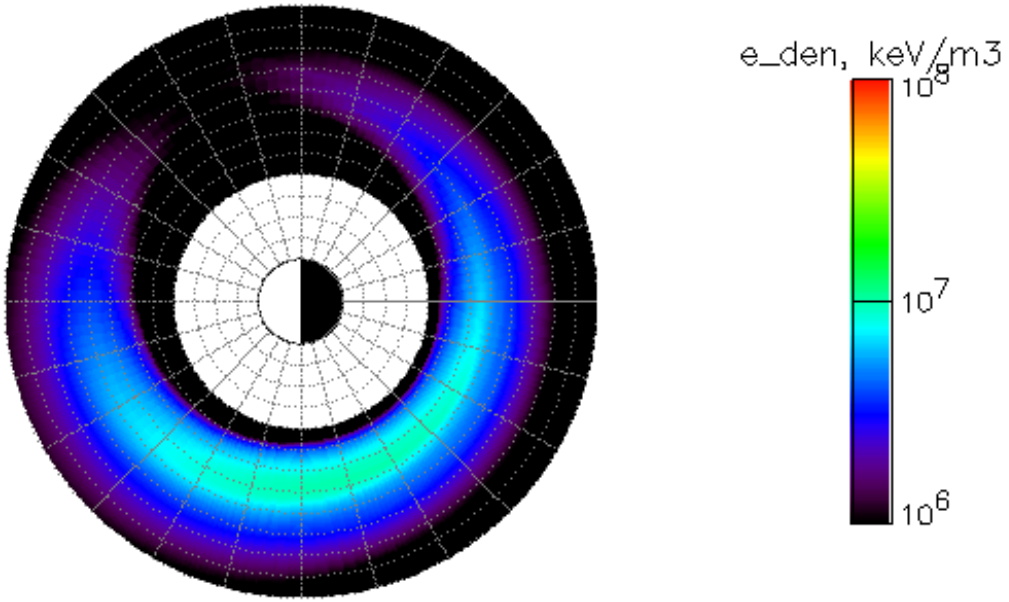
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

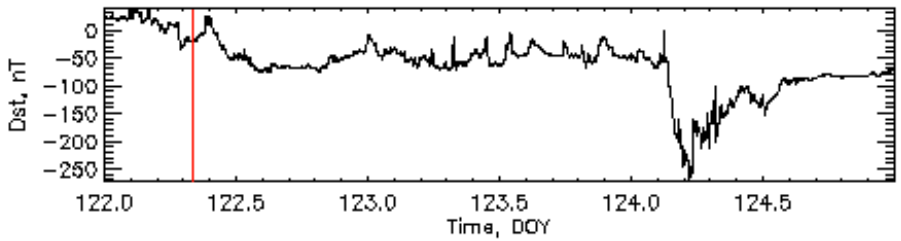
Ring Current Protons



Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

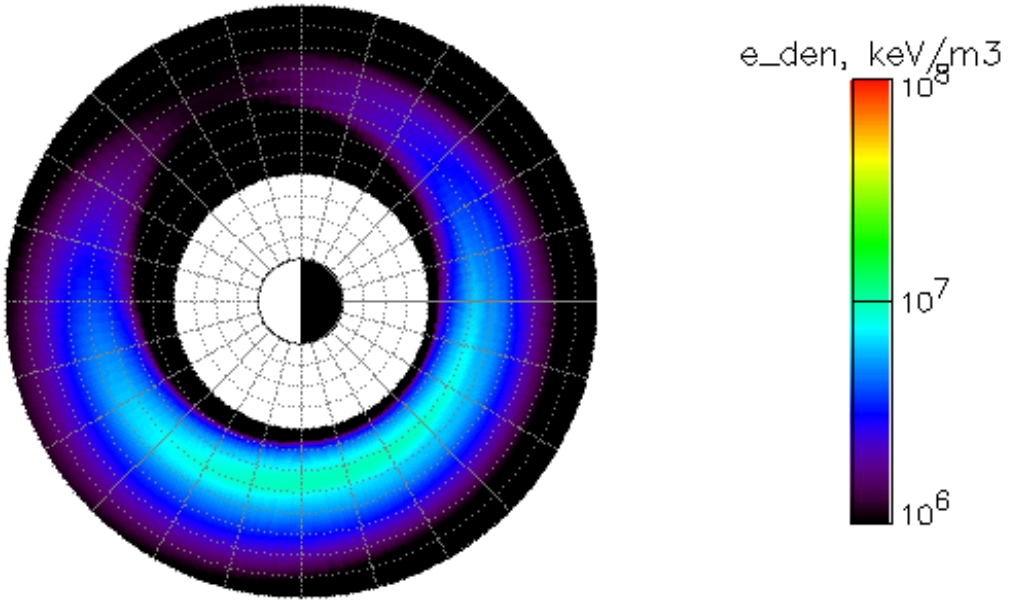
Ring Current Protons

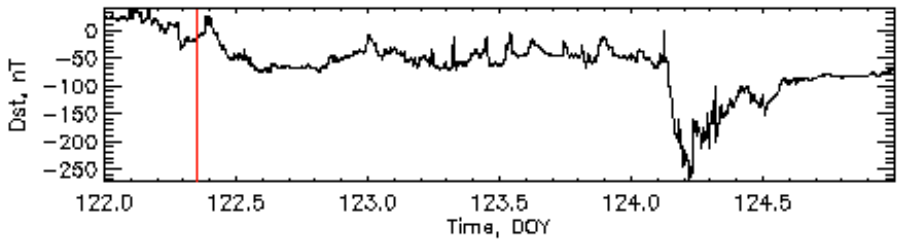




Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

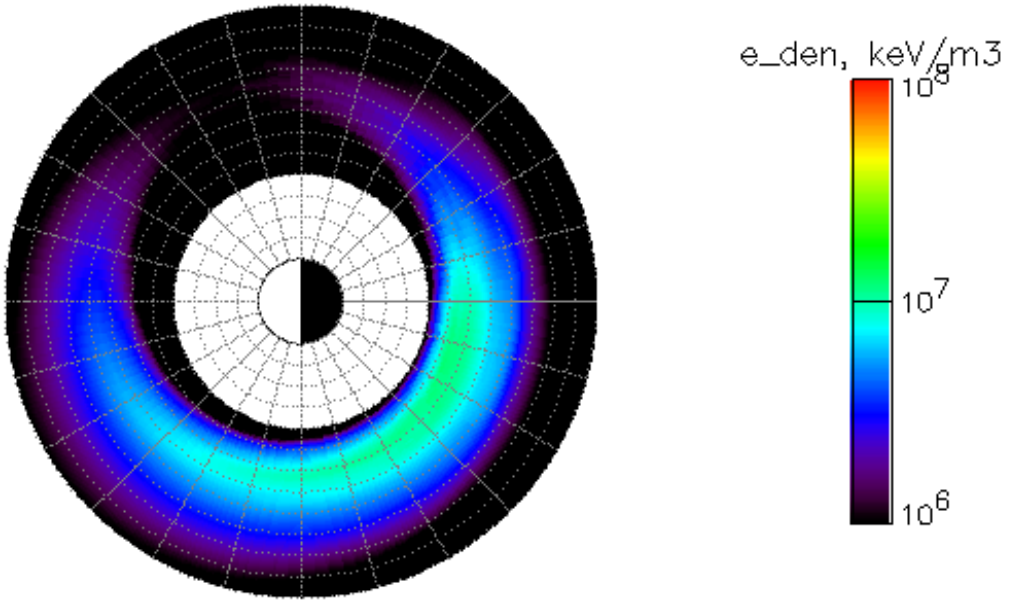
Ring Current Protons

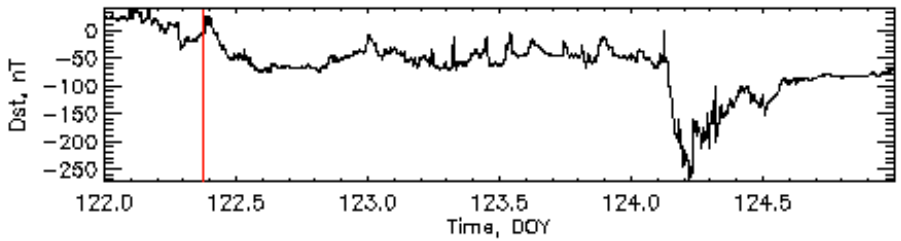




Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

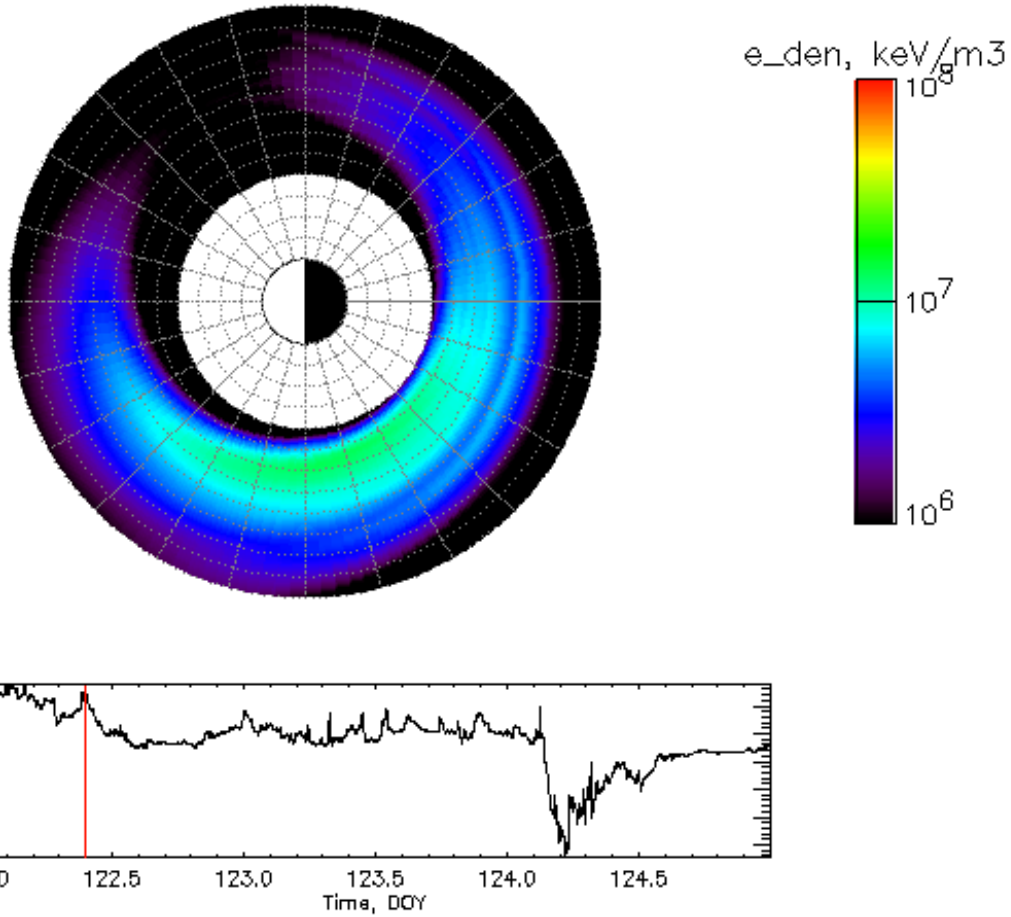
Ring Current Protons





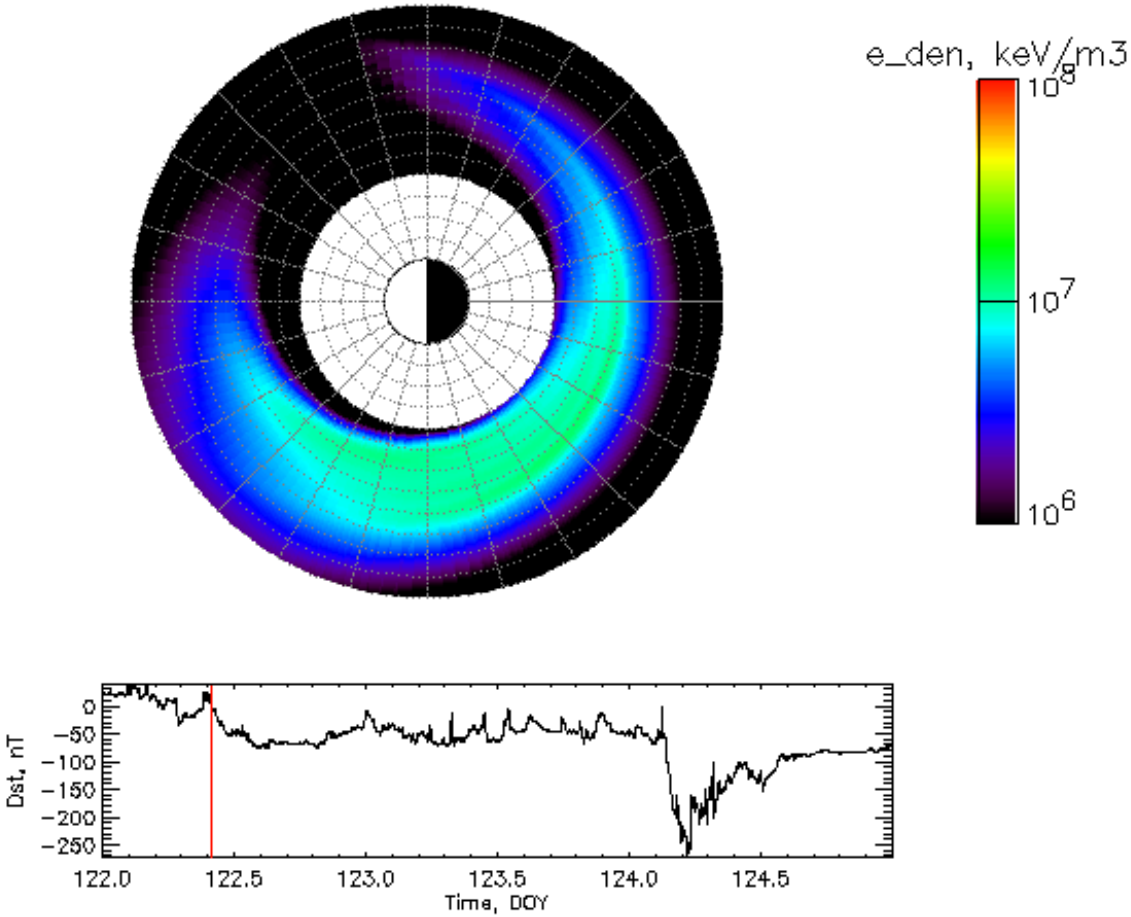
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



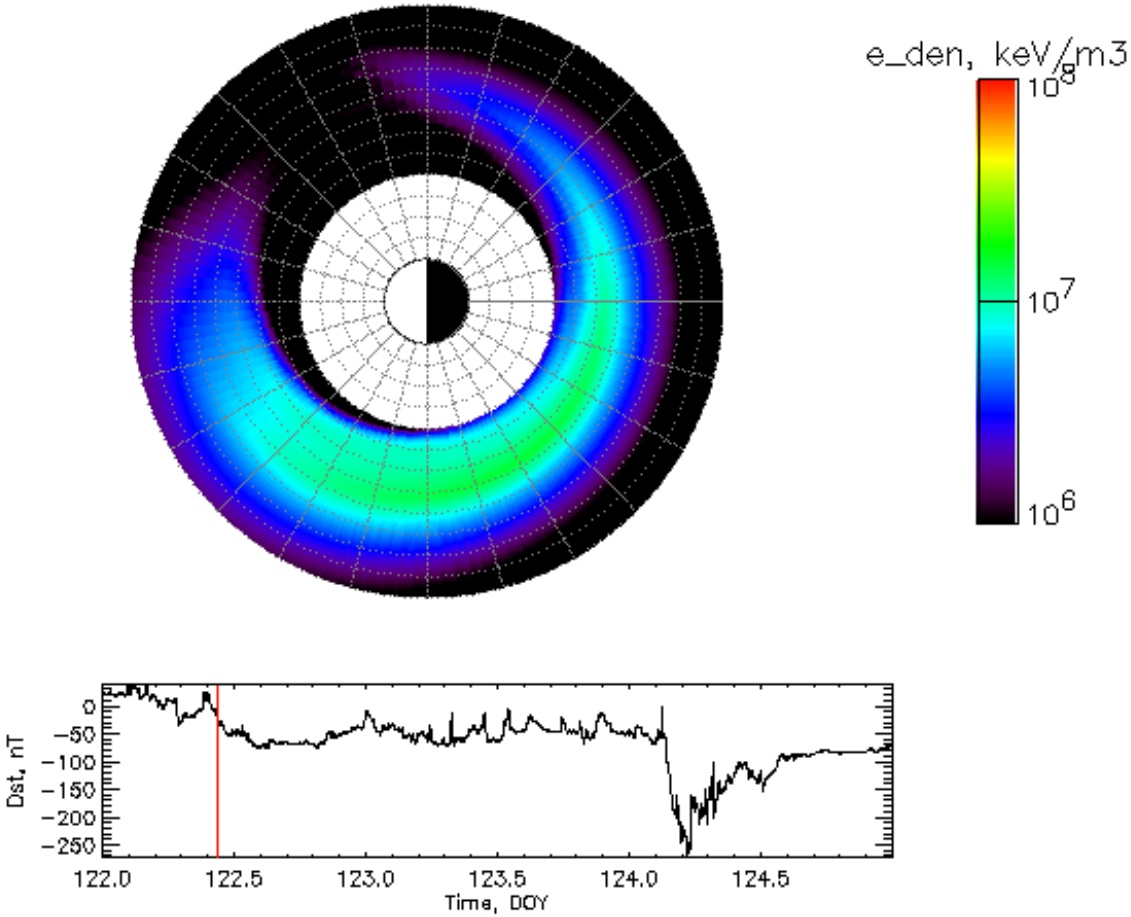
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



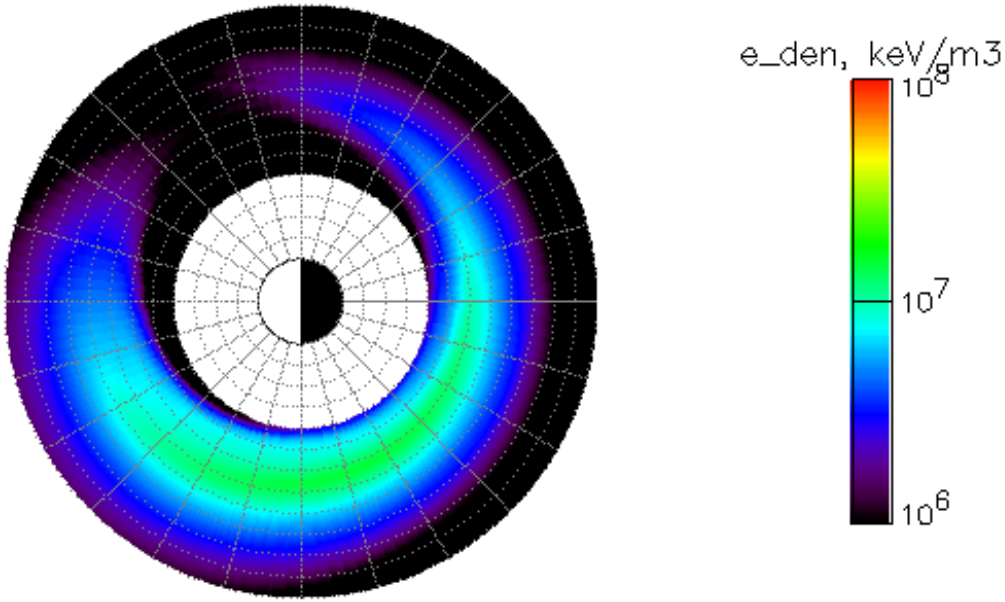
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

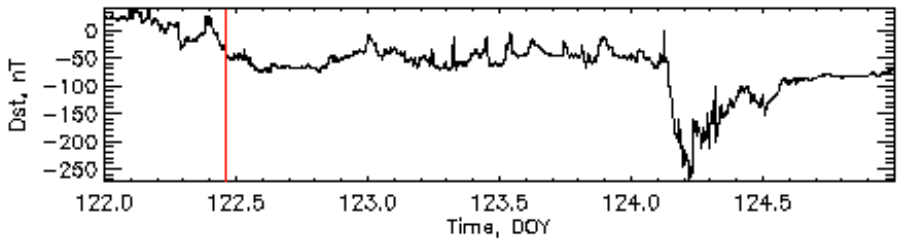
Ring Current Protons



Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

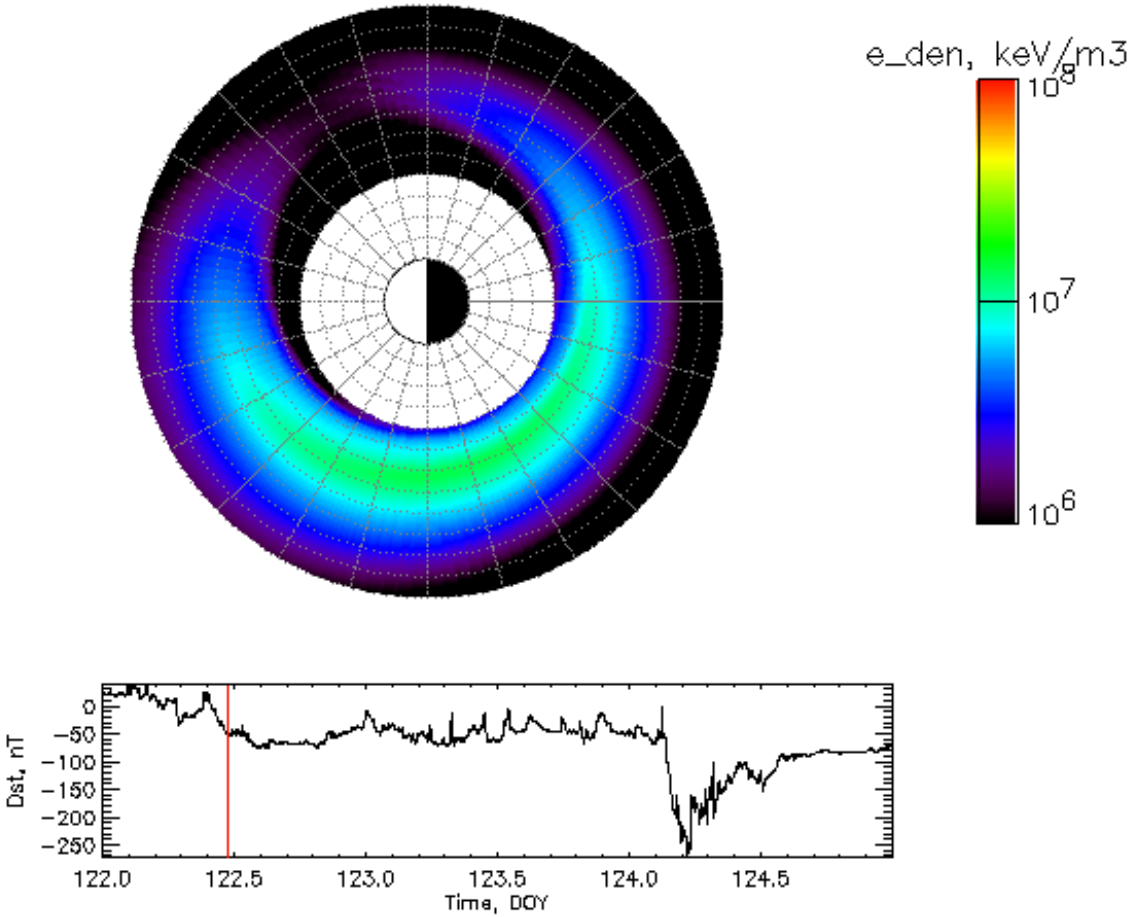
Ring Current Protons





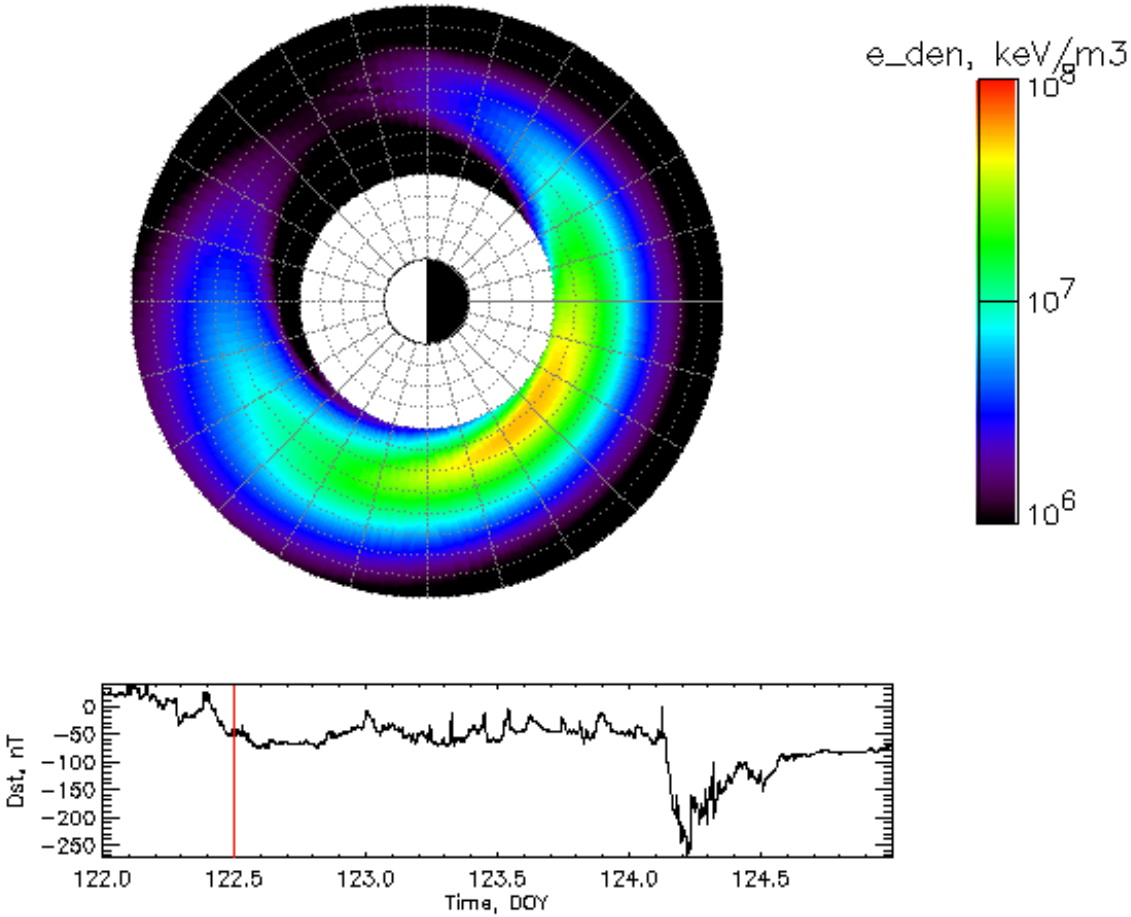
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



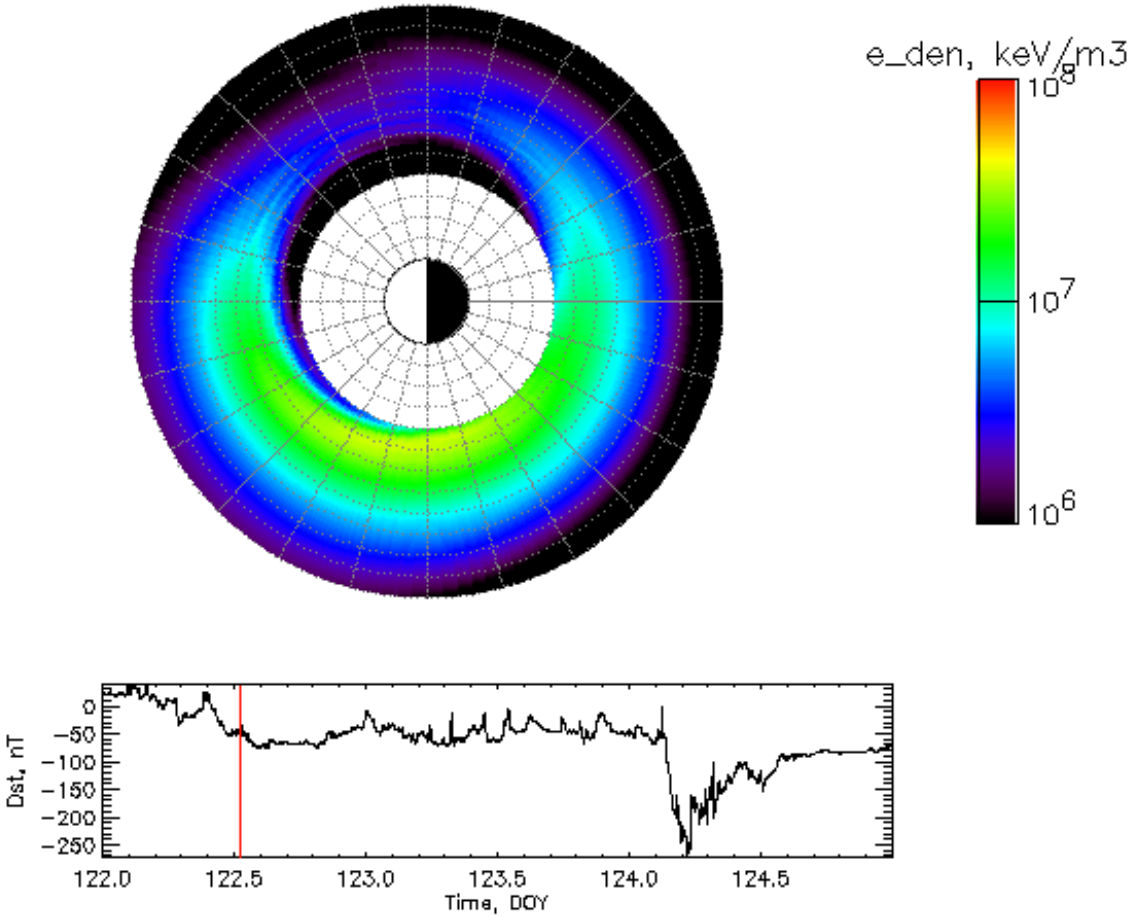
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



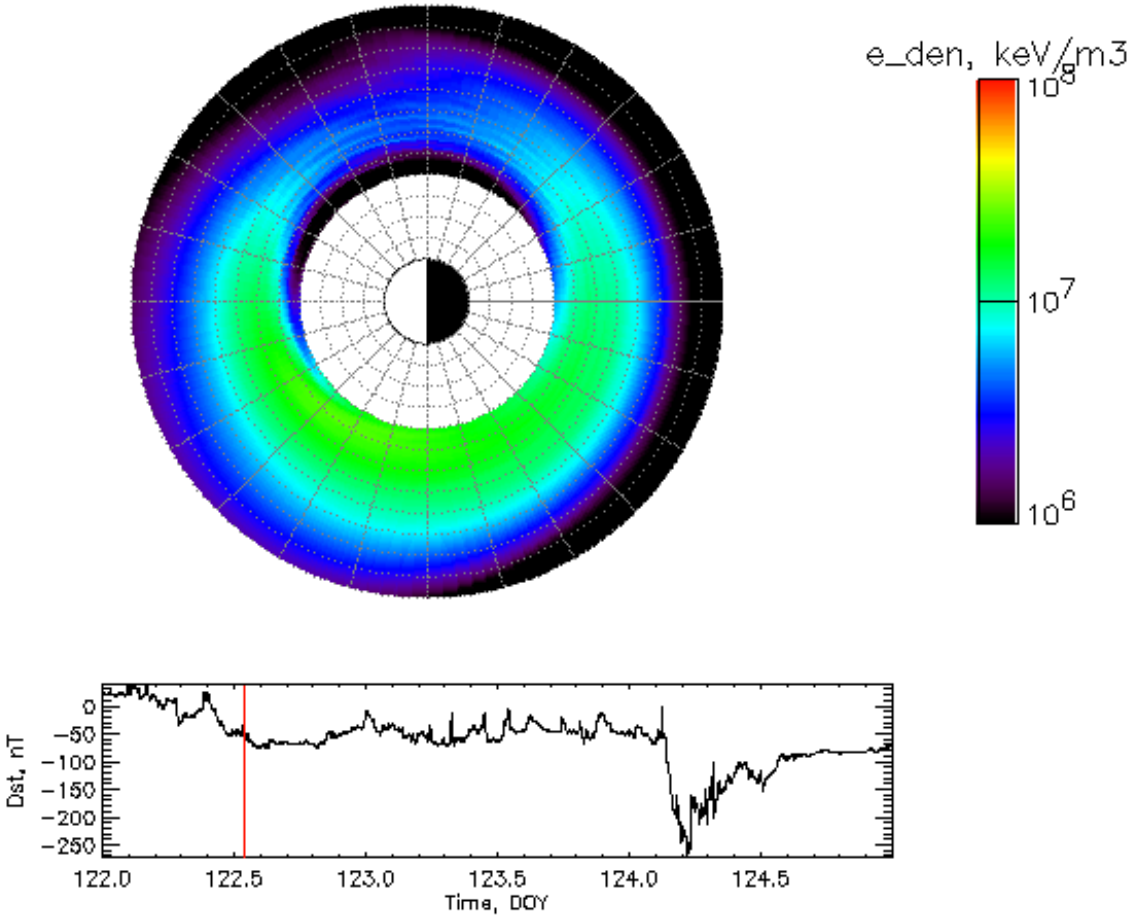
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



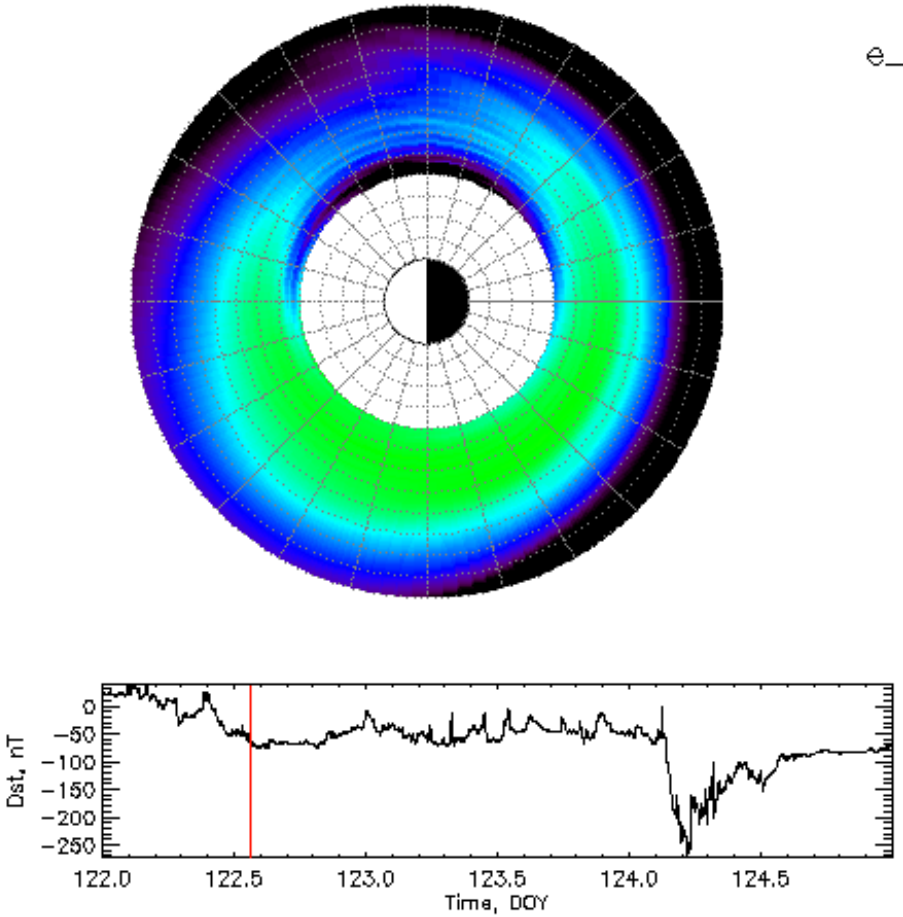
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



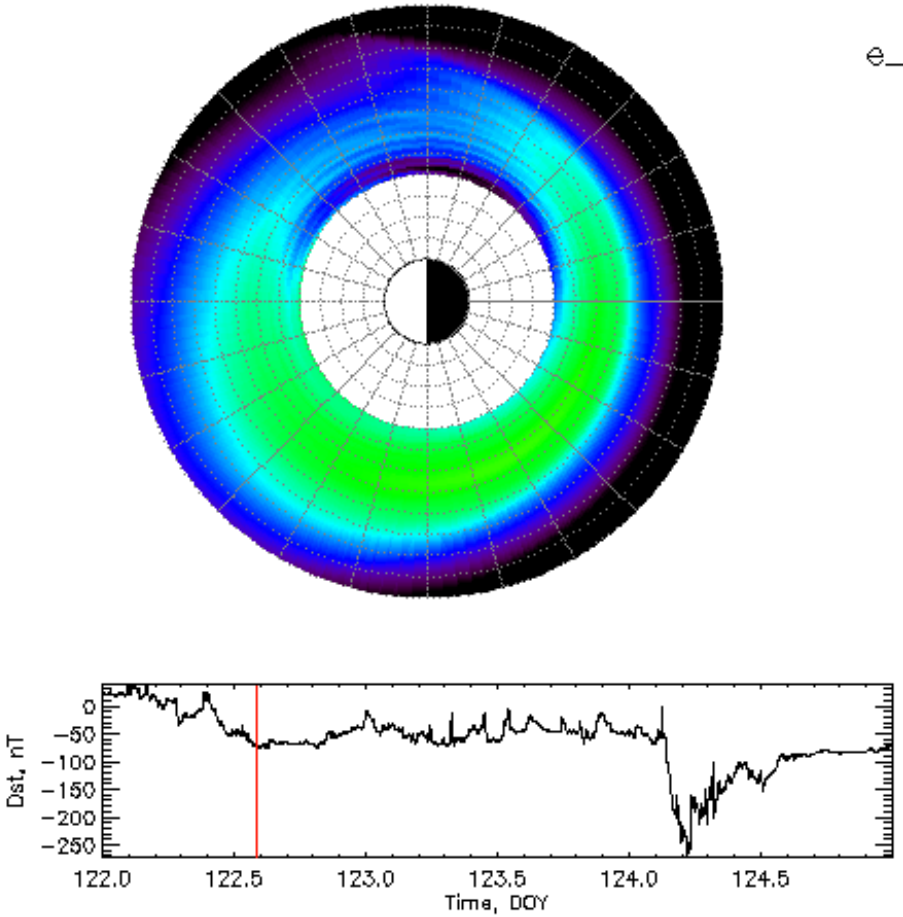
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



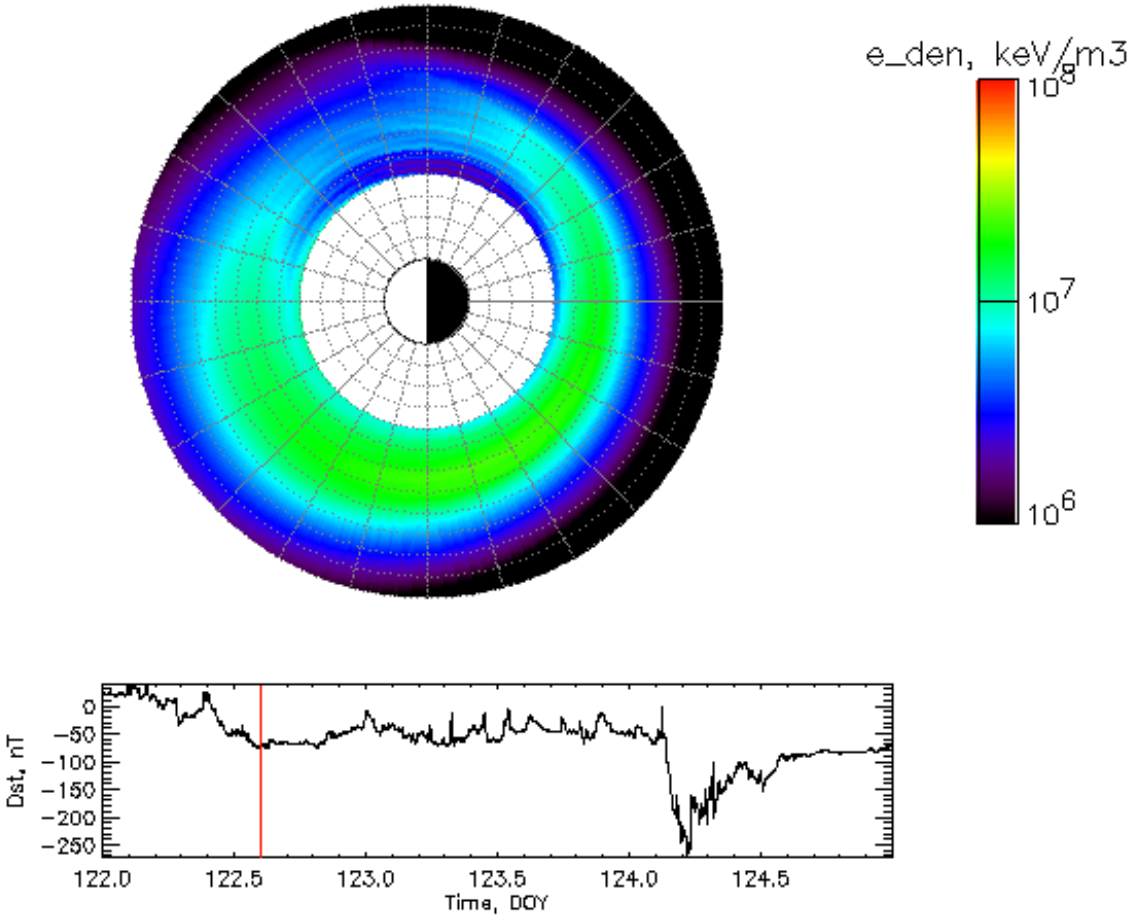
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



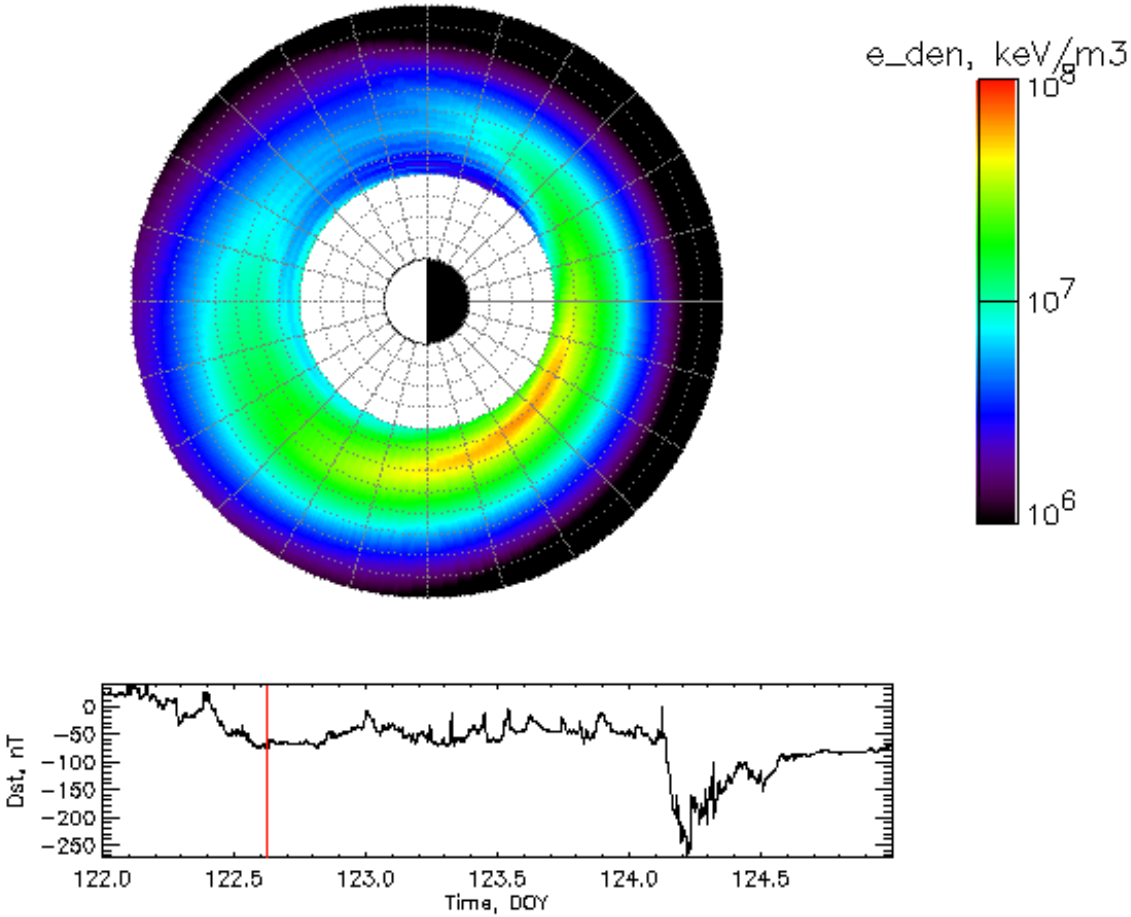
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



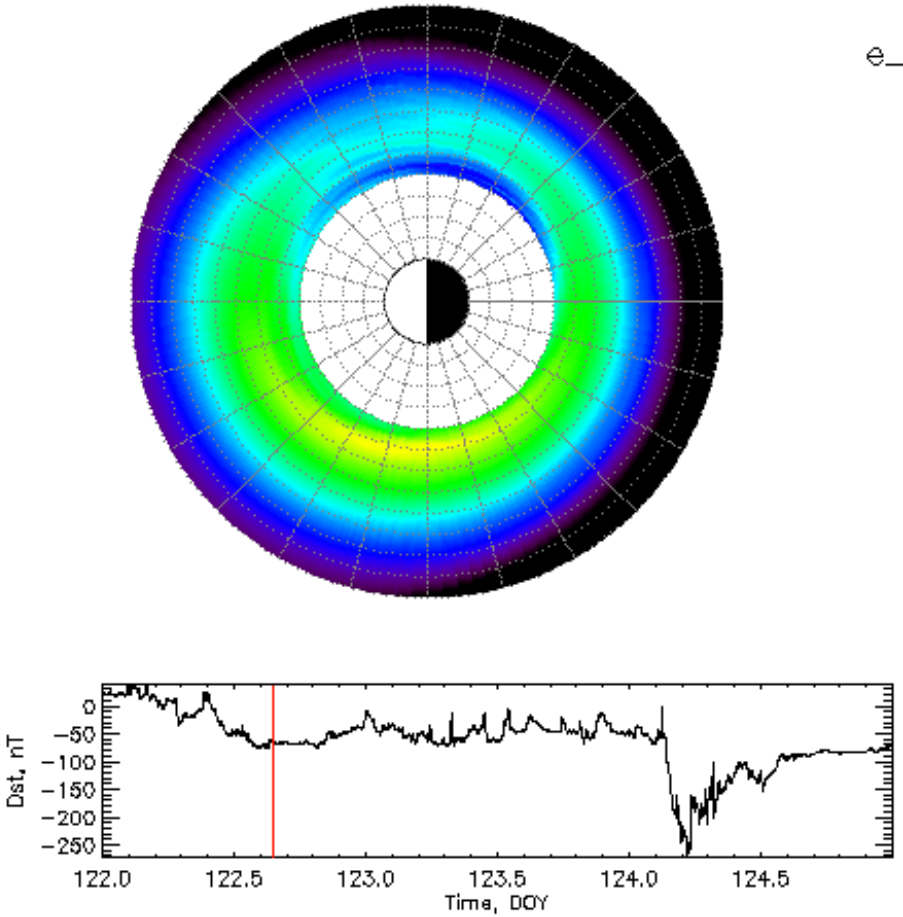
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



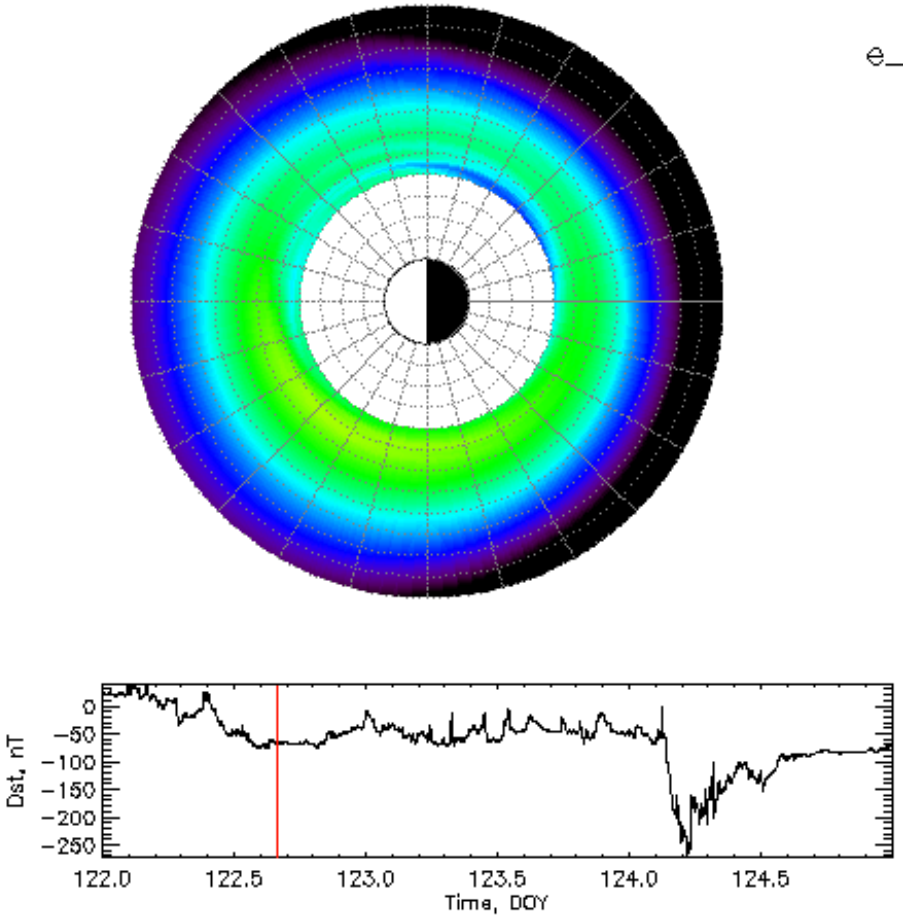
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



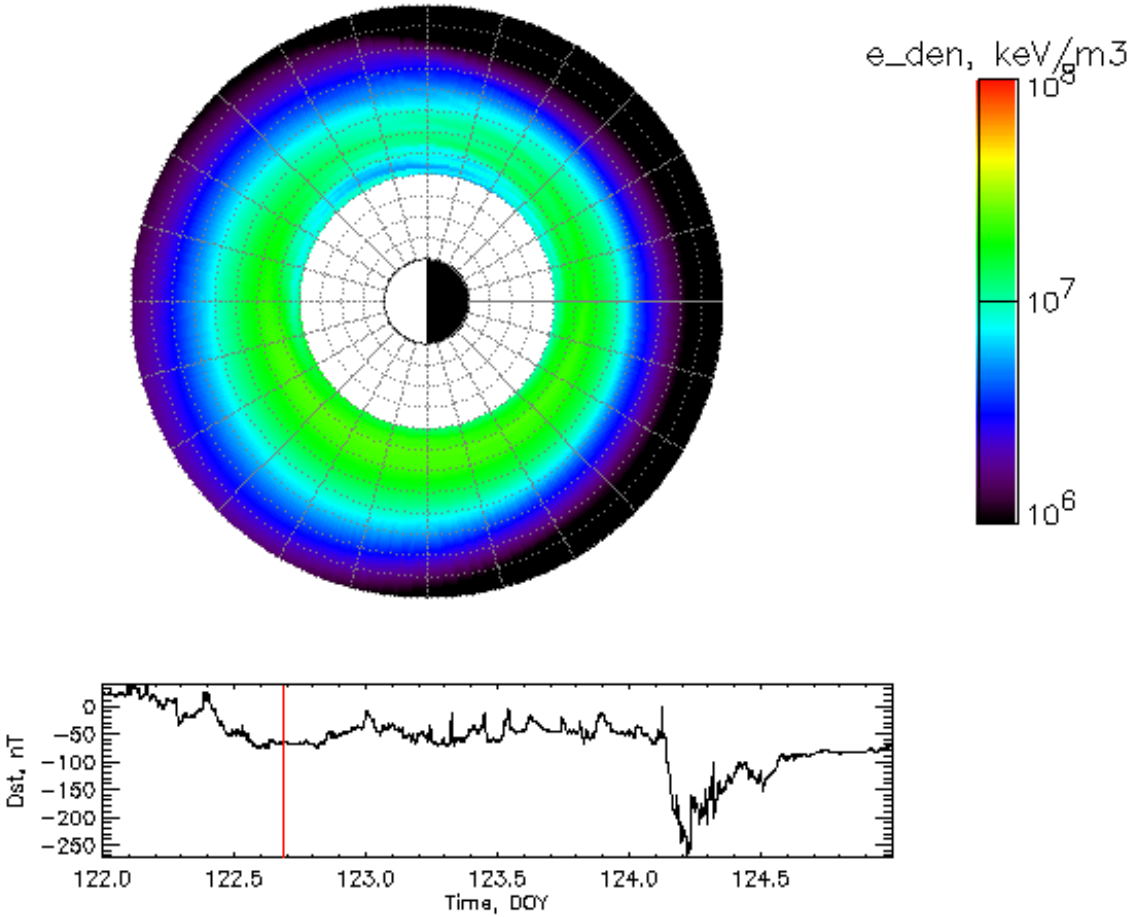
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



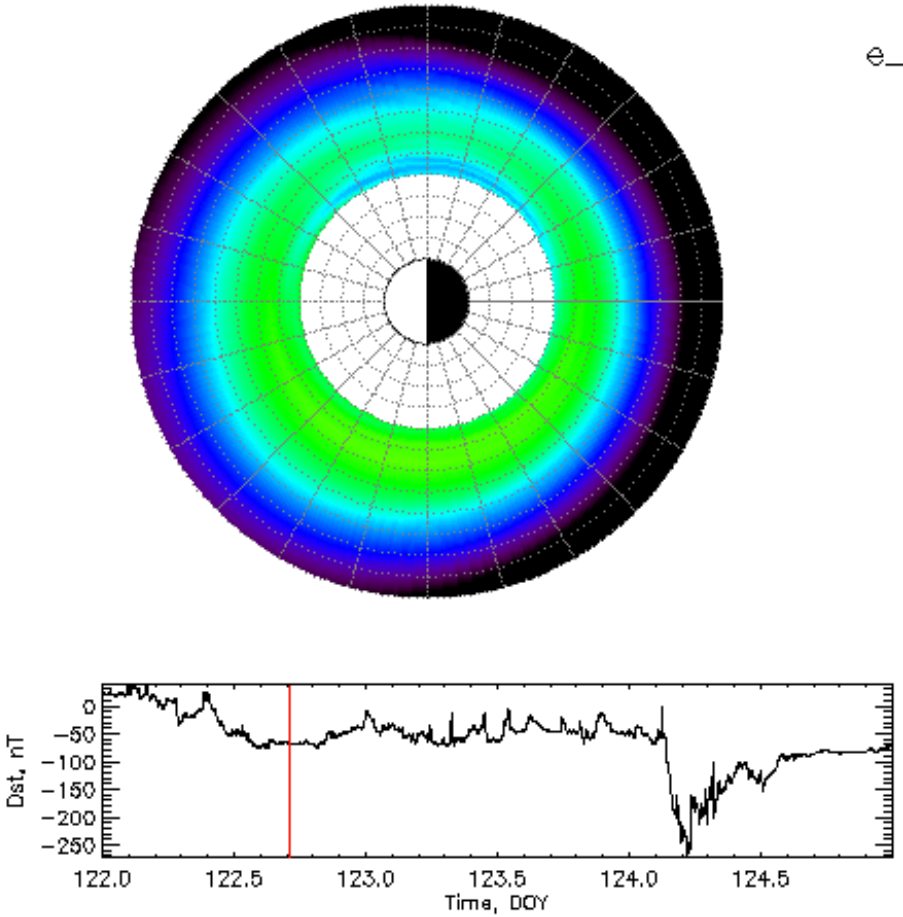
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



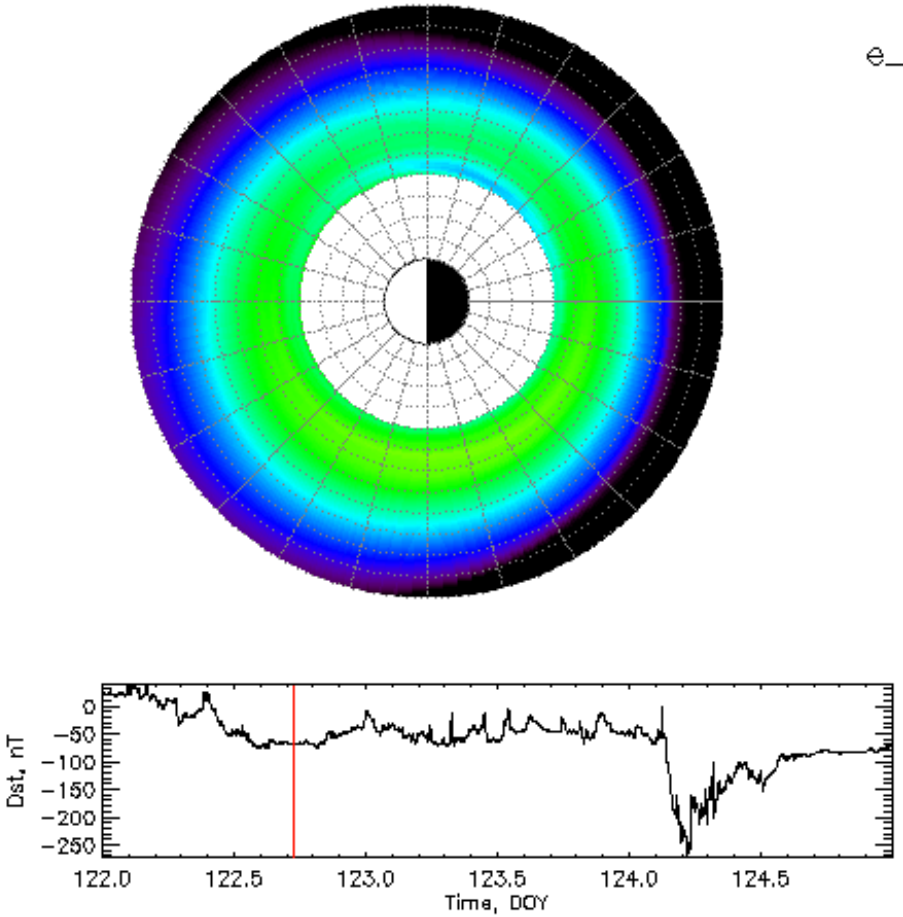
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



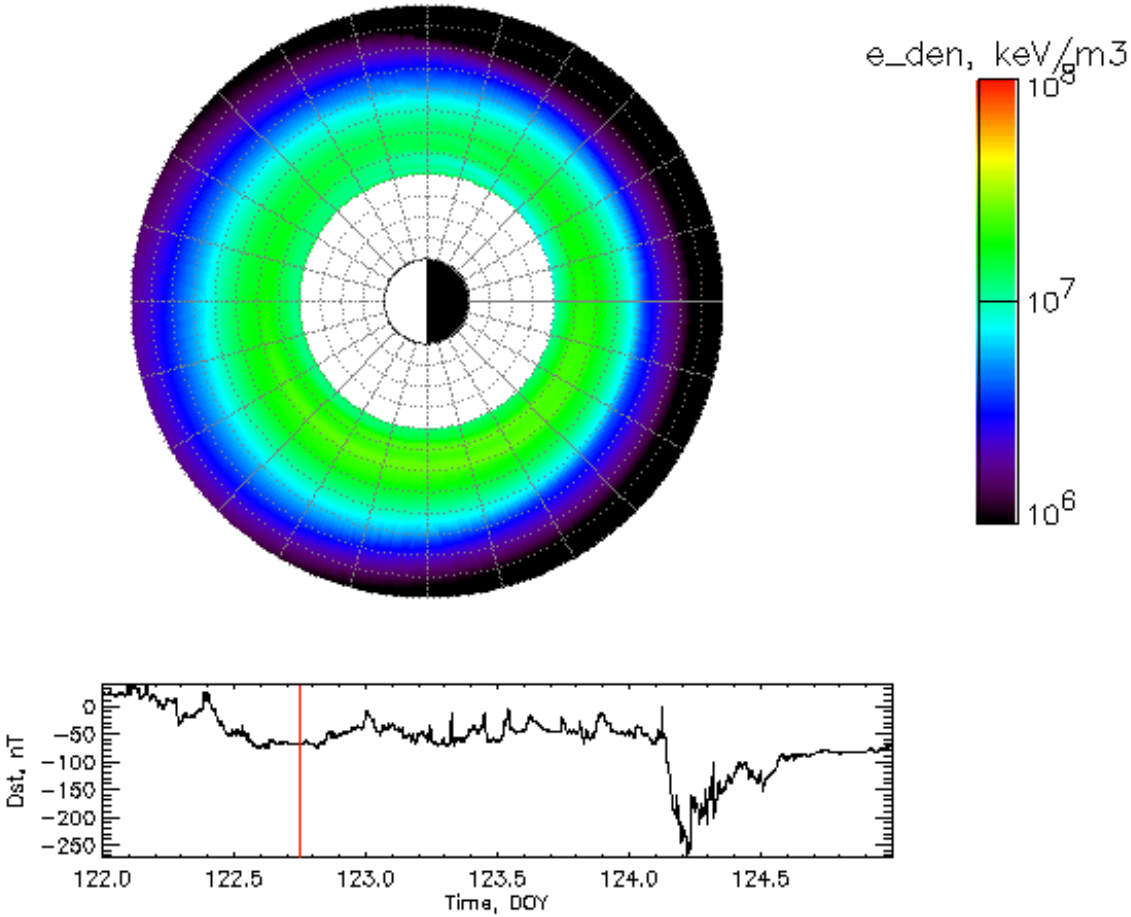
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



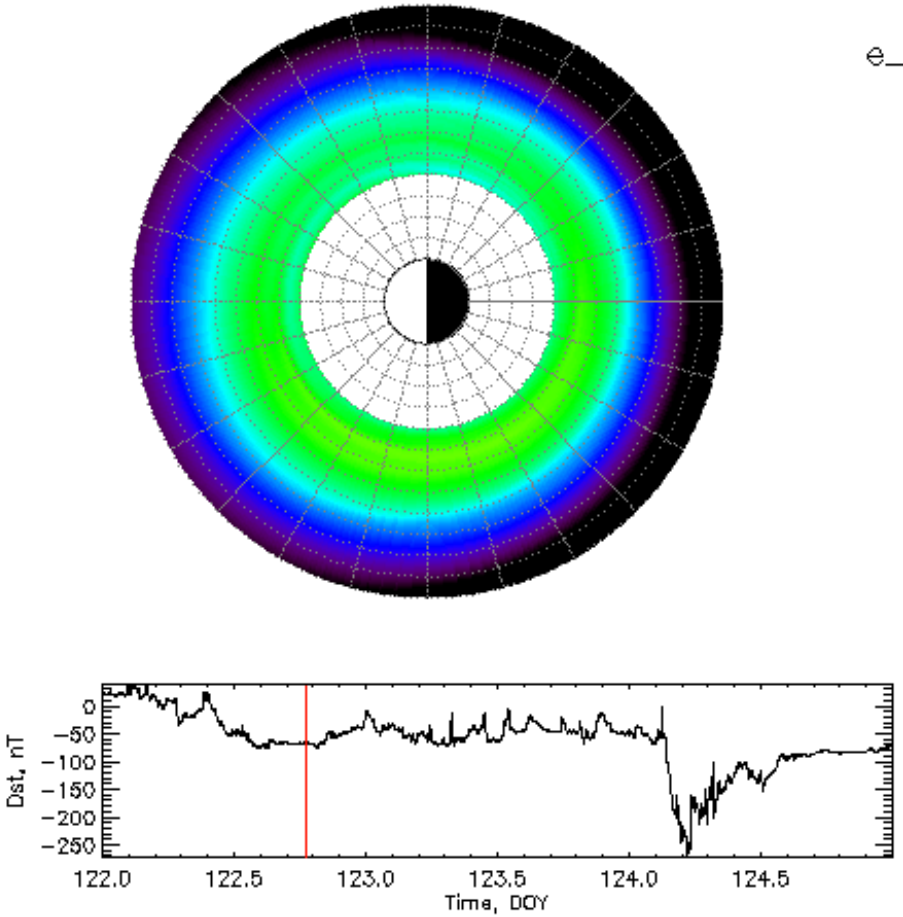
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



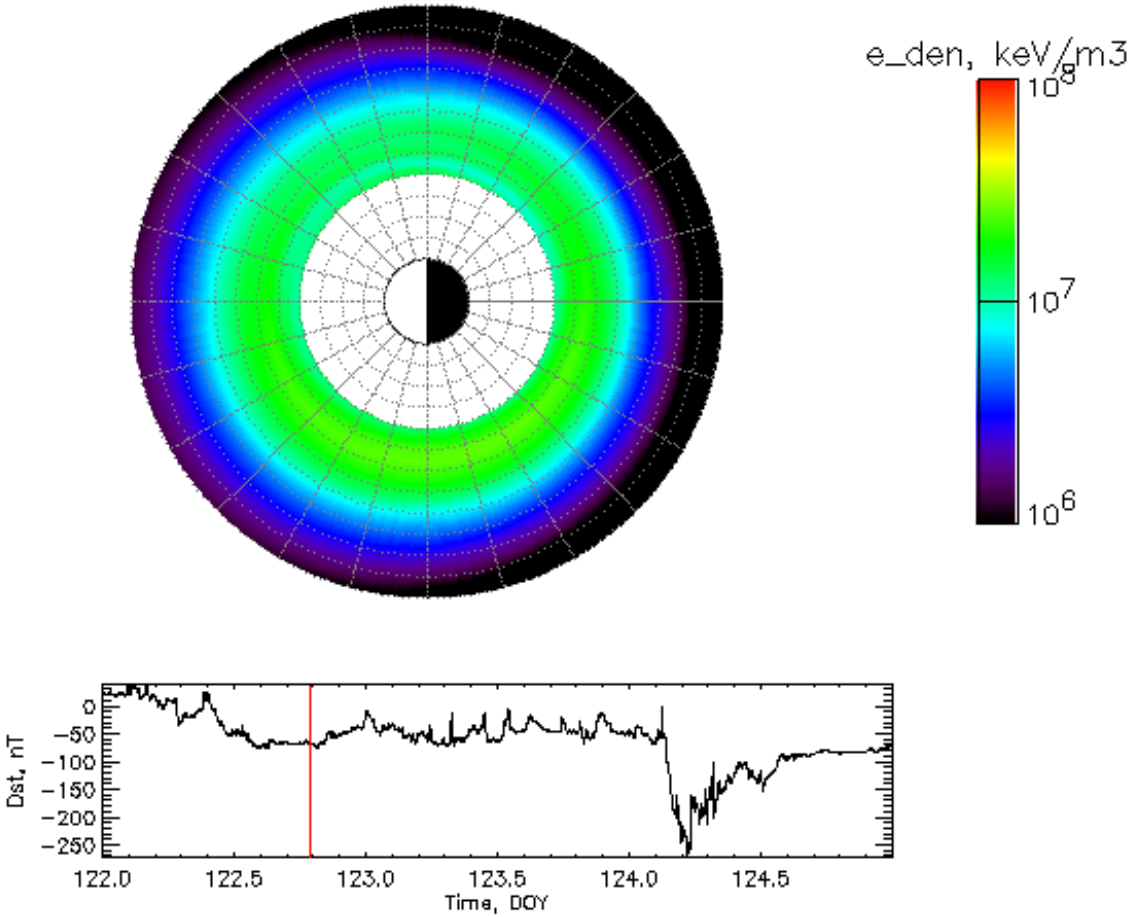
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



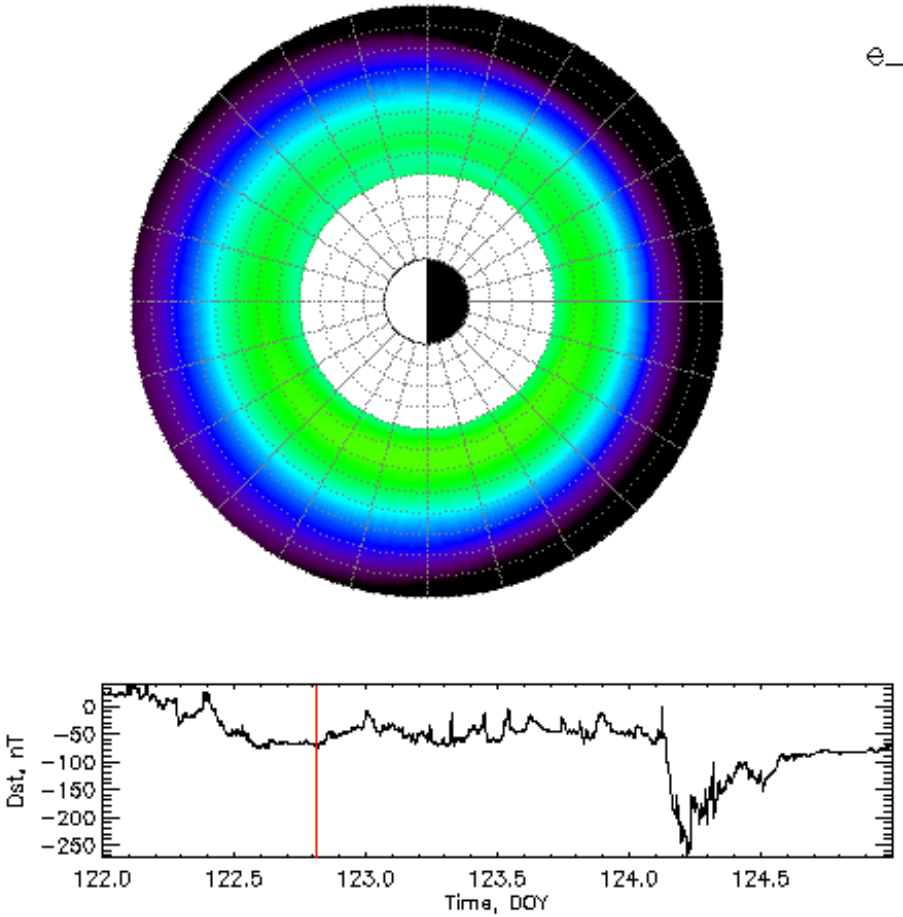
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



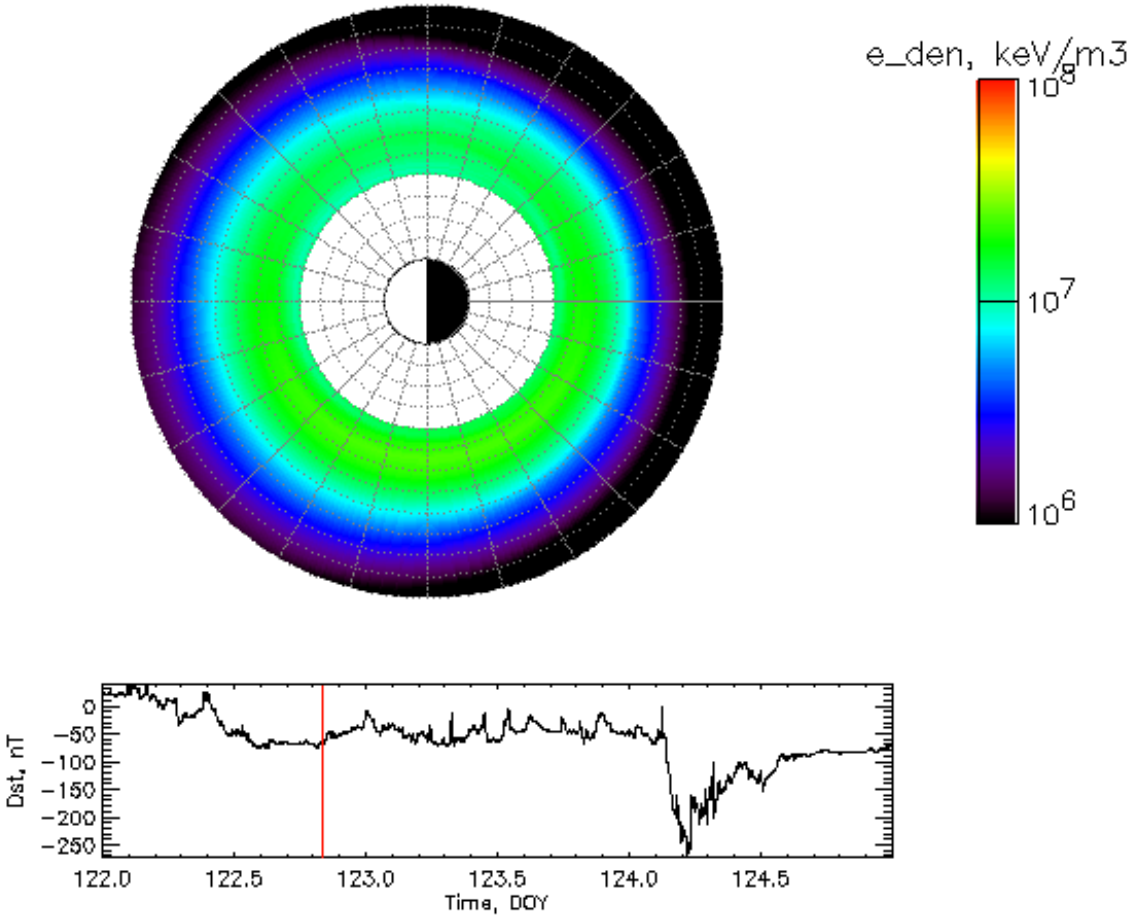
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



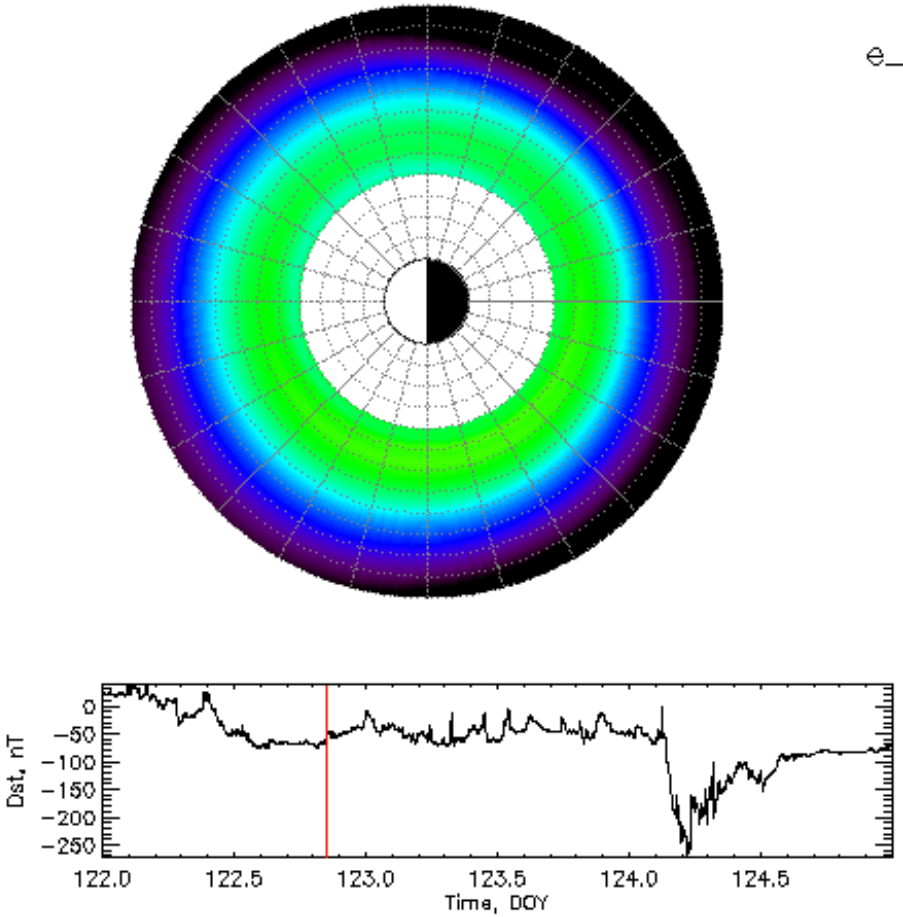
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



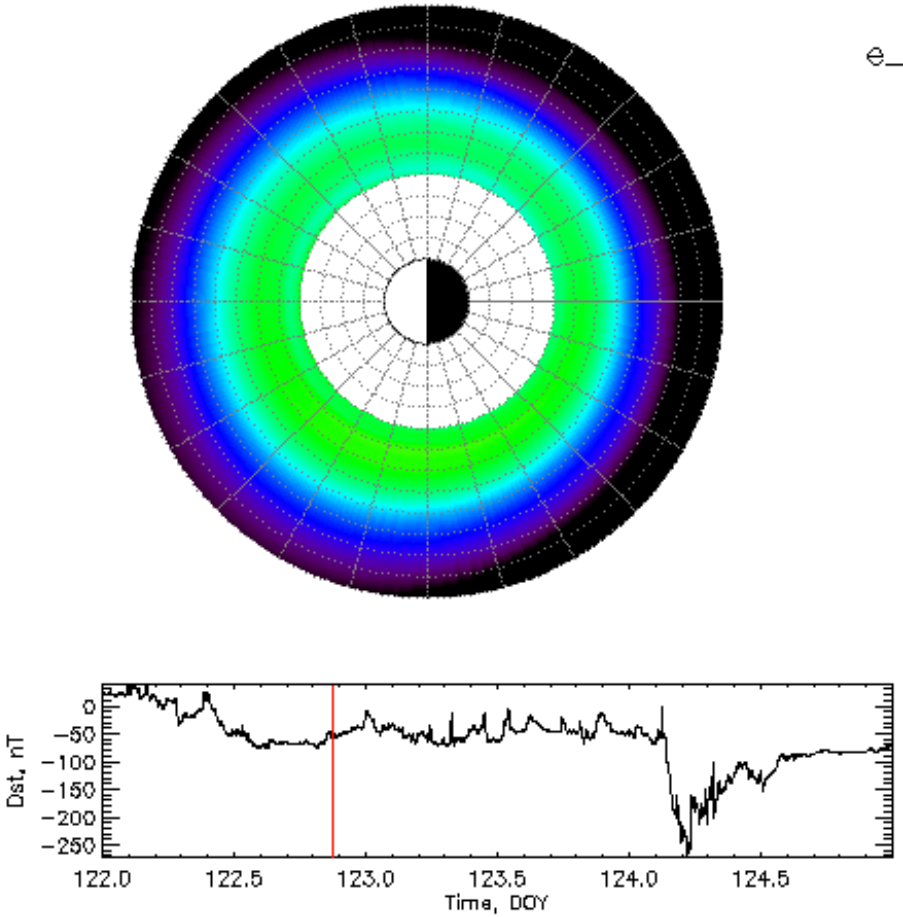
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



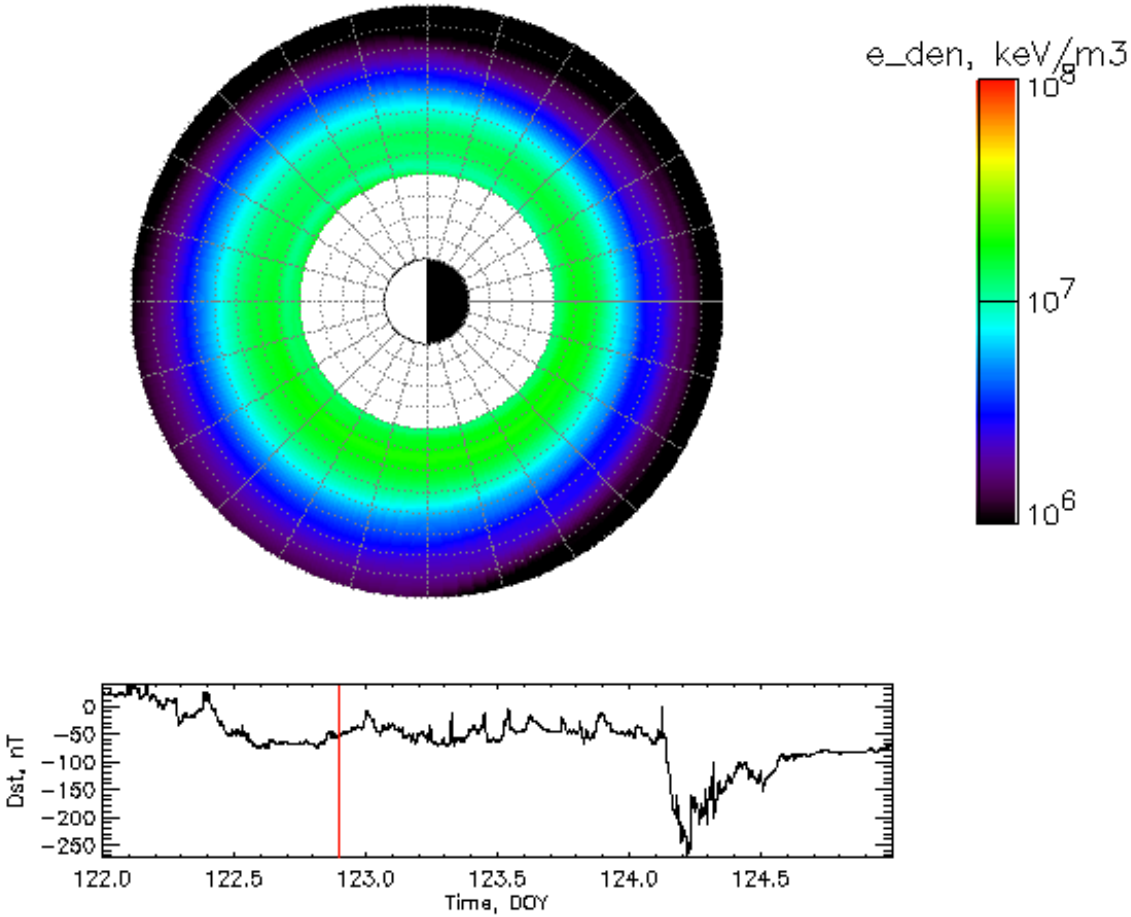
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



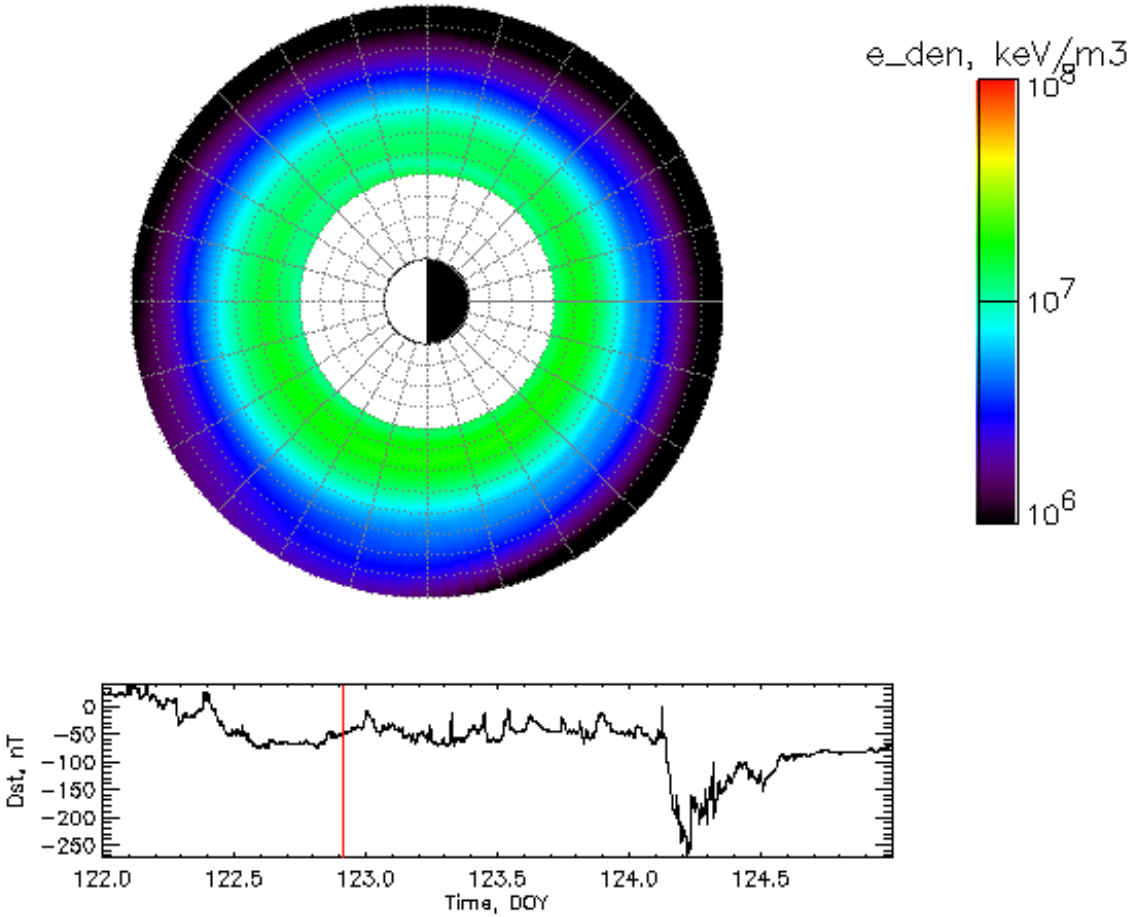
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



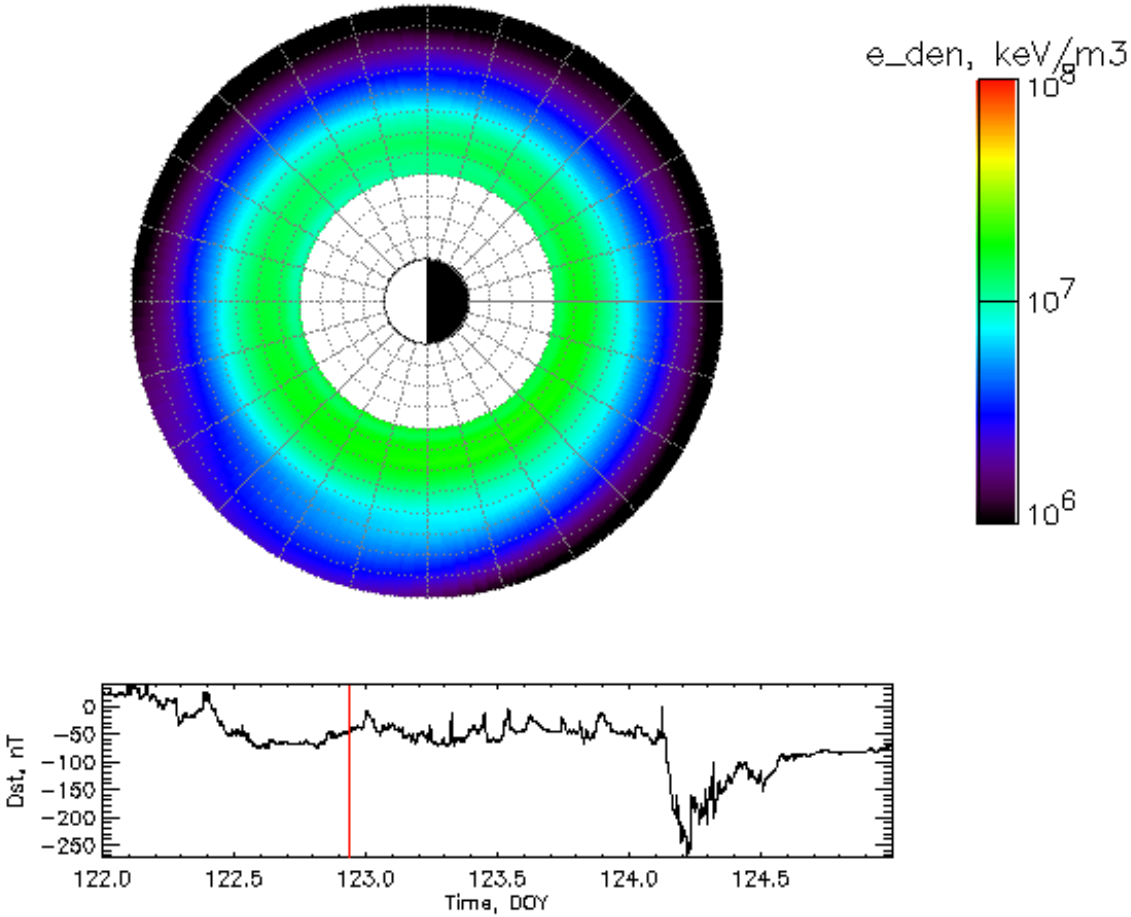
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



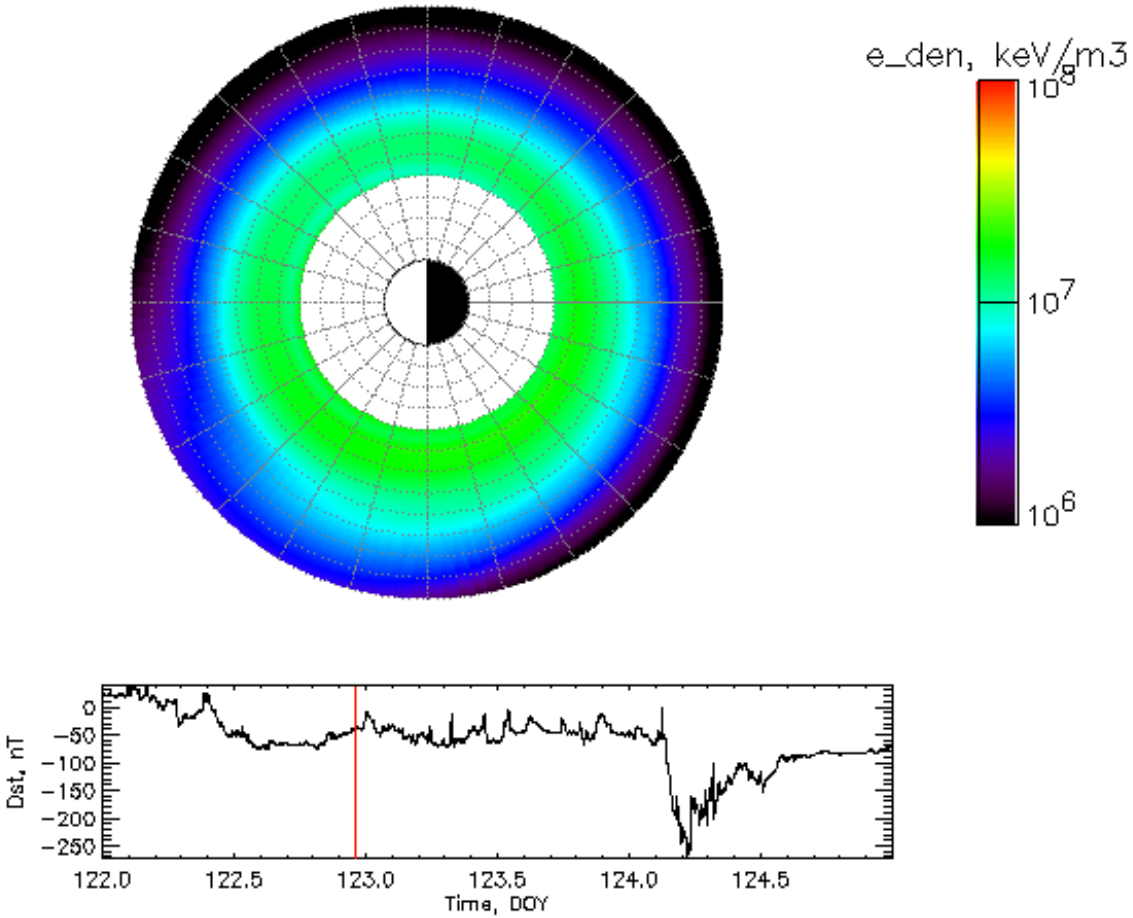
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



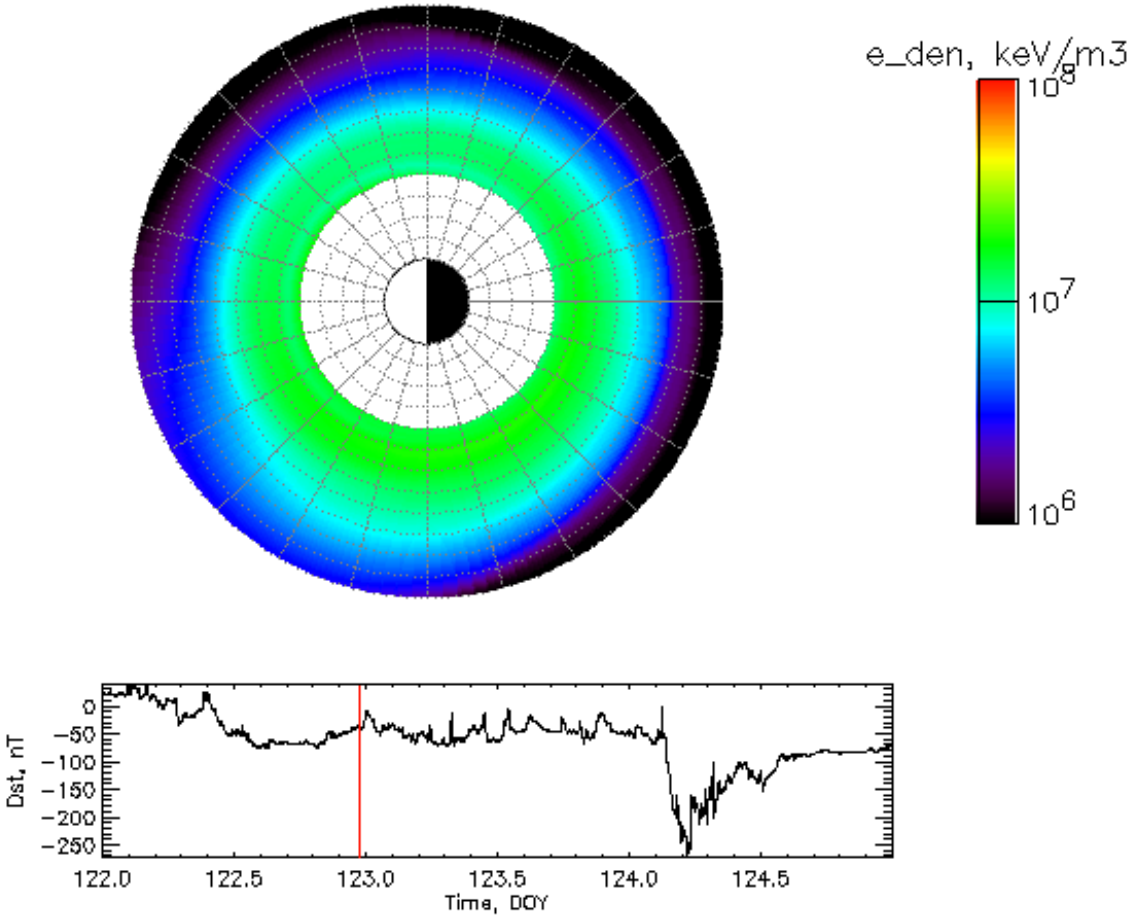
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



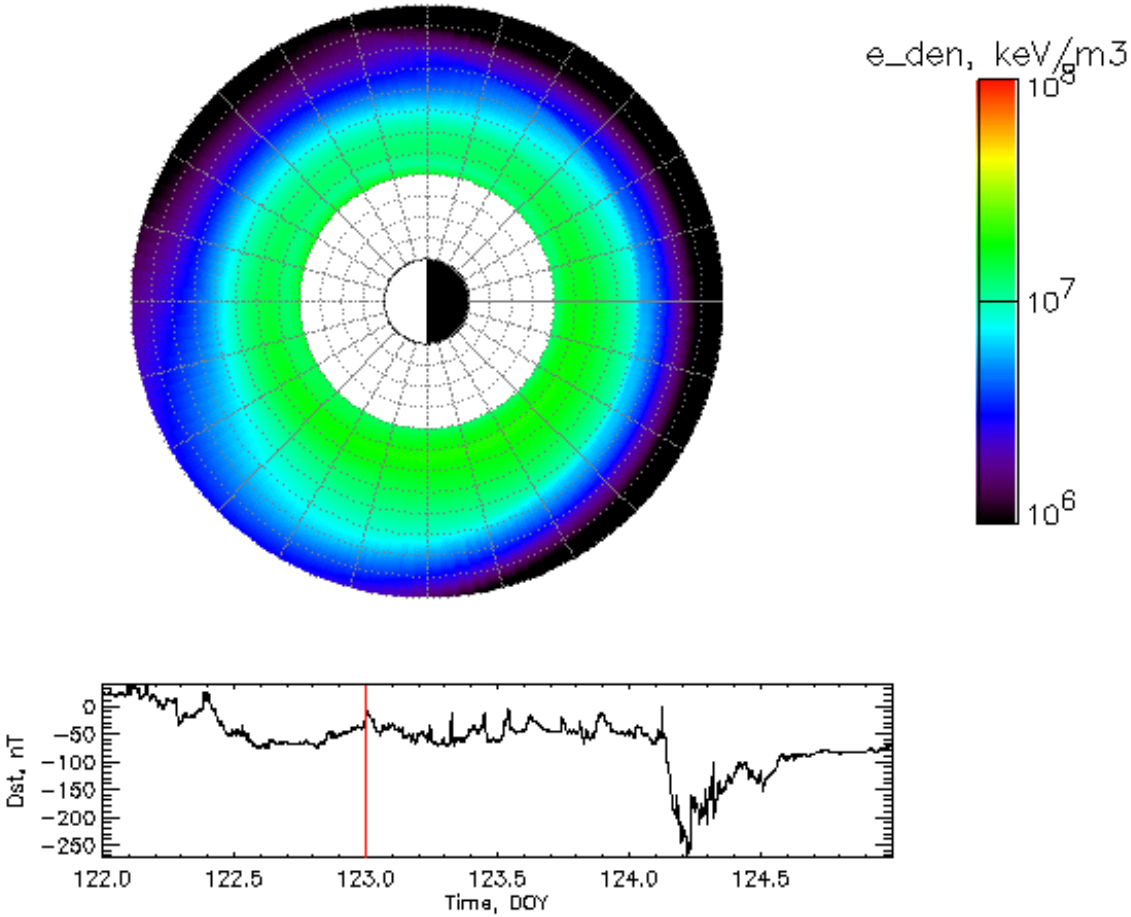
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



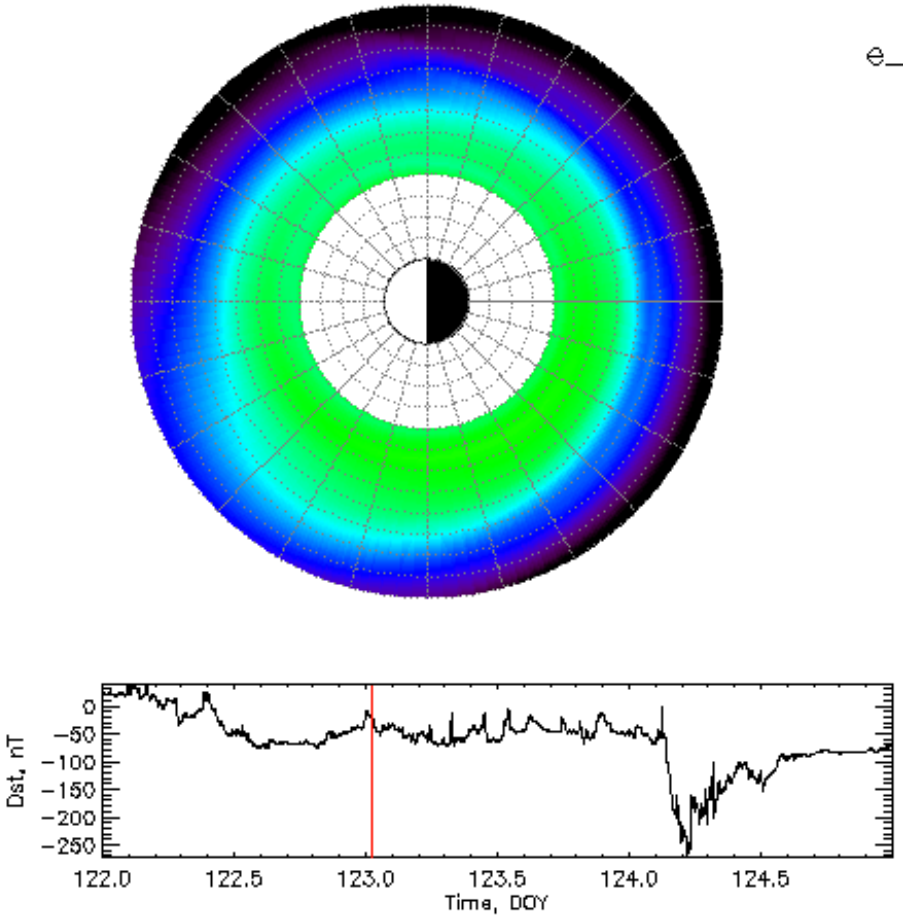
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



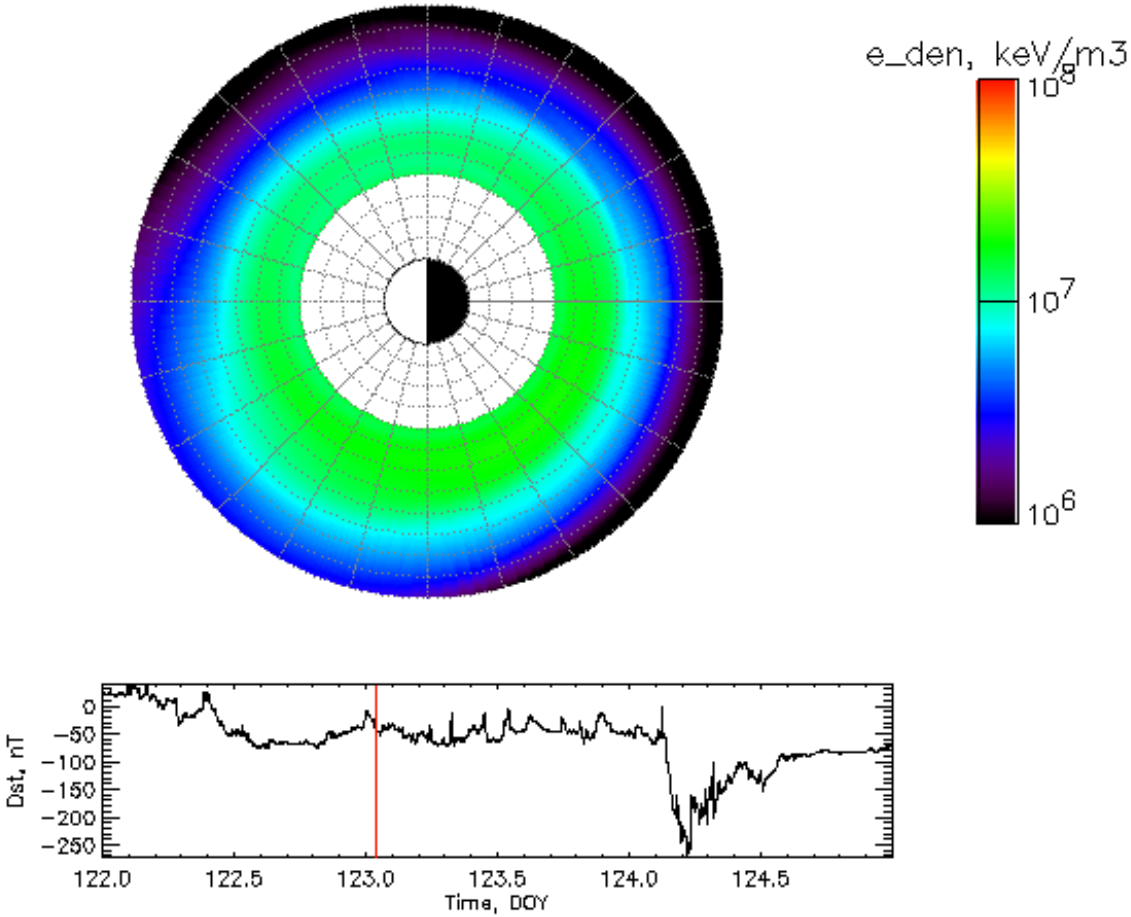
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



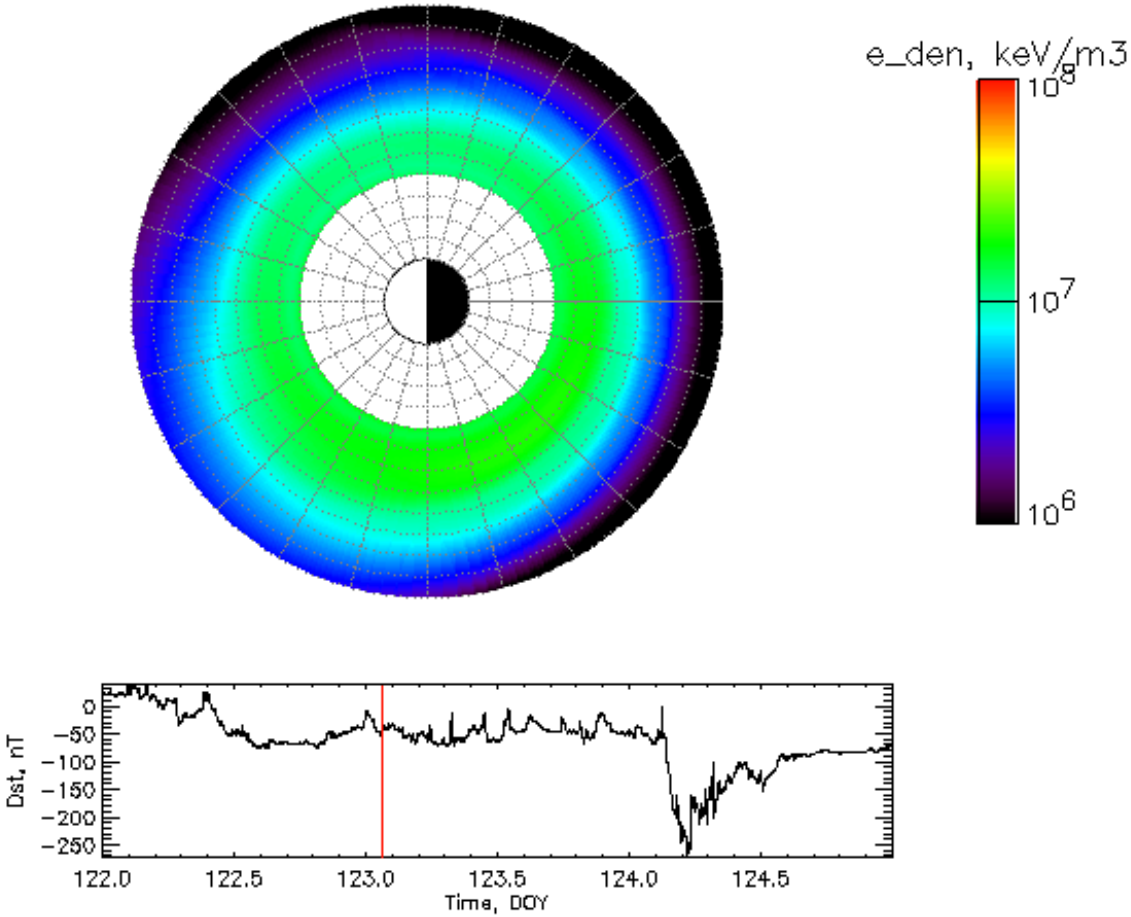
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



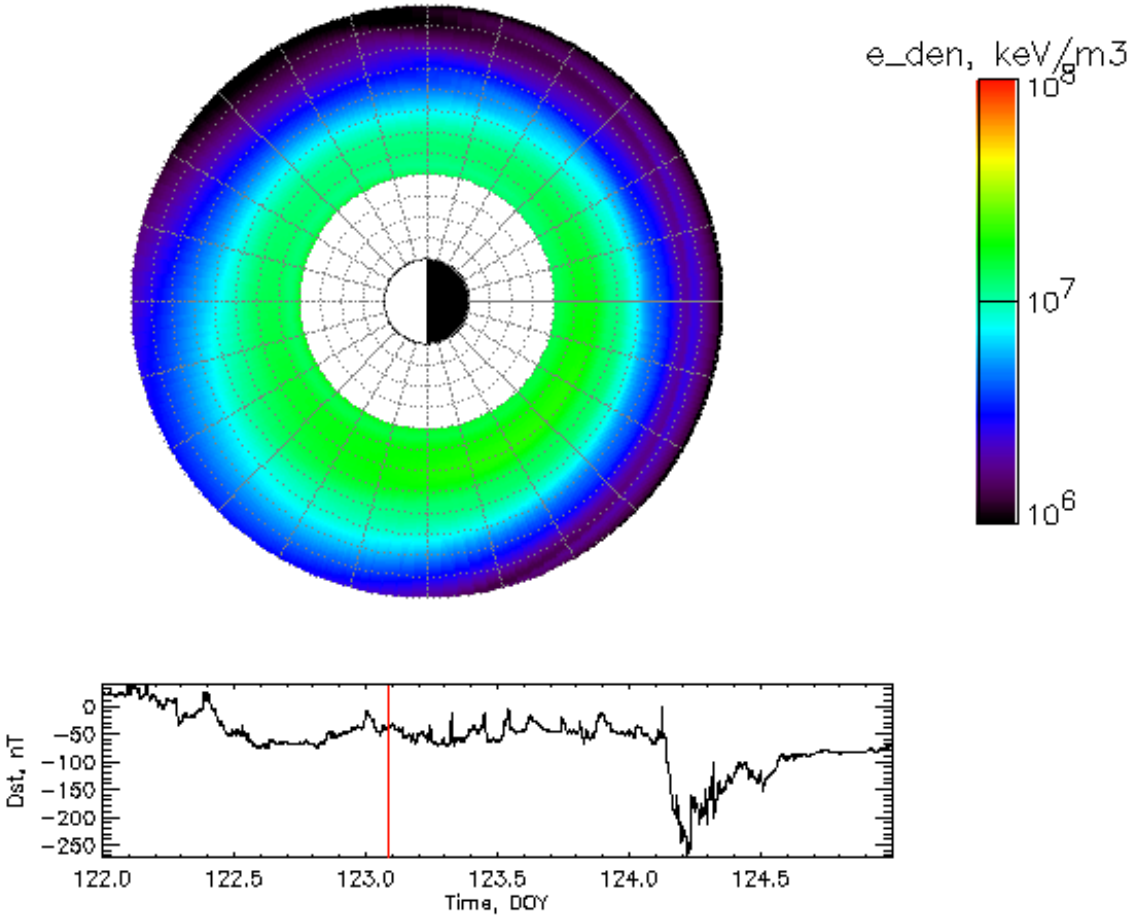
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



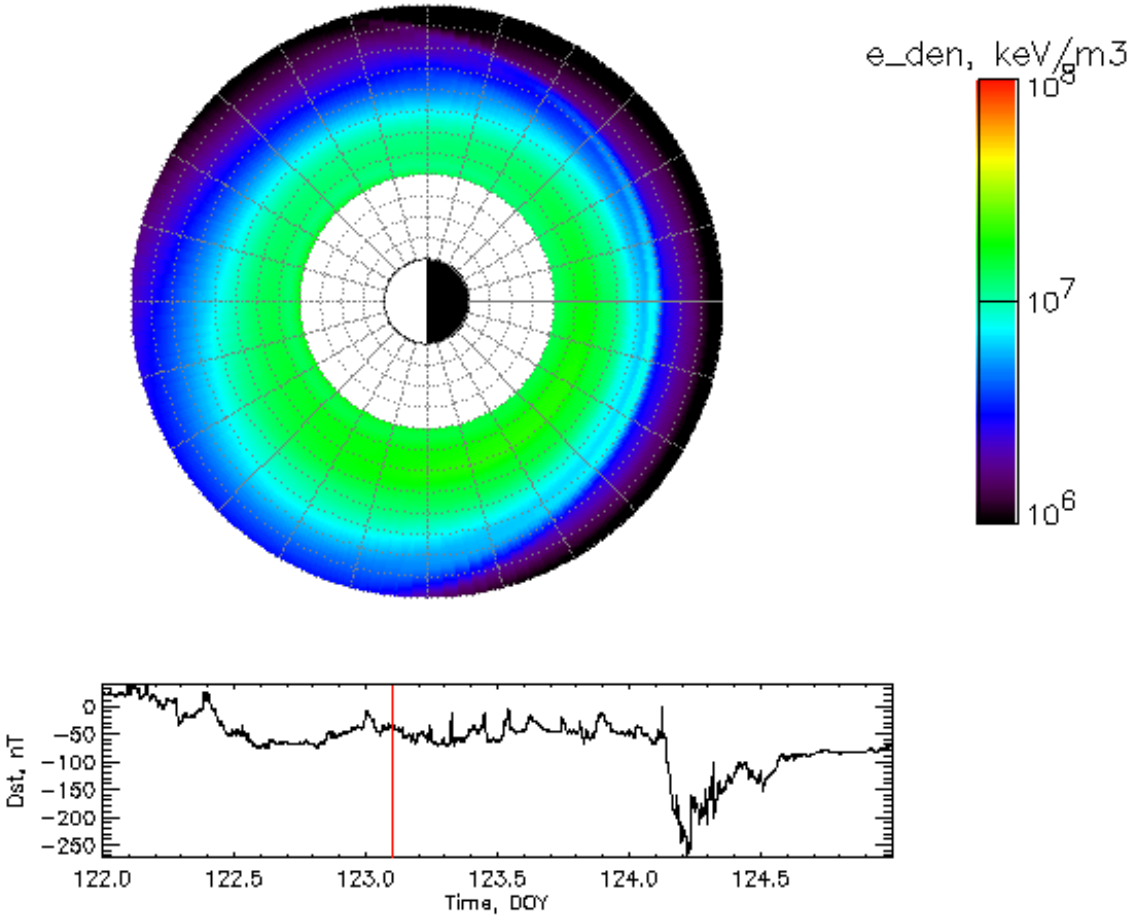
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



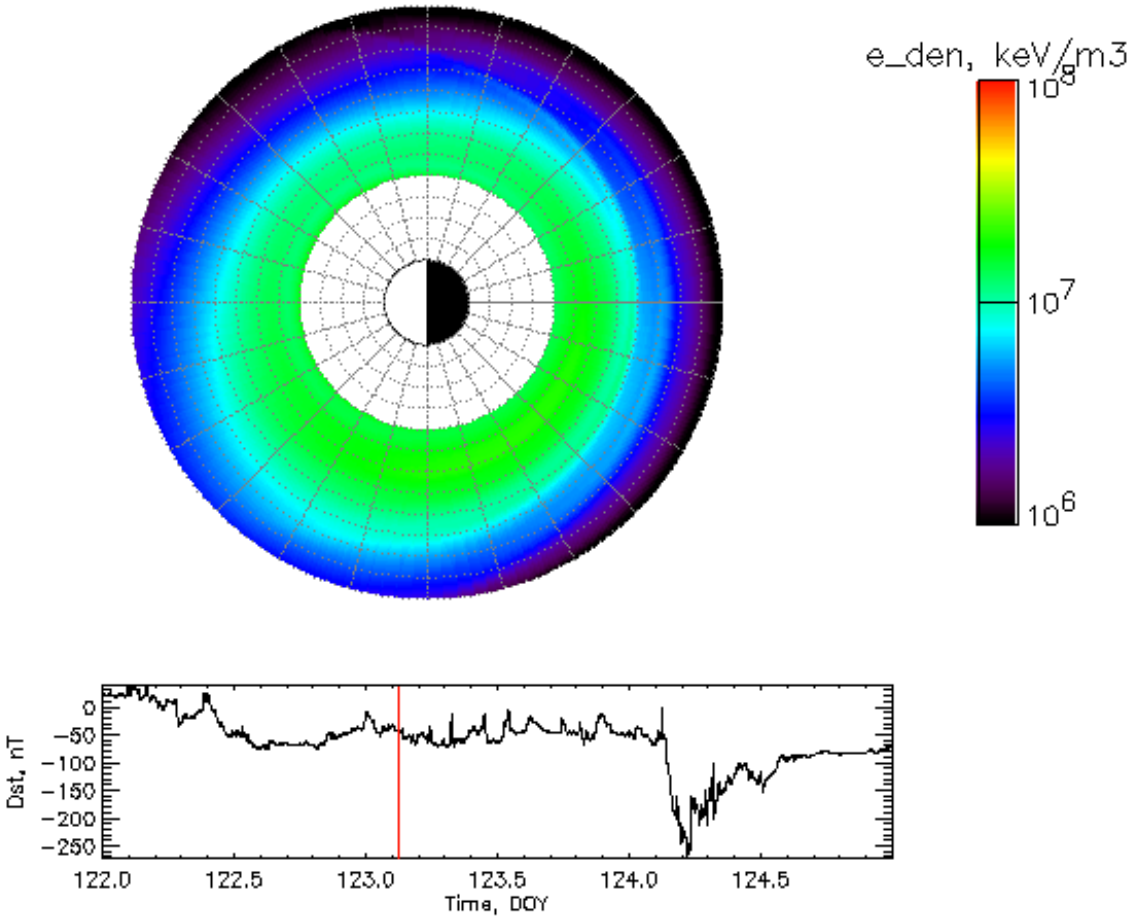
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



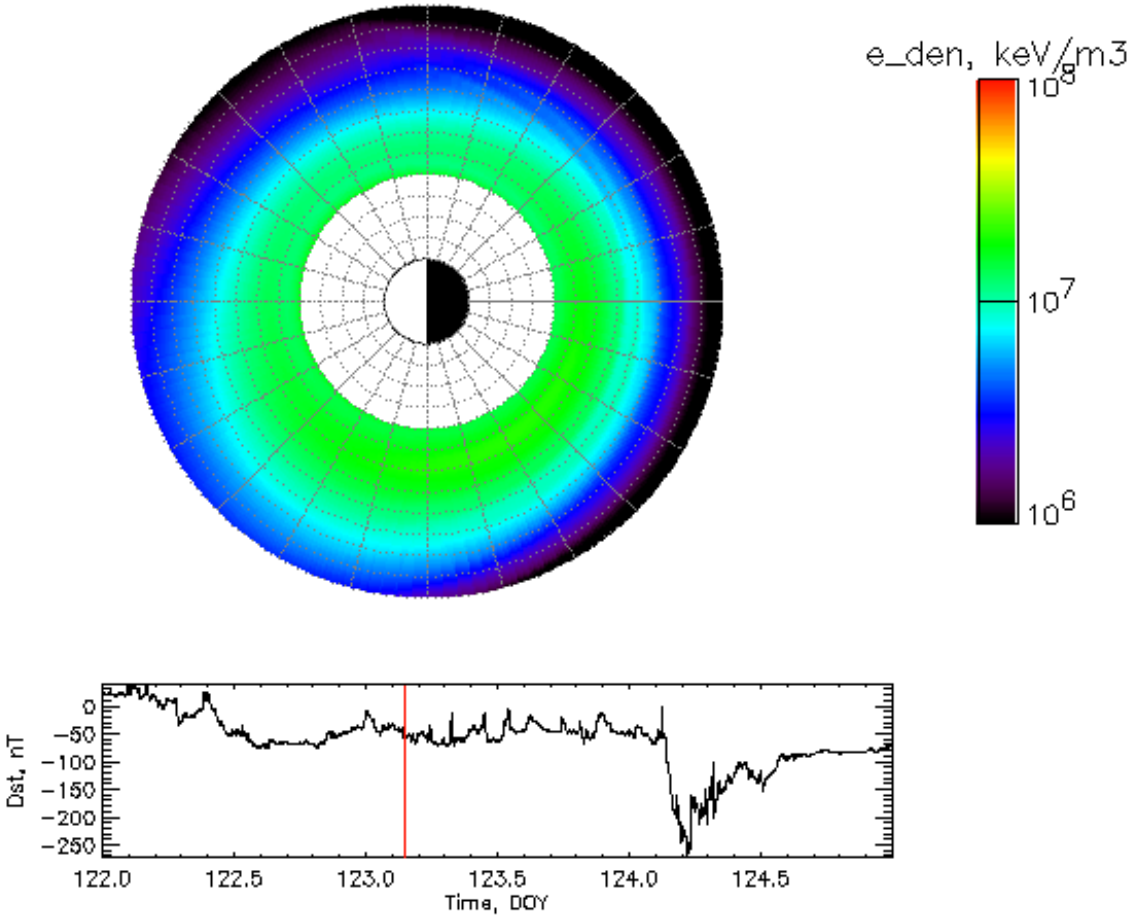
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



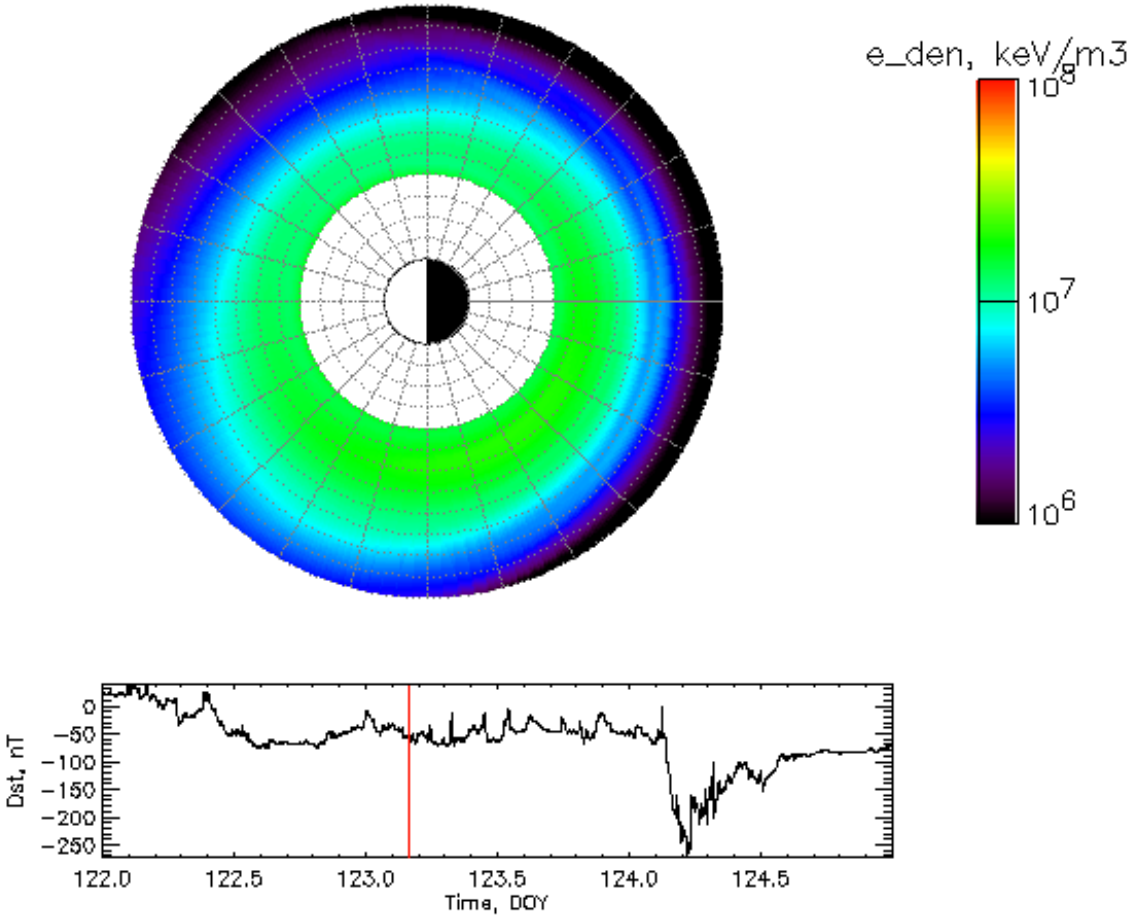
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



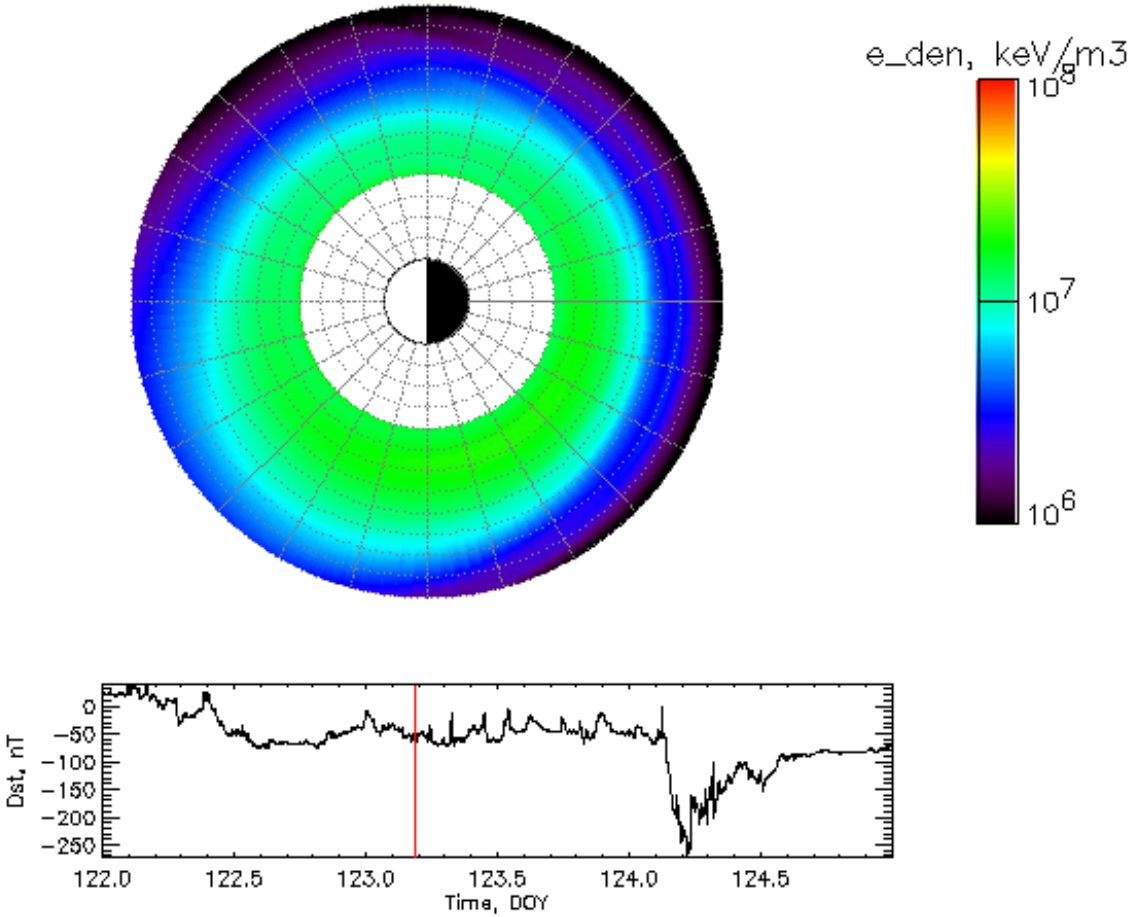
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



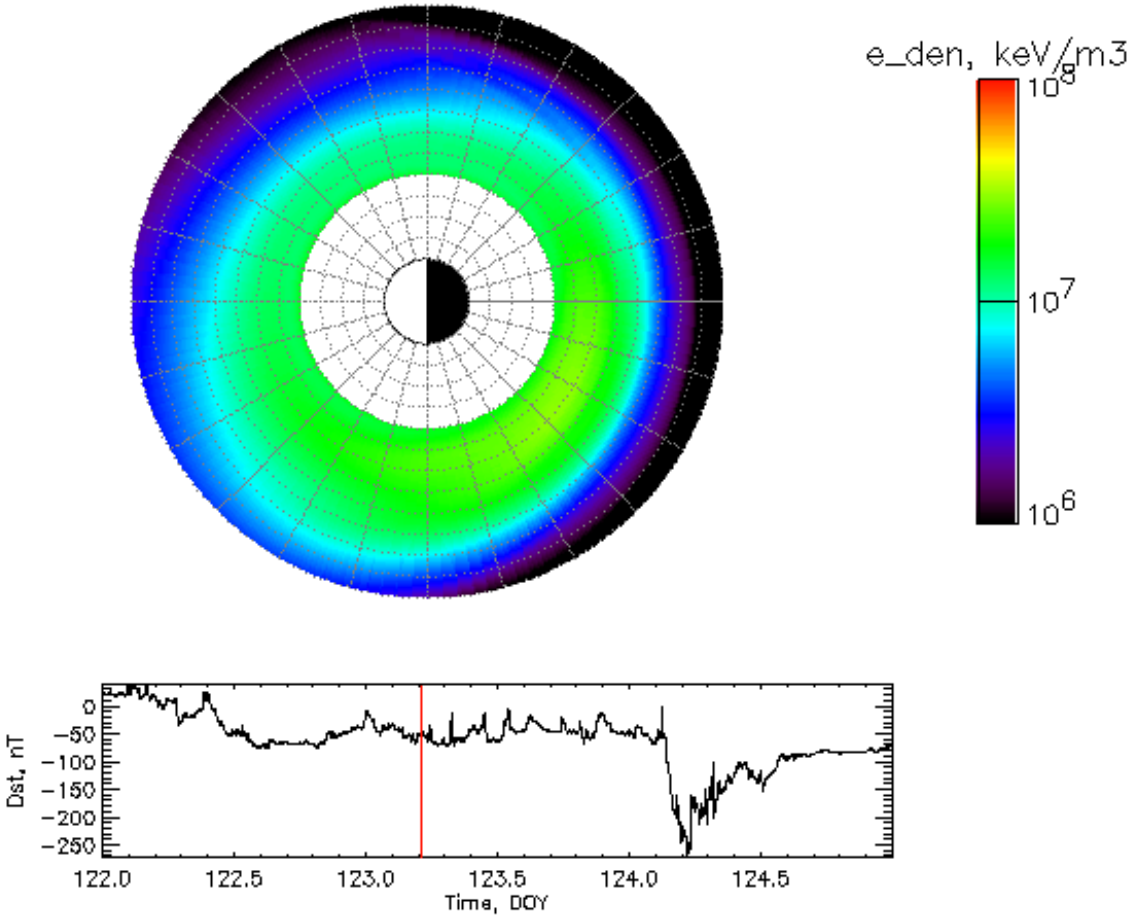
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



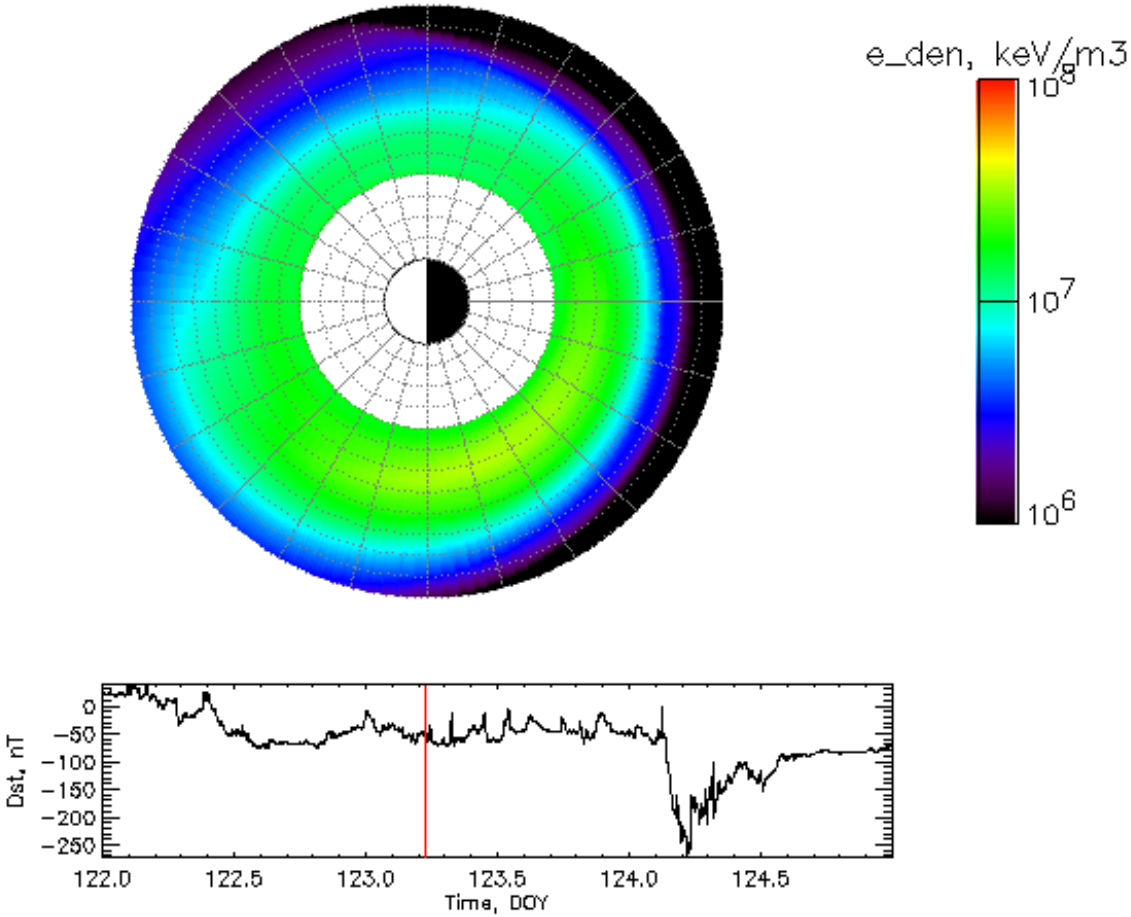
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



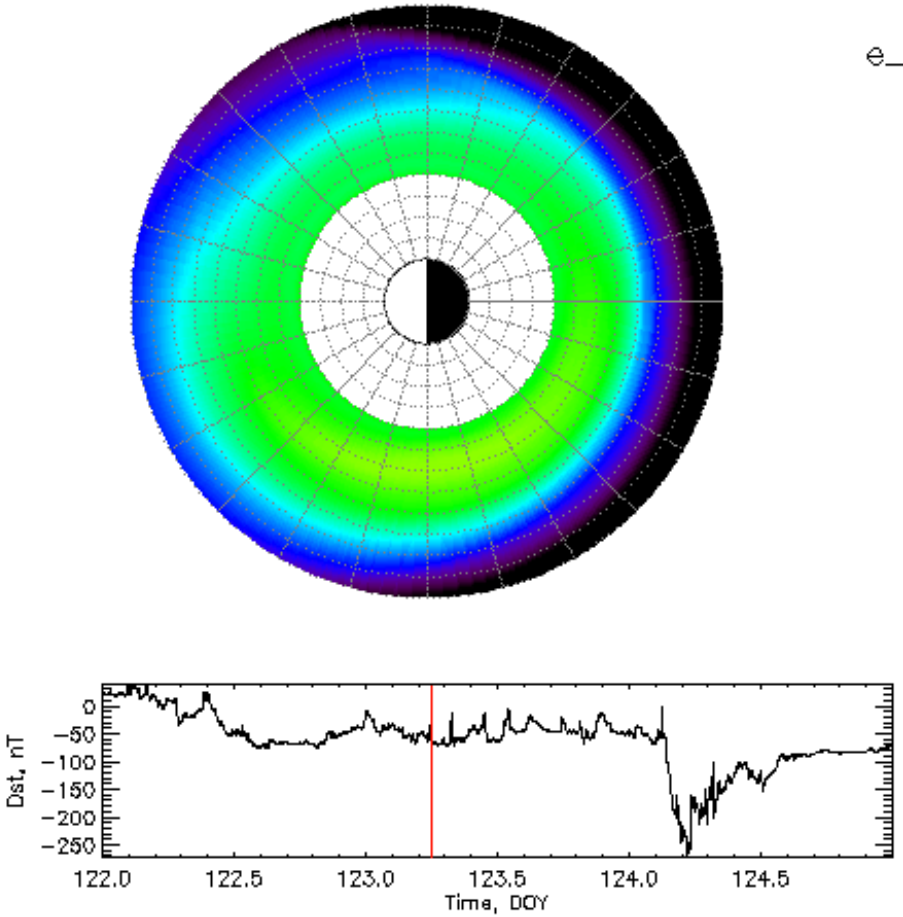
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



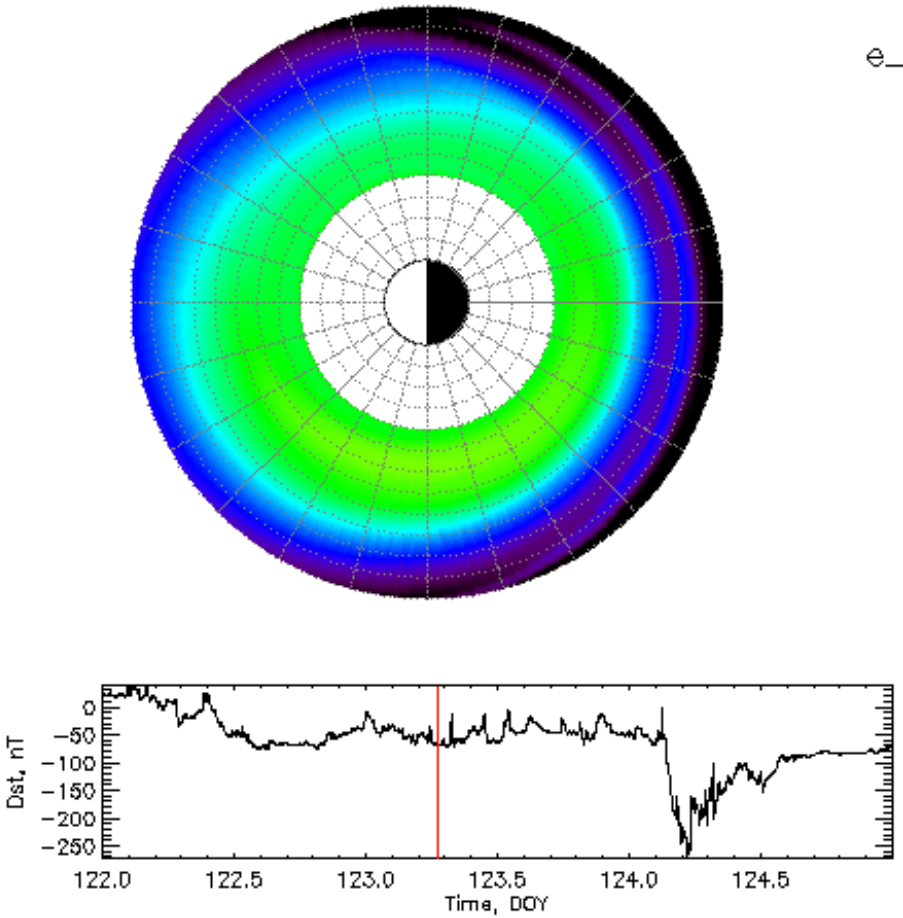
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



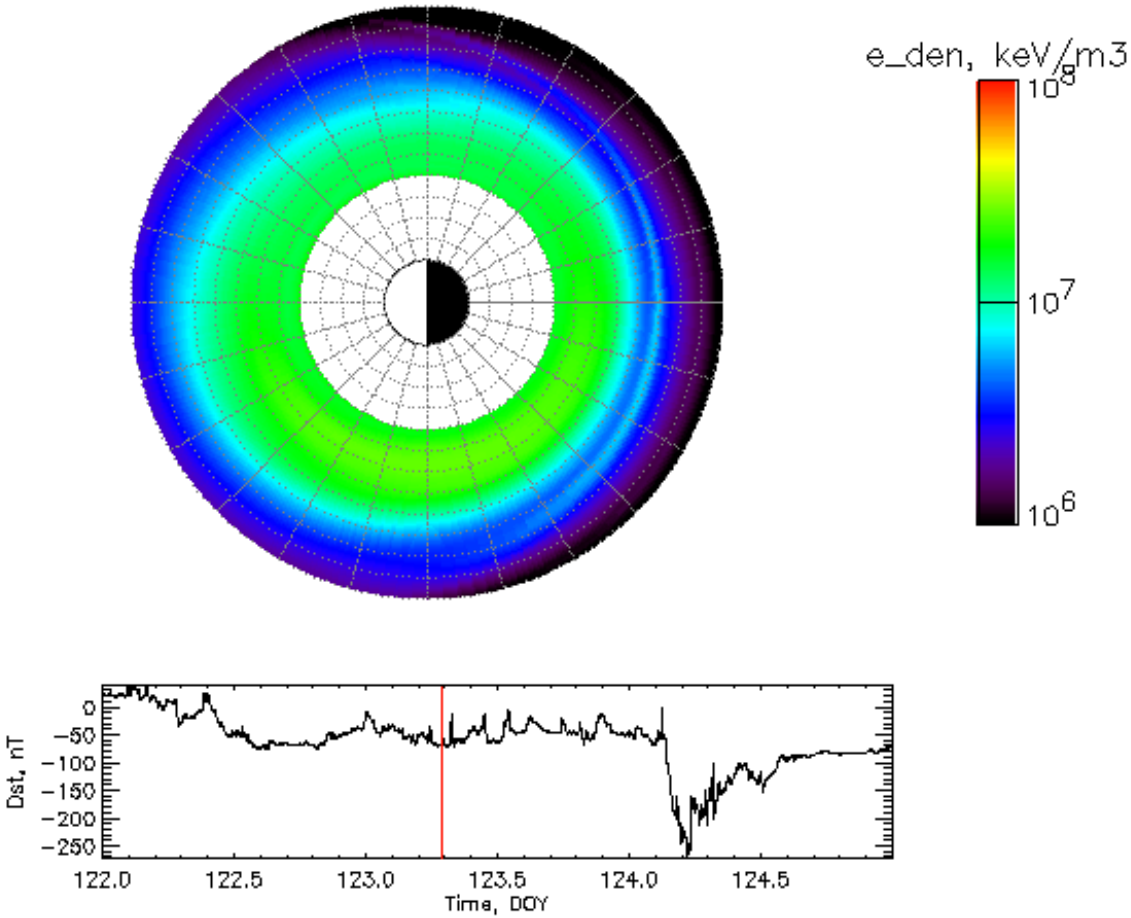
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



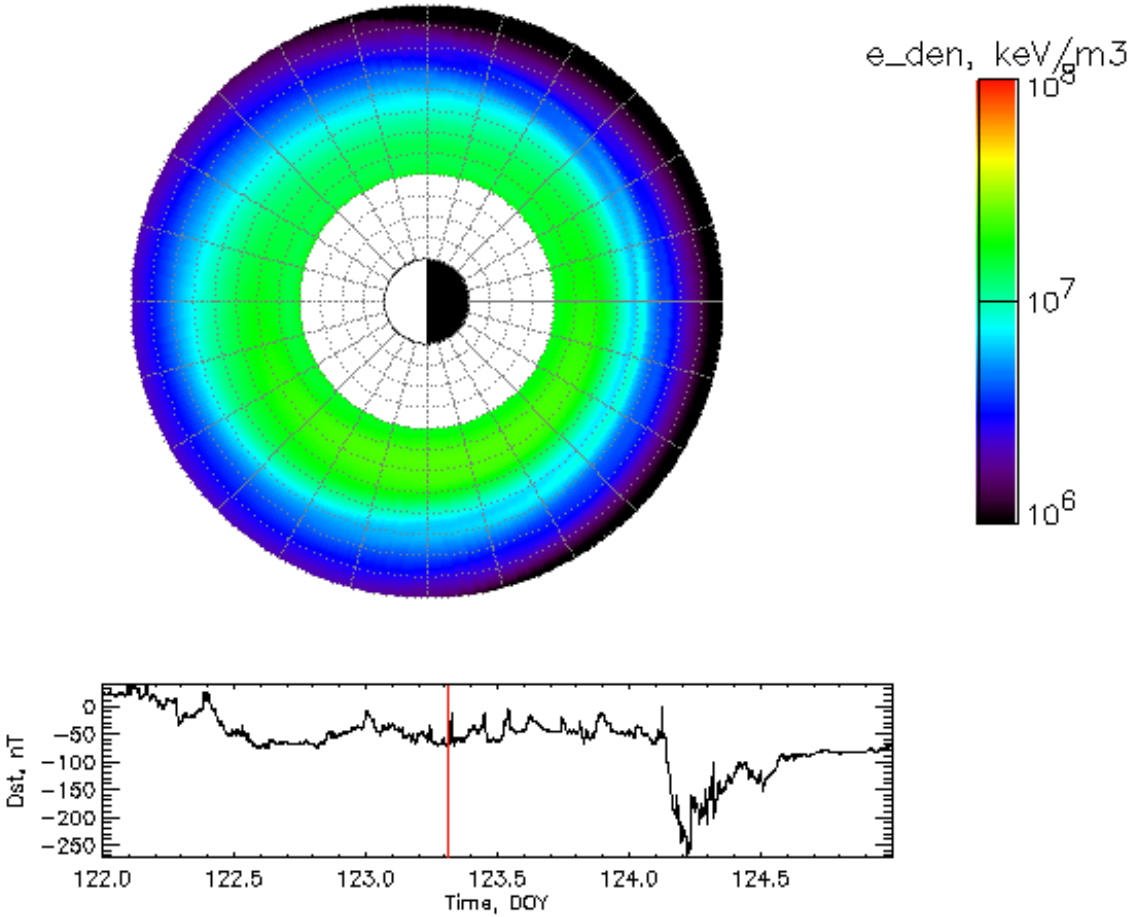
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



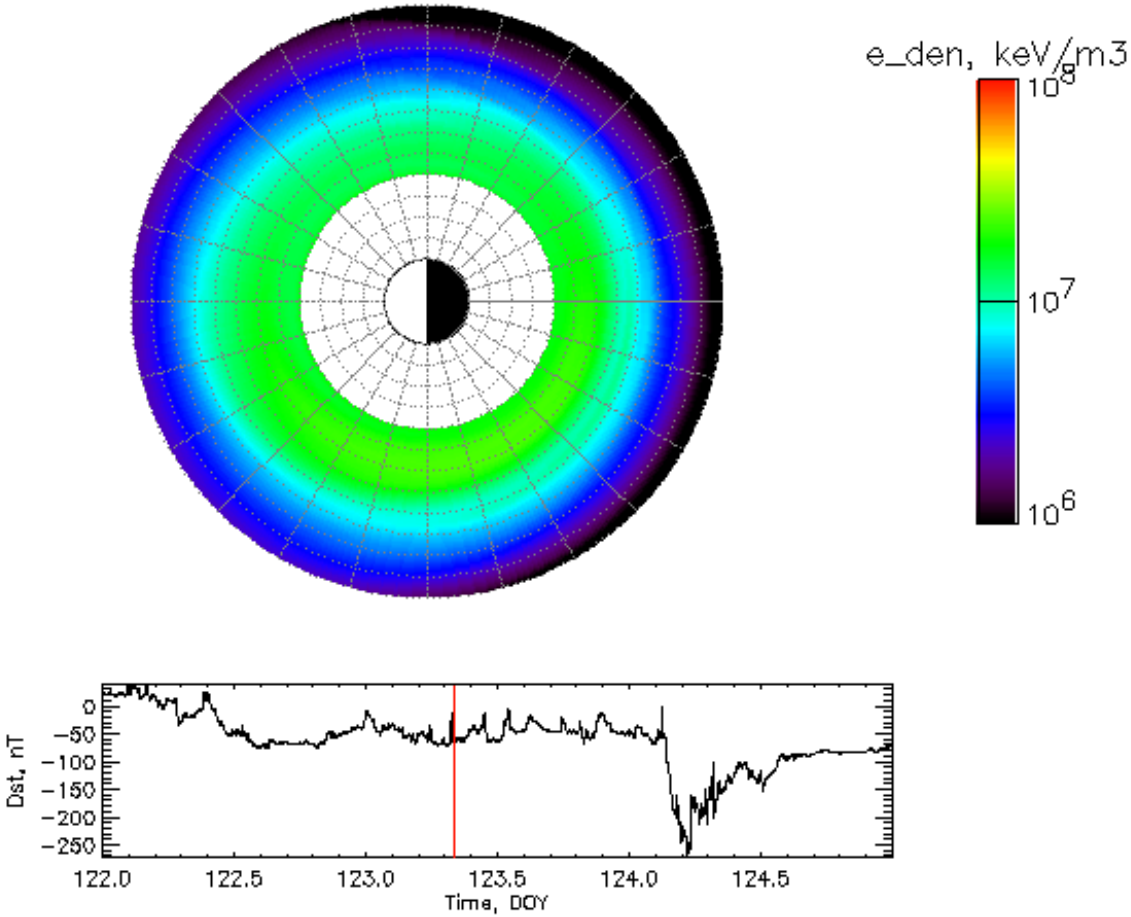
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



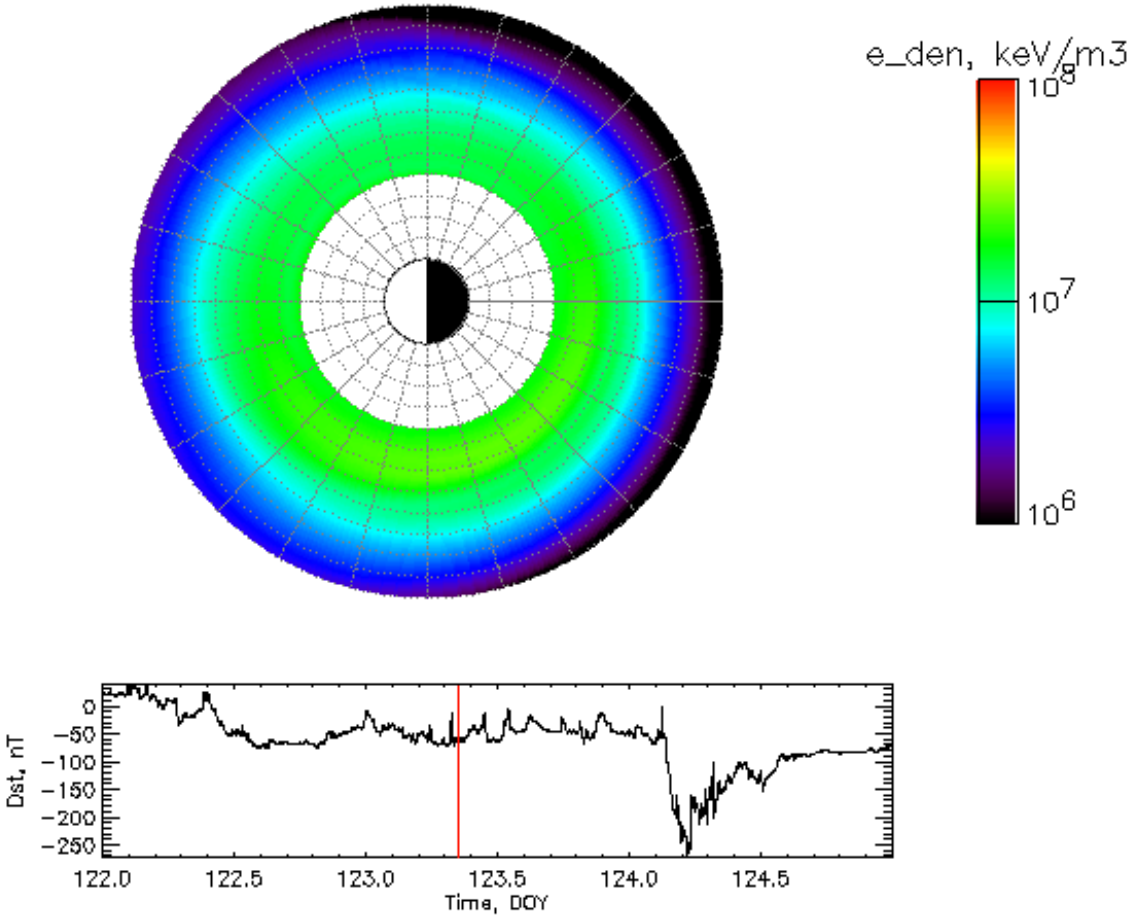
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



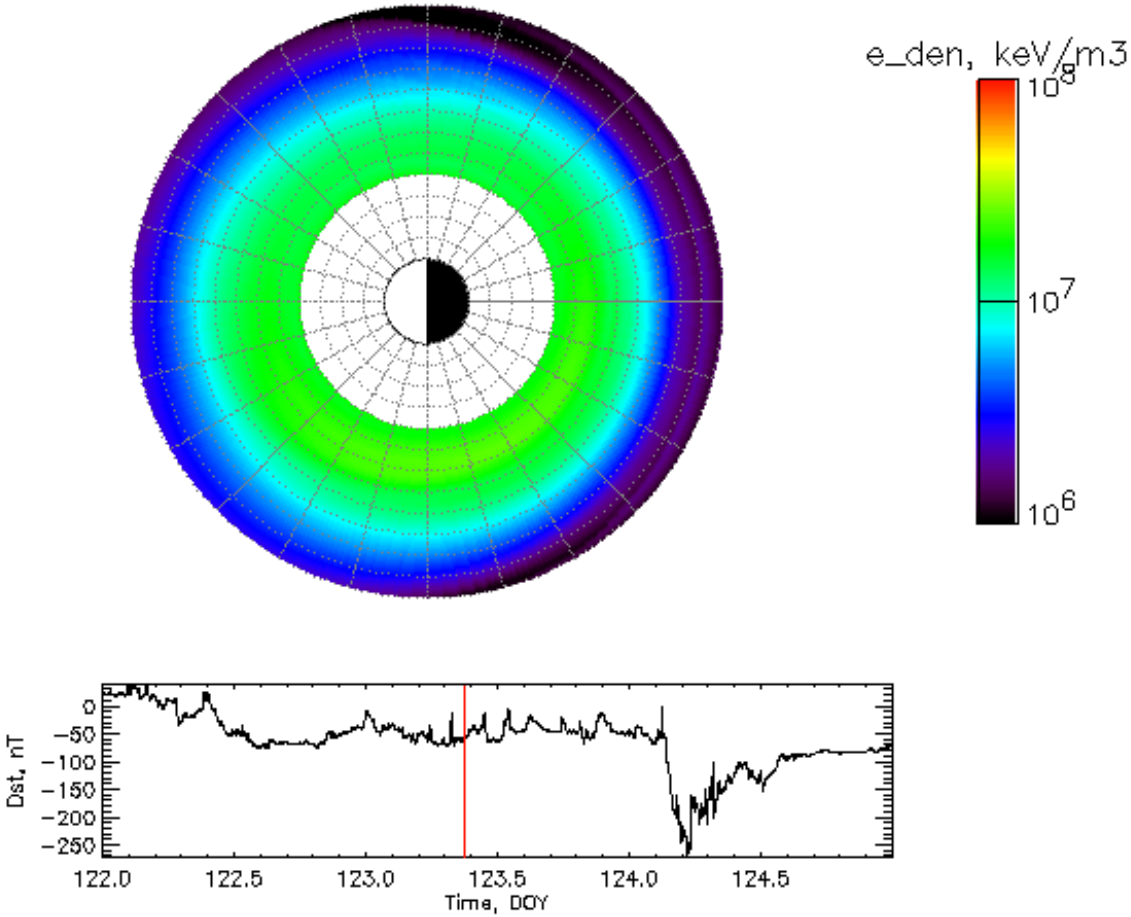
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



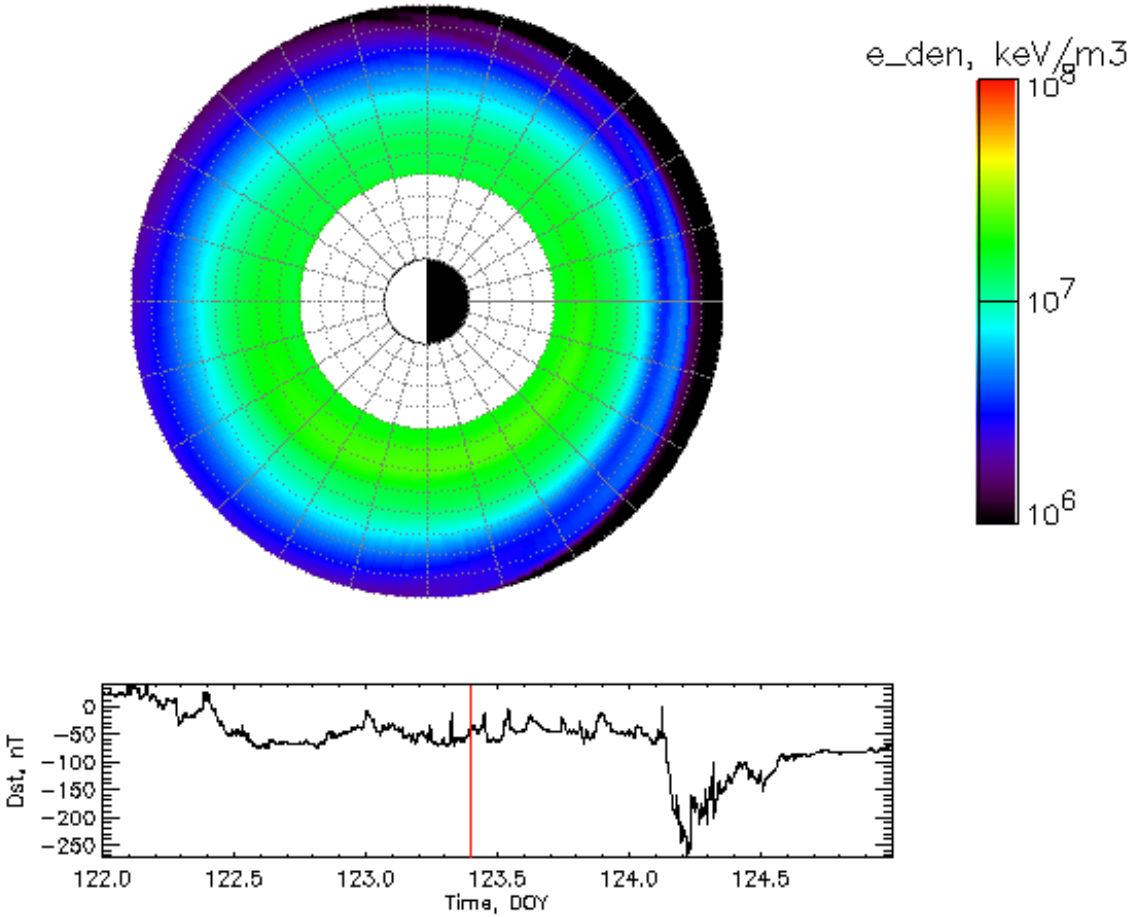
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



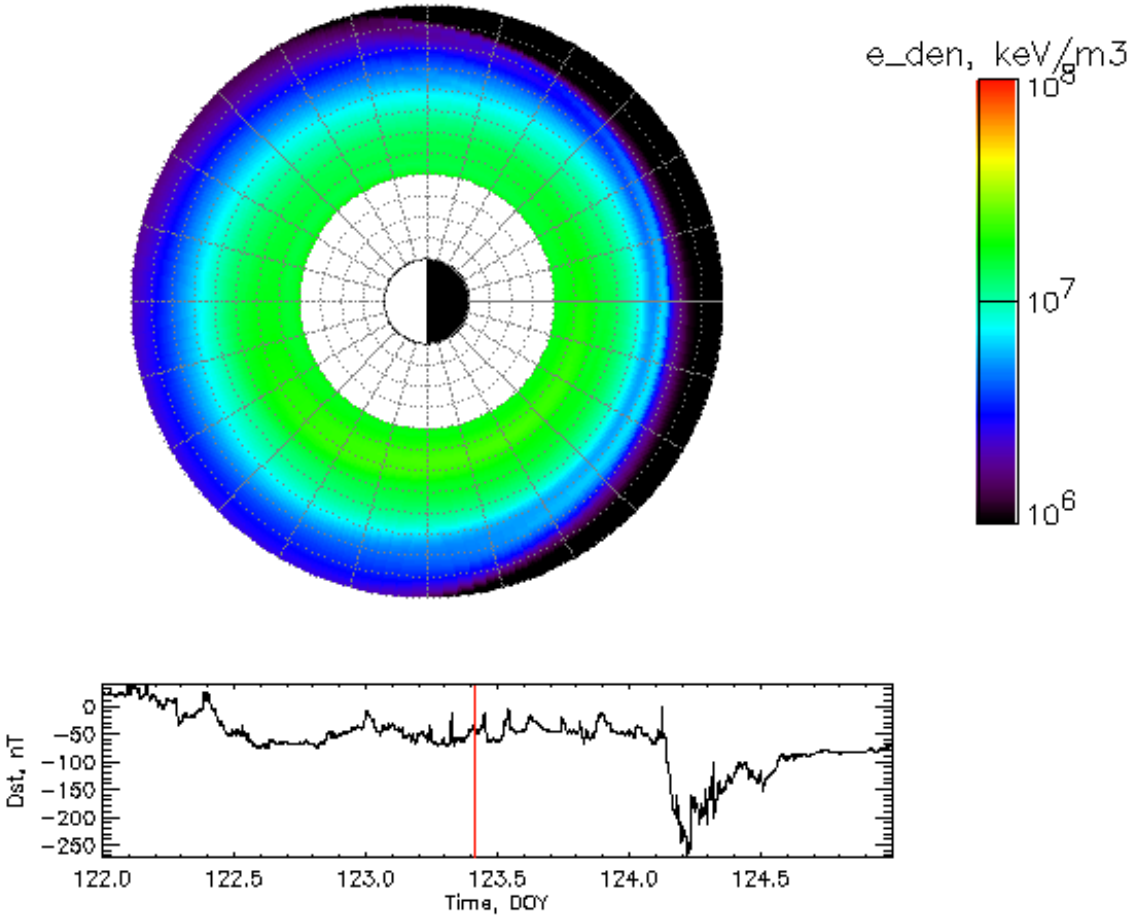
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



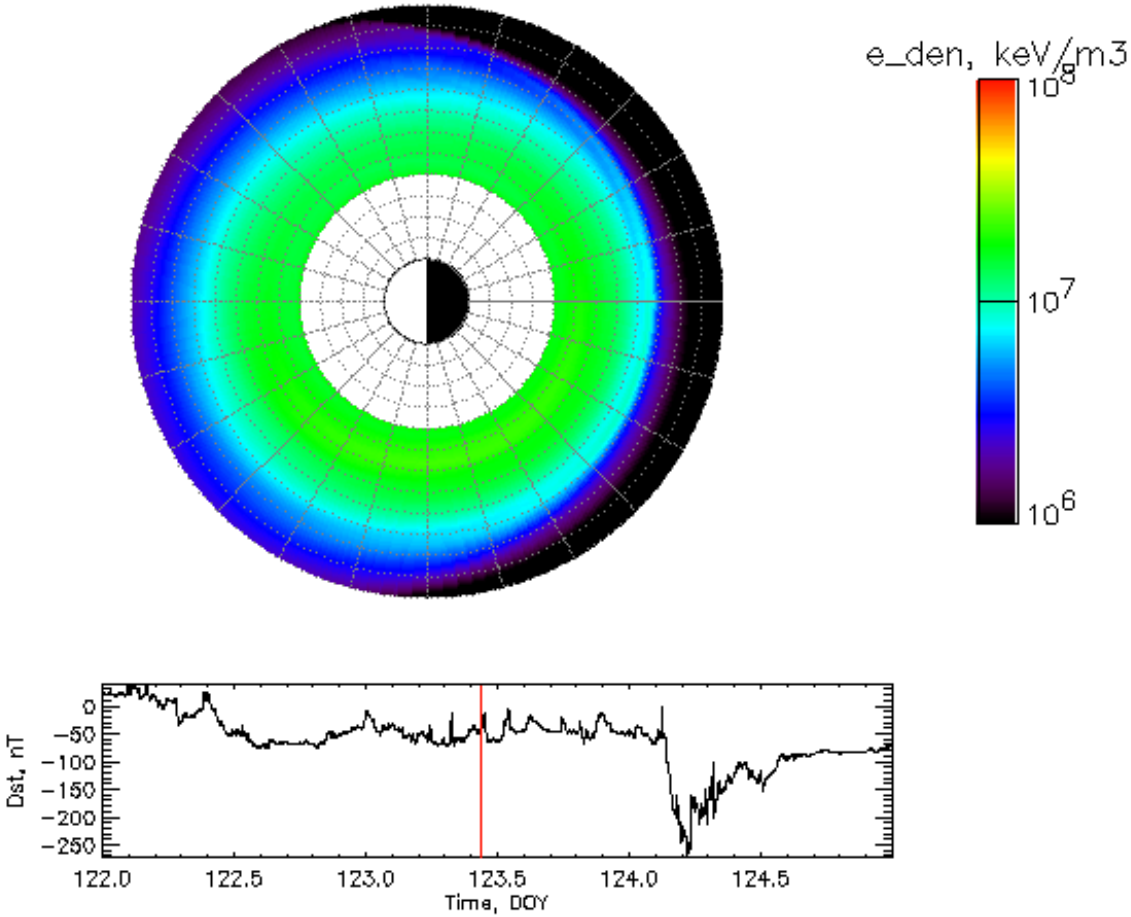
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



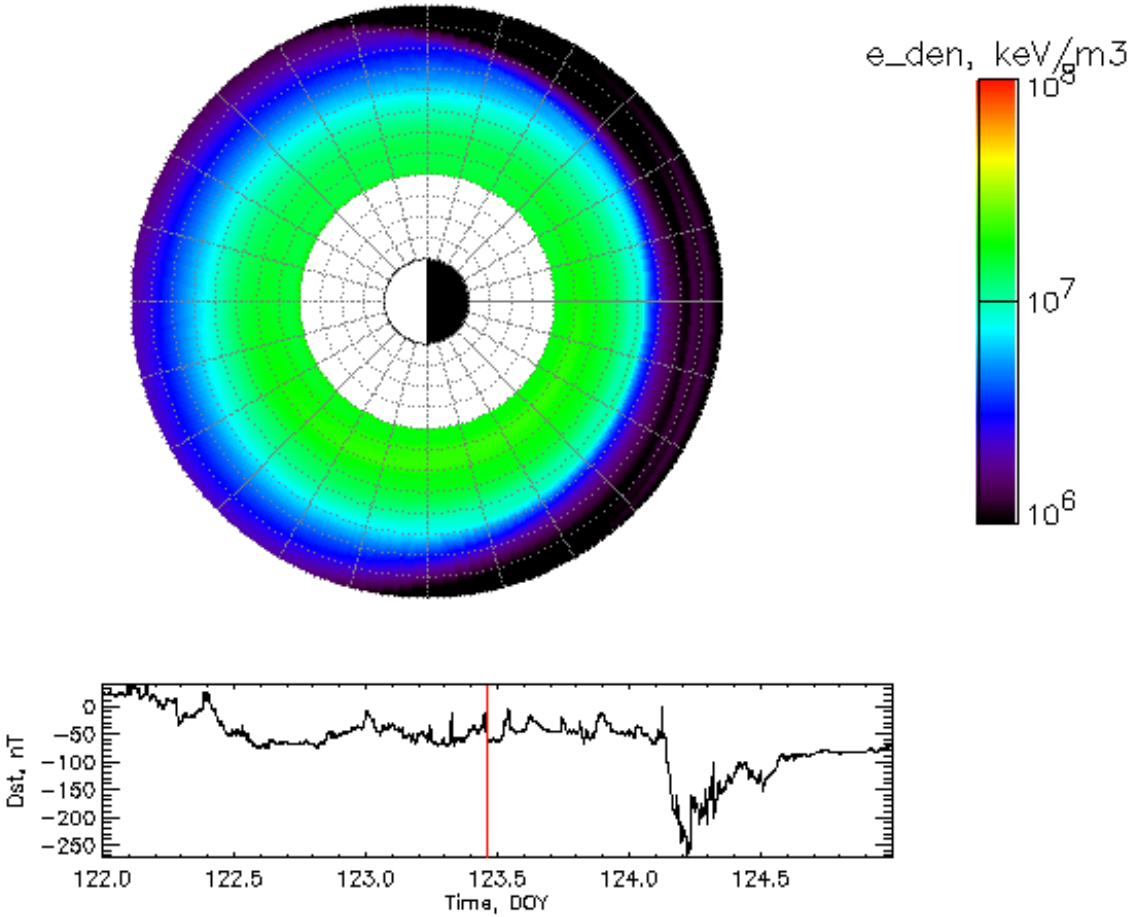
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



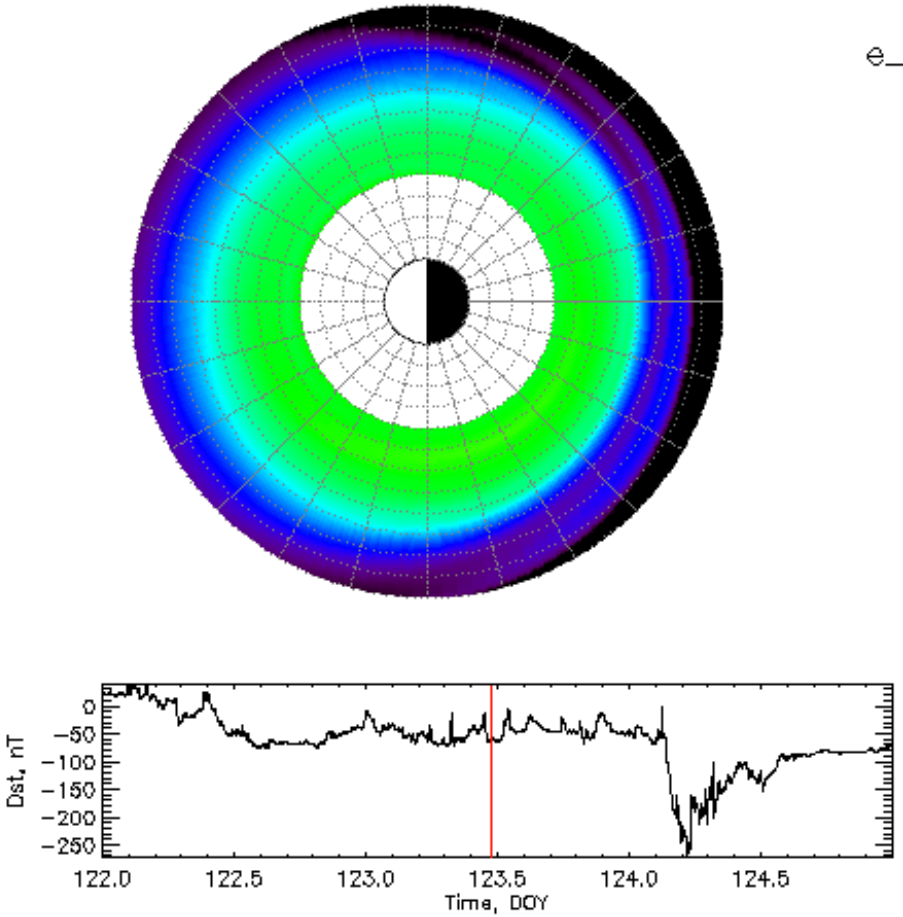
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



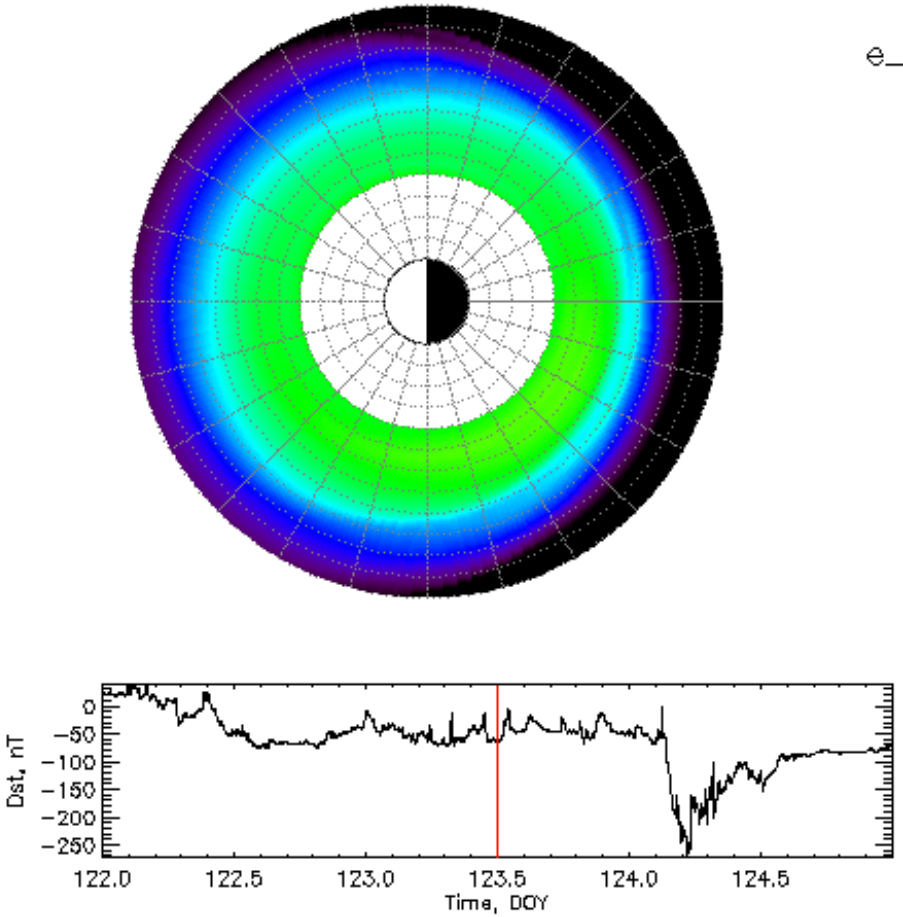
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



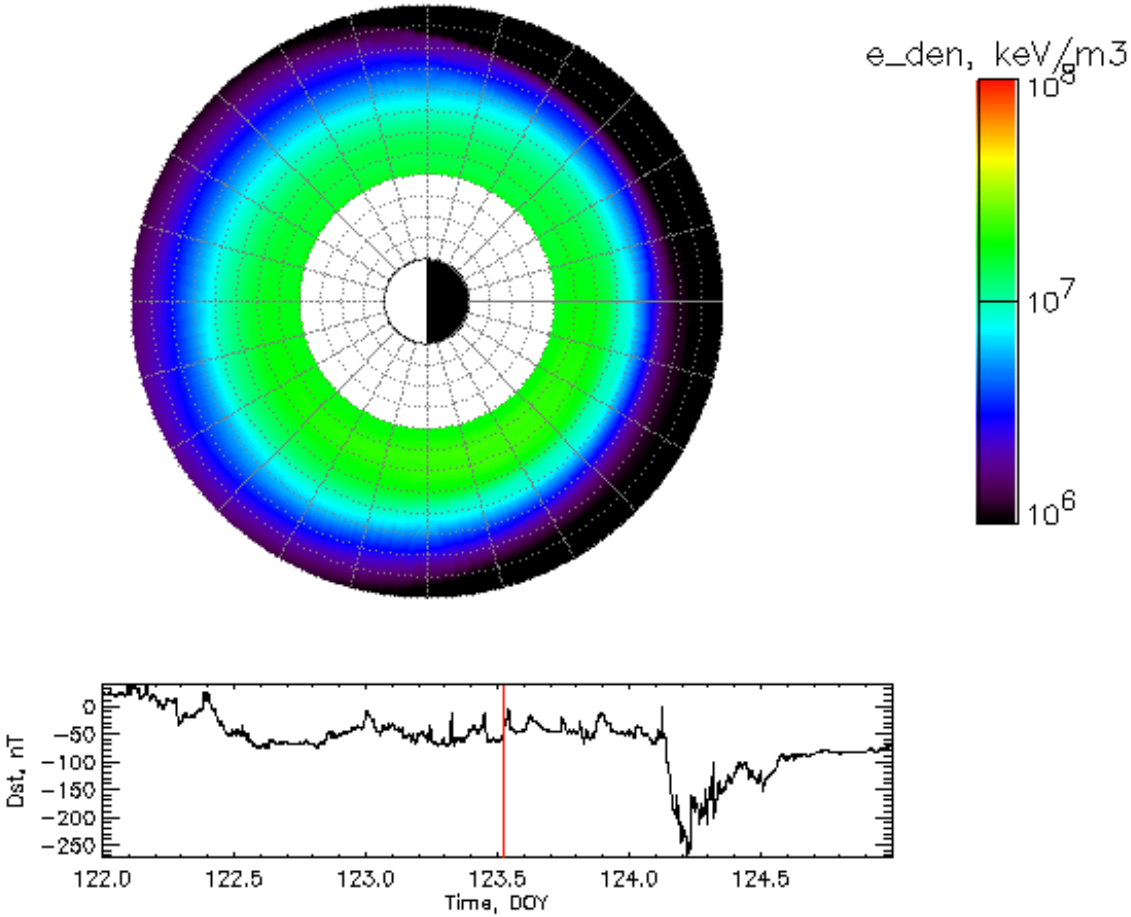
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



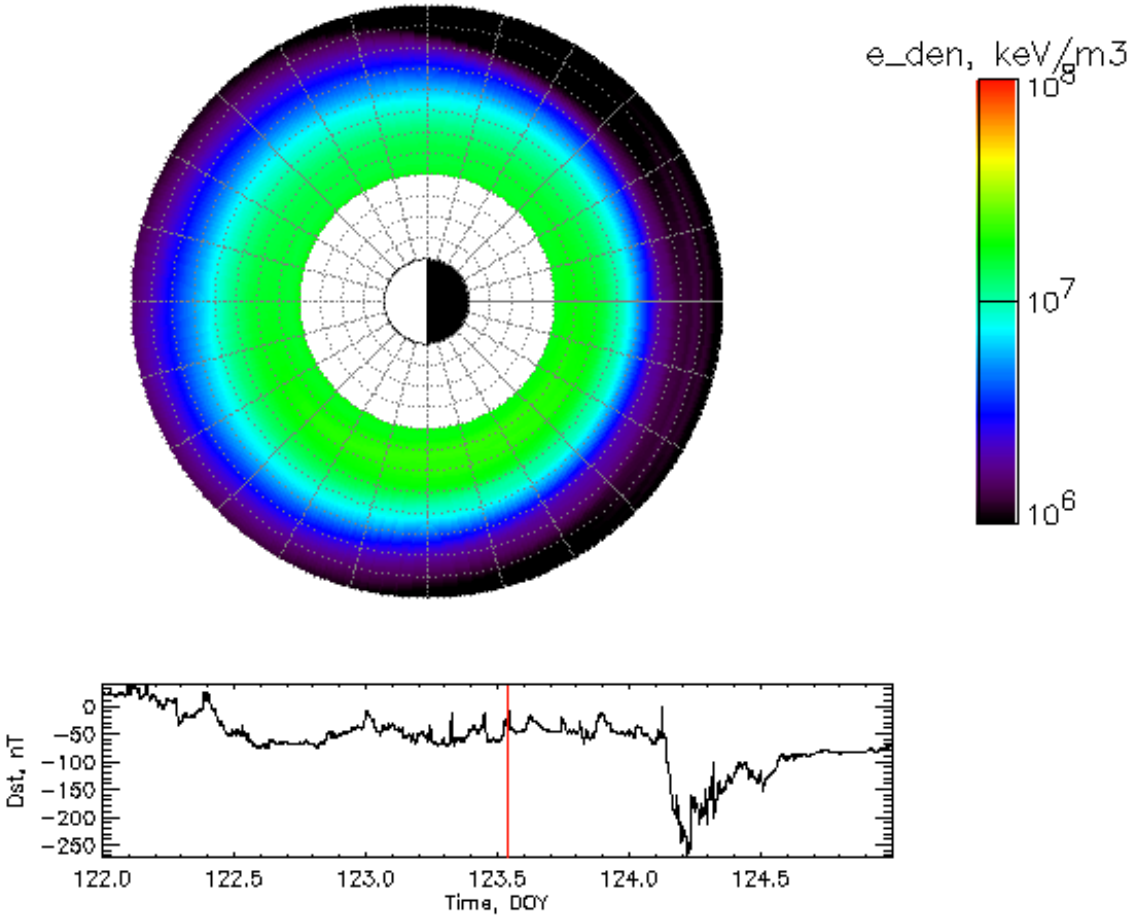
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



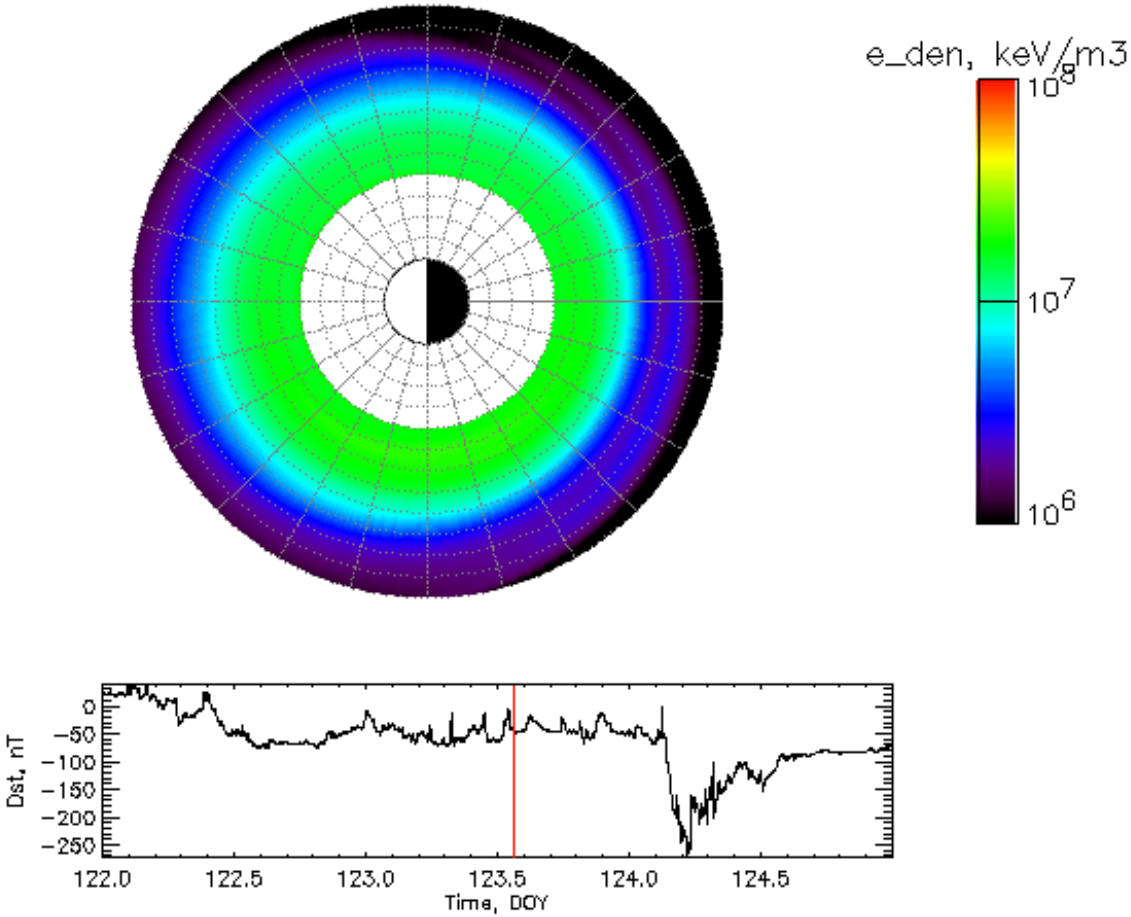
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



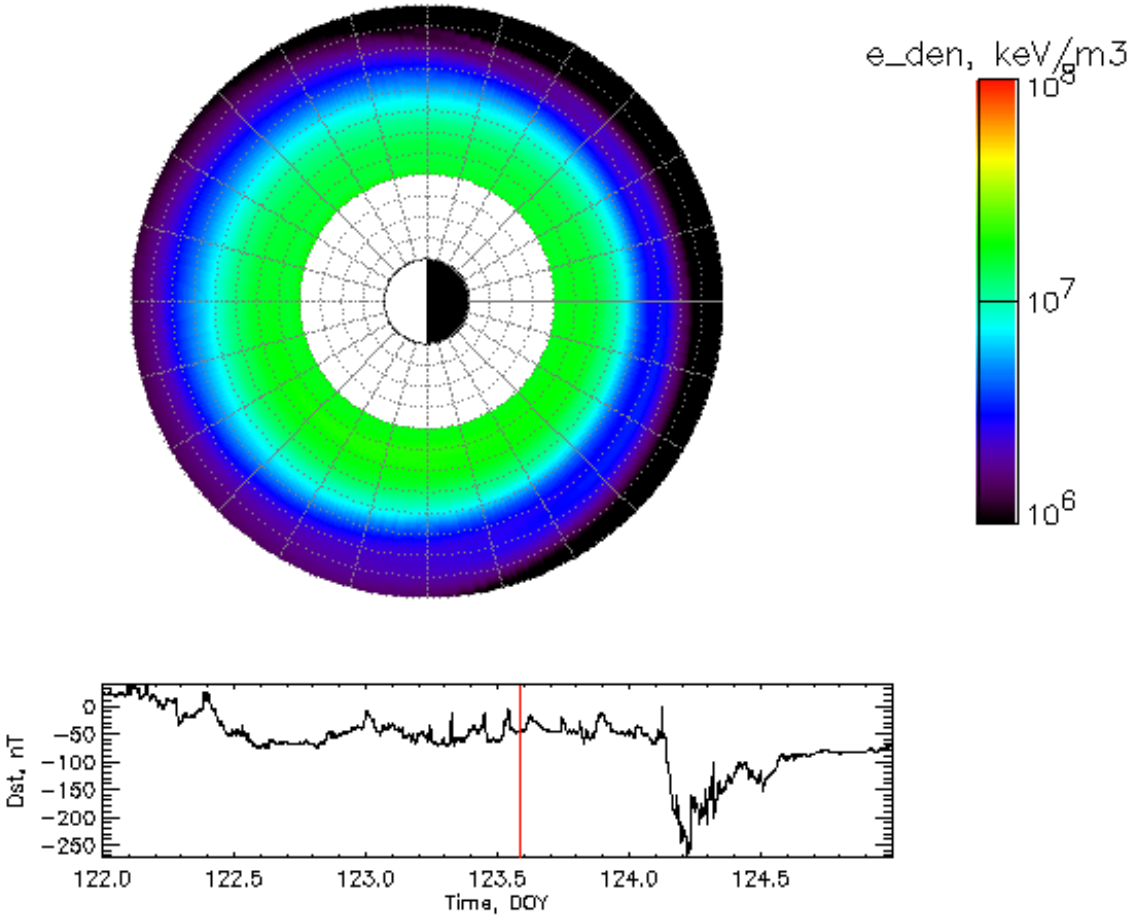
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



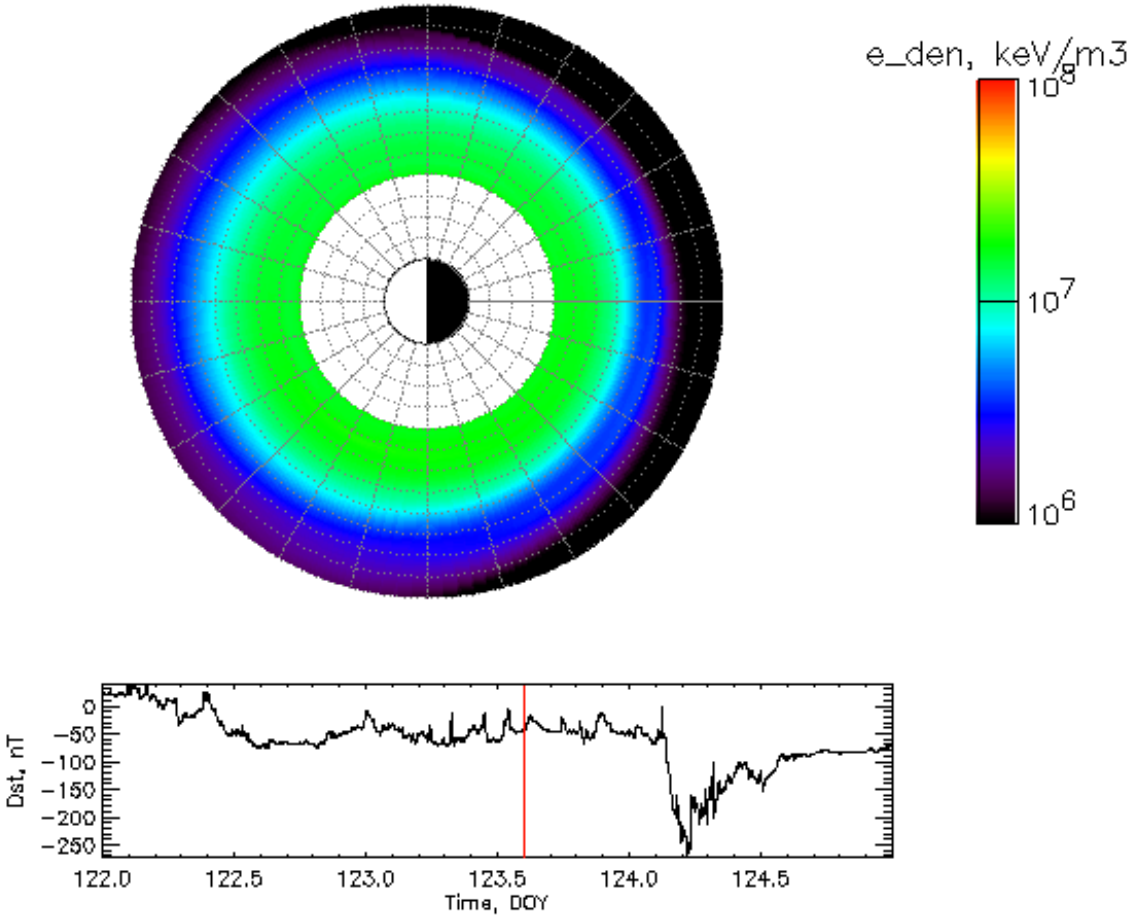
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



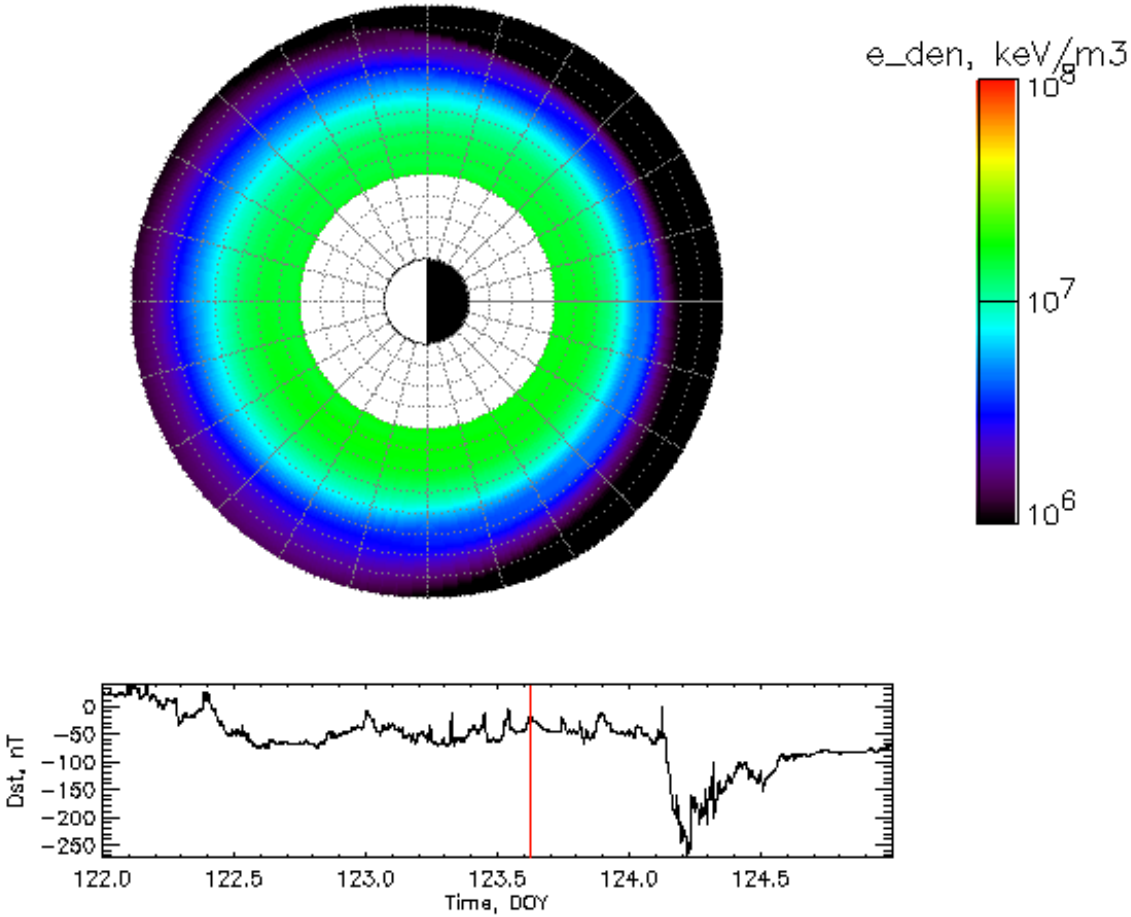
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



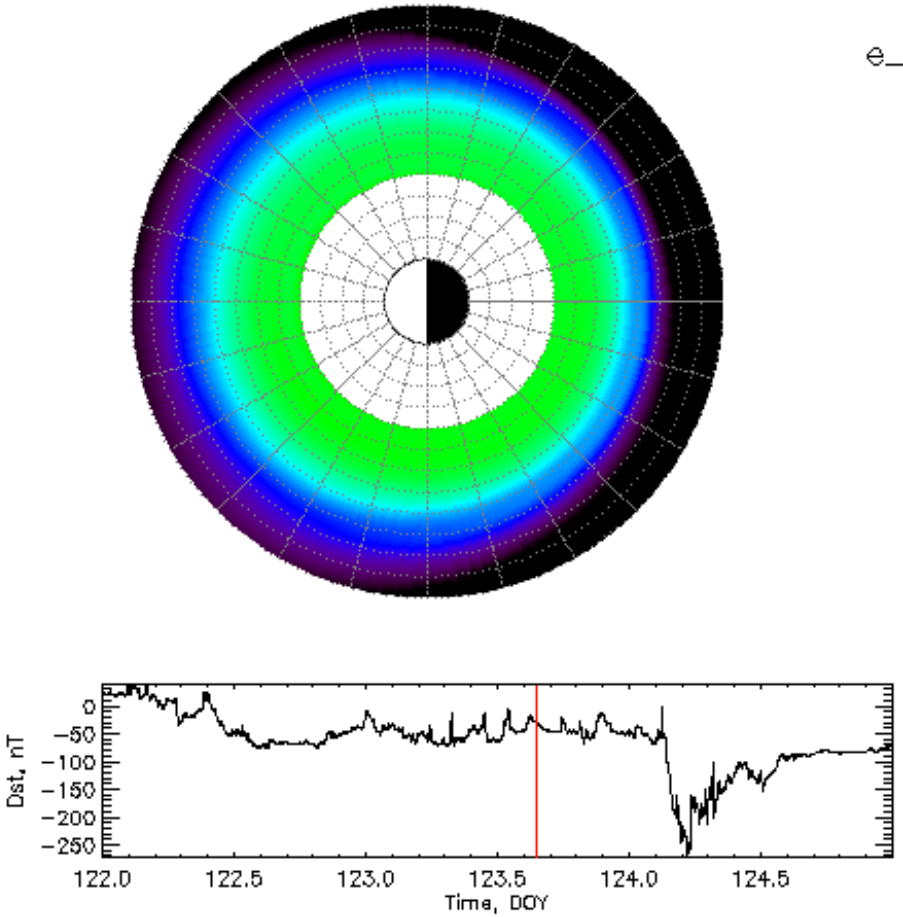
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



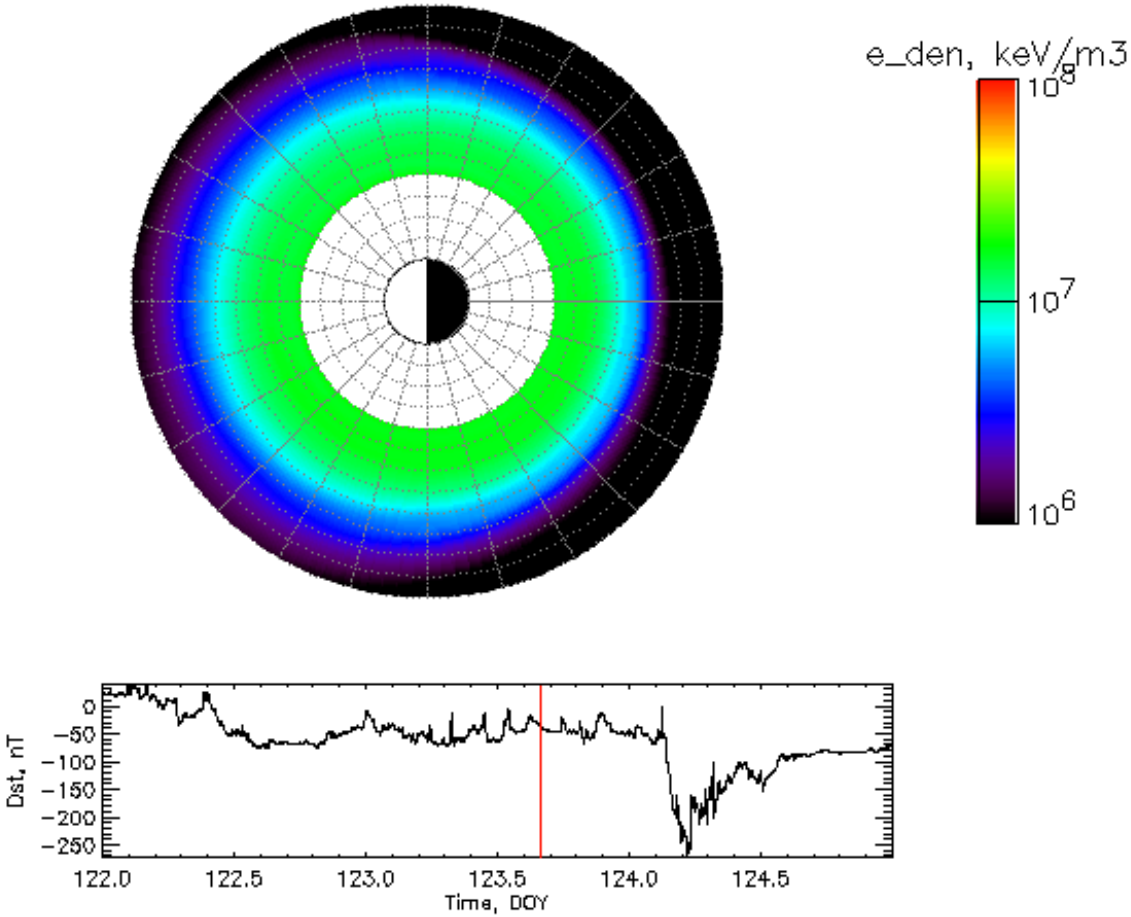
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



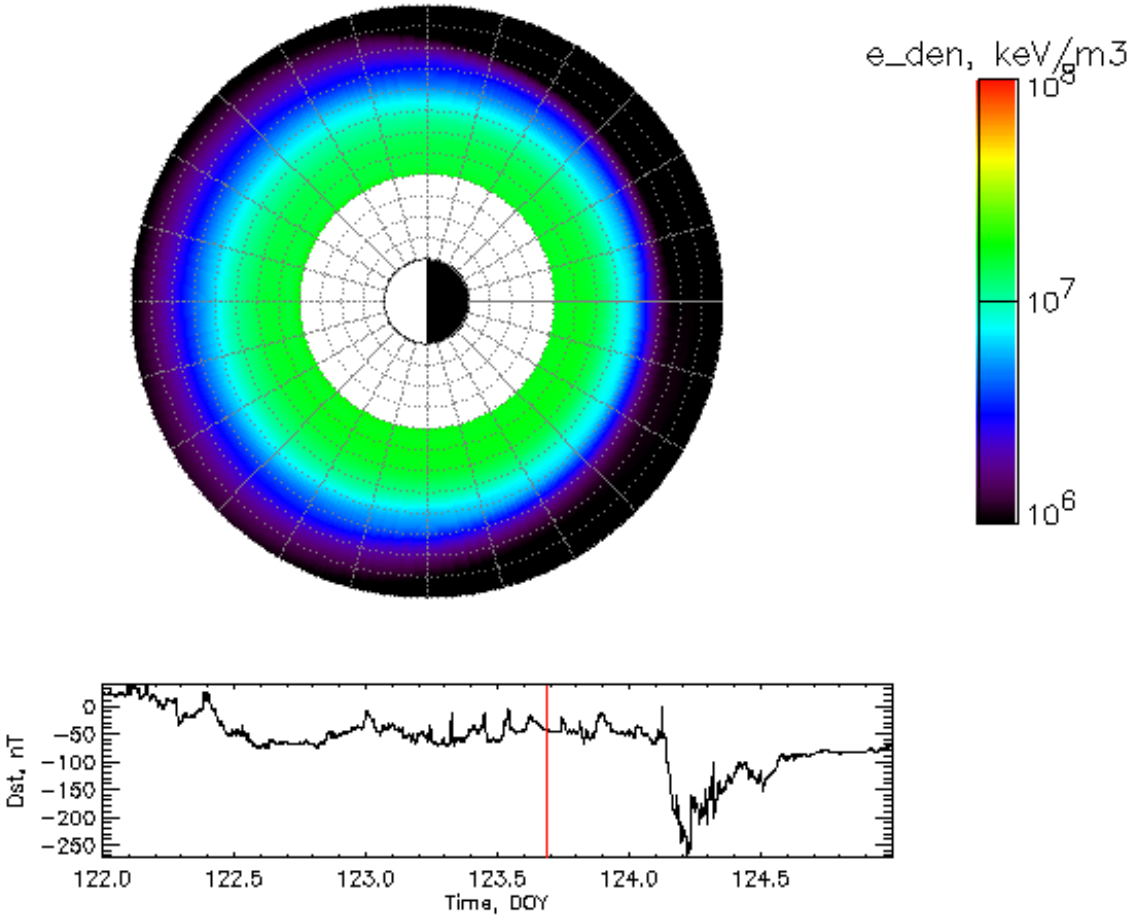
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



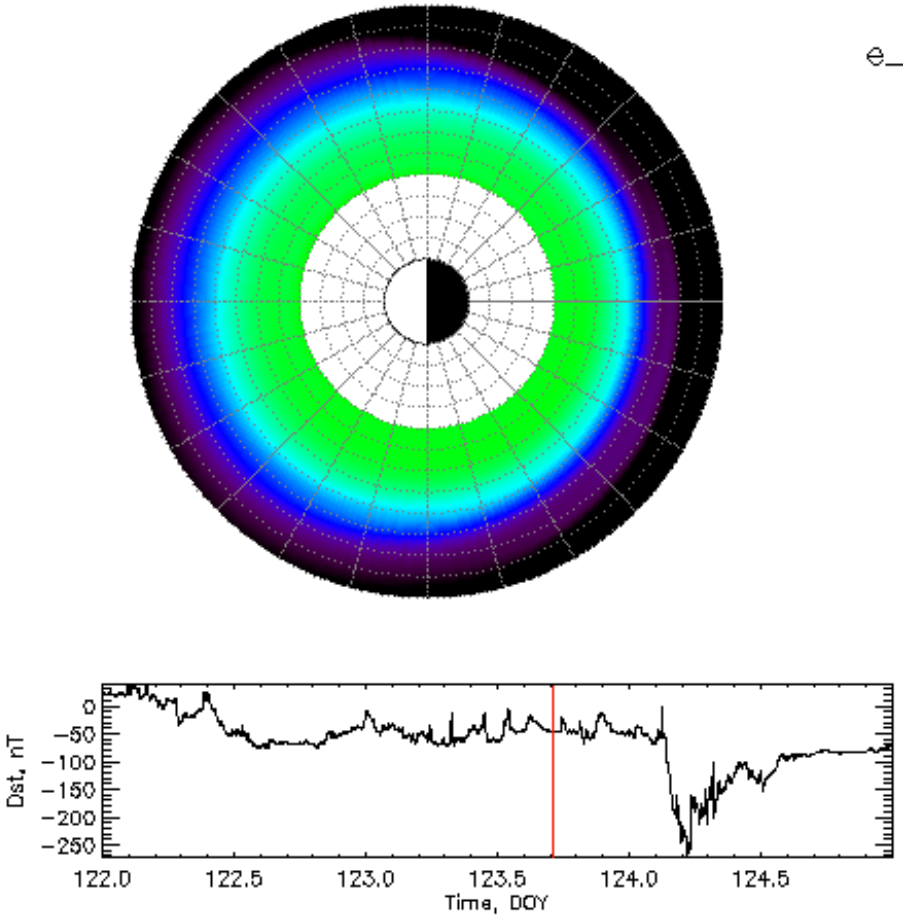
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



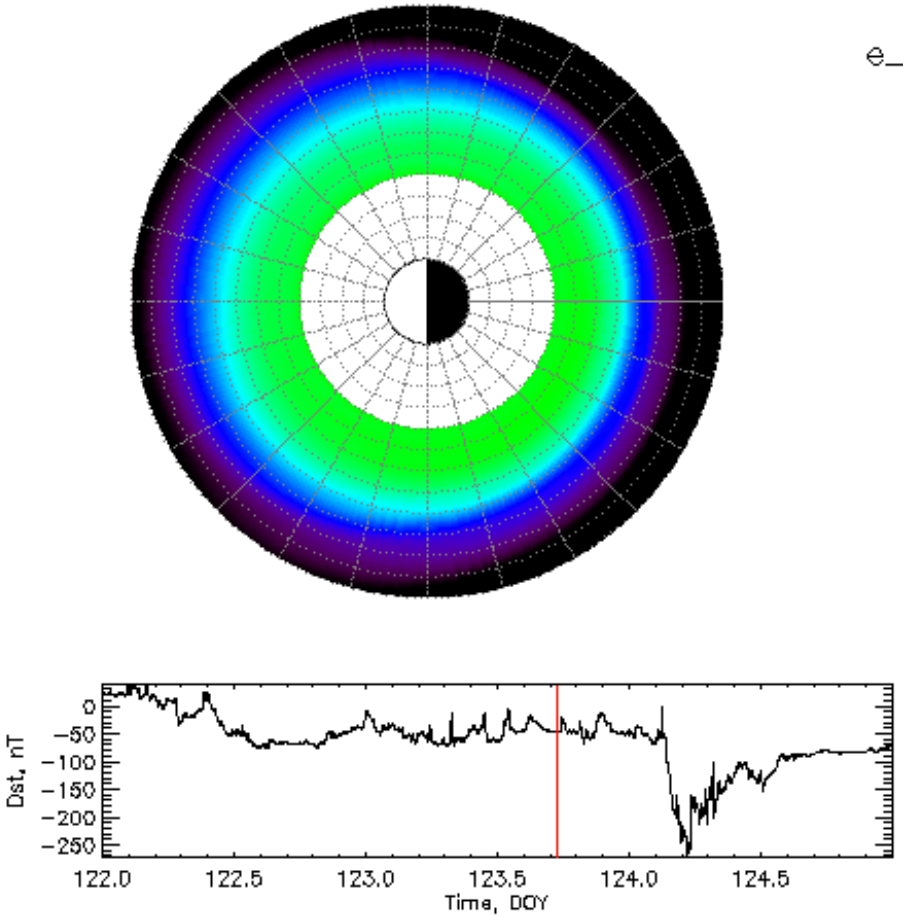
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



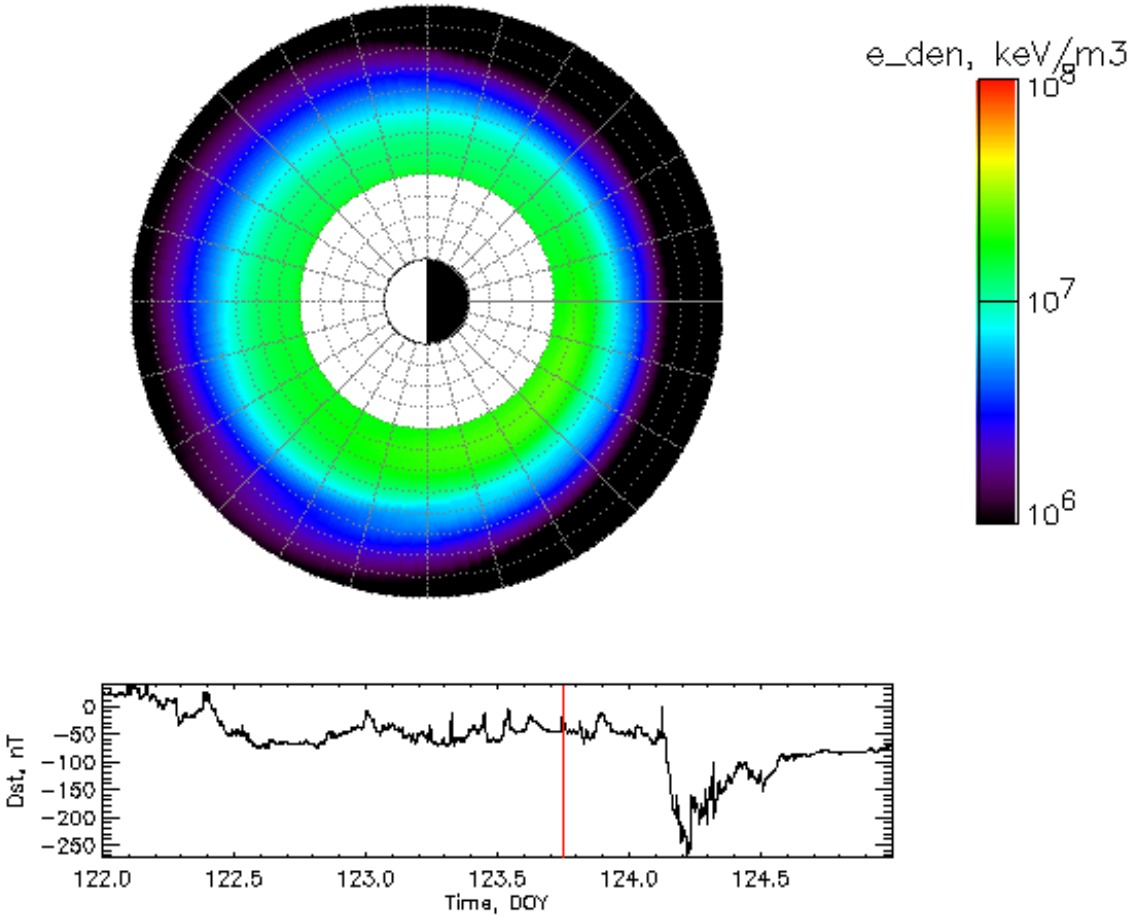
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



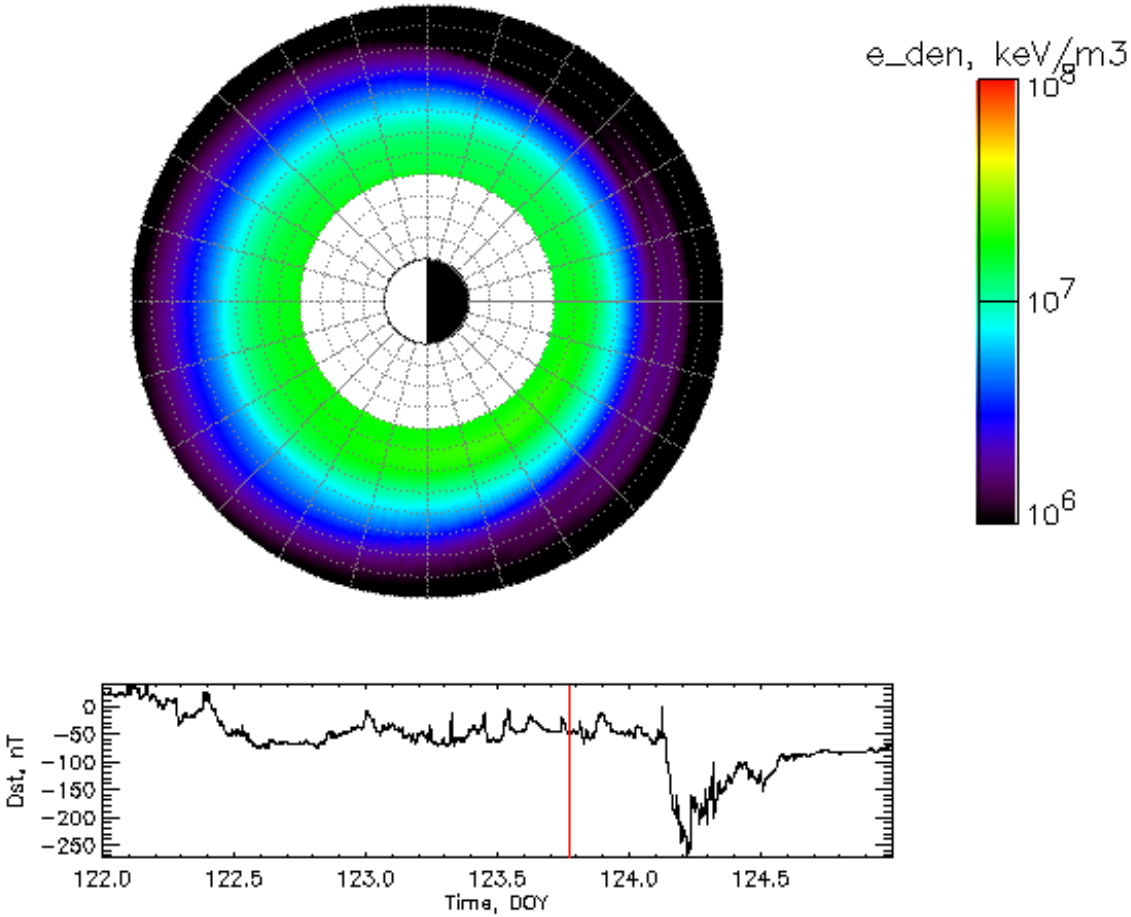
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



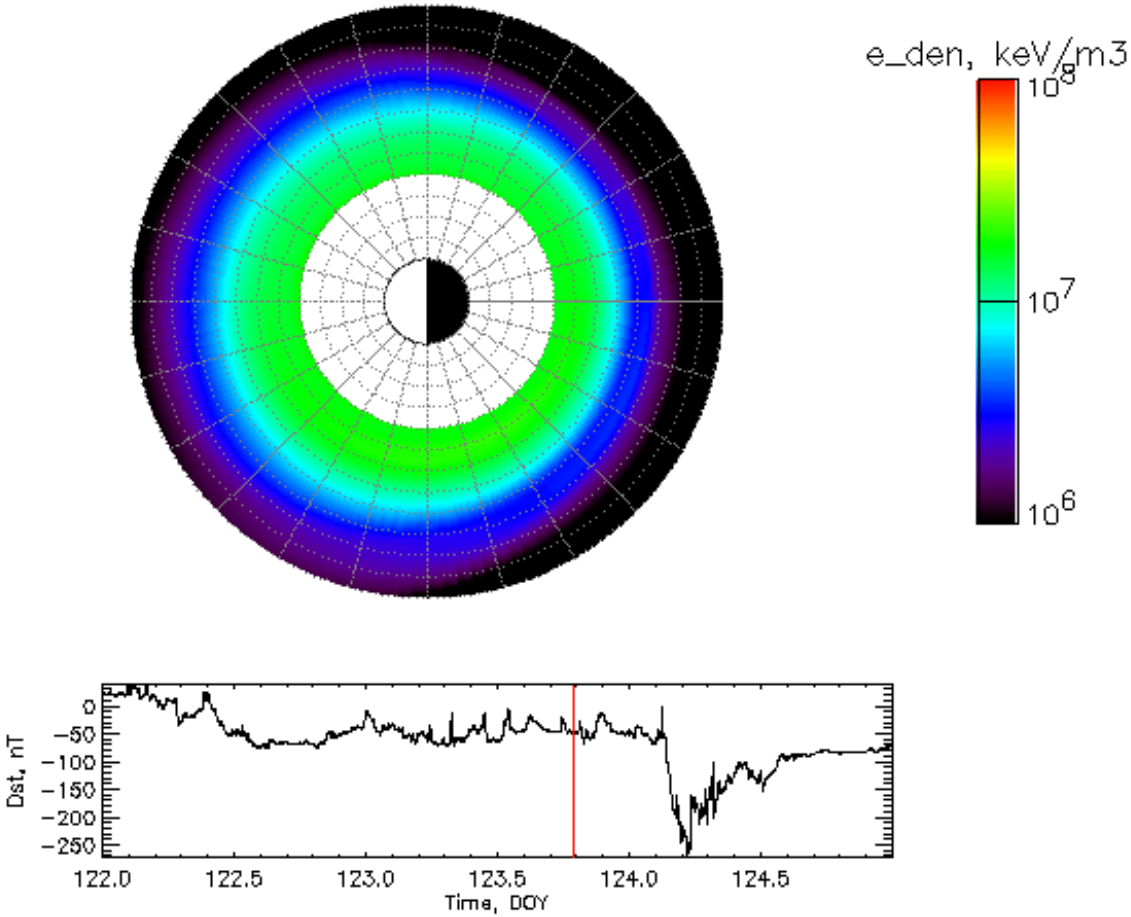
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



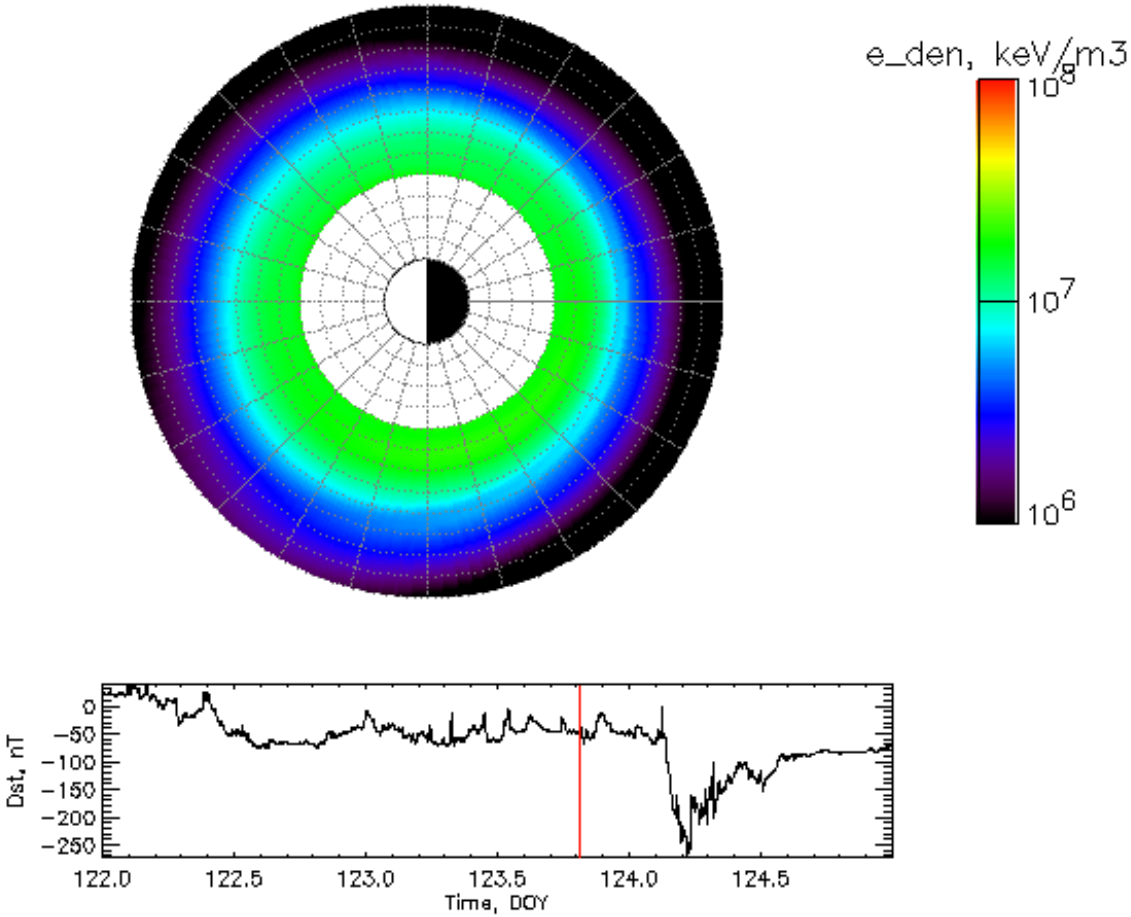
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



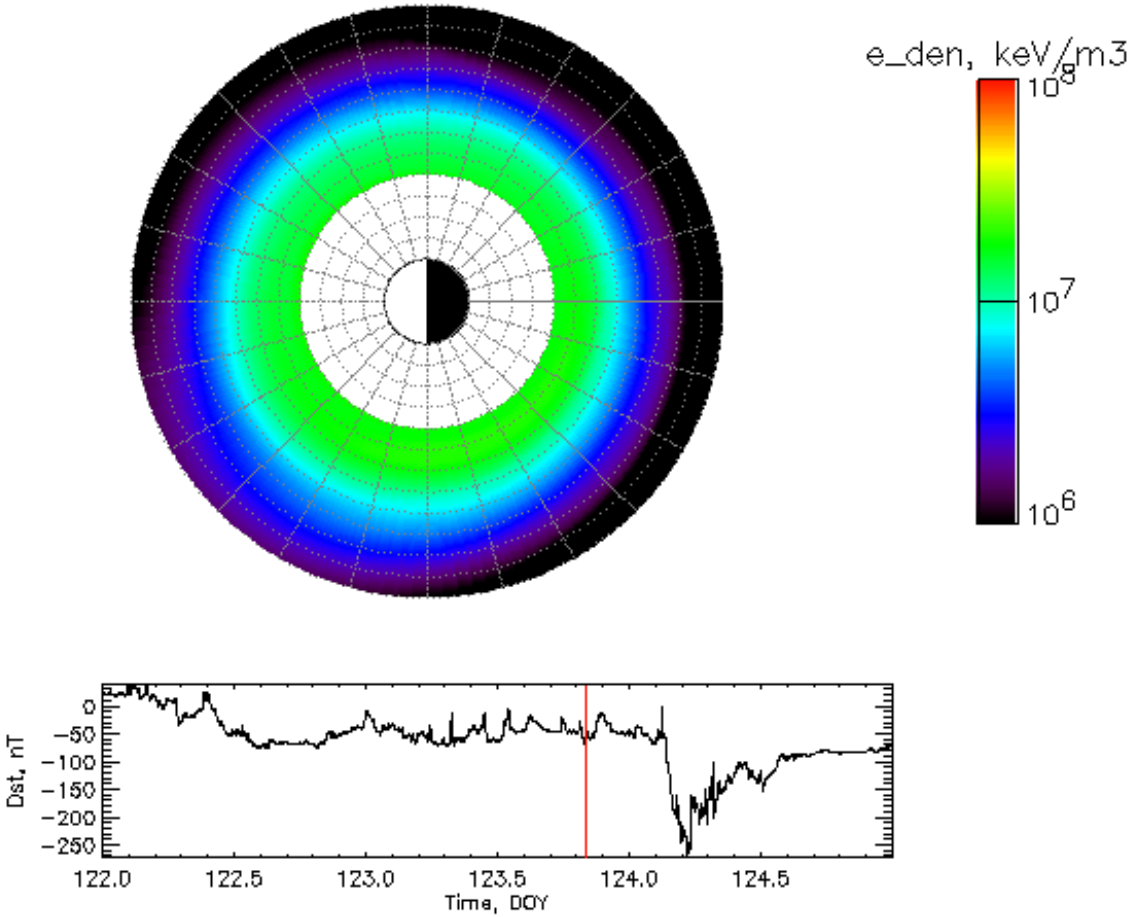
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



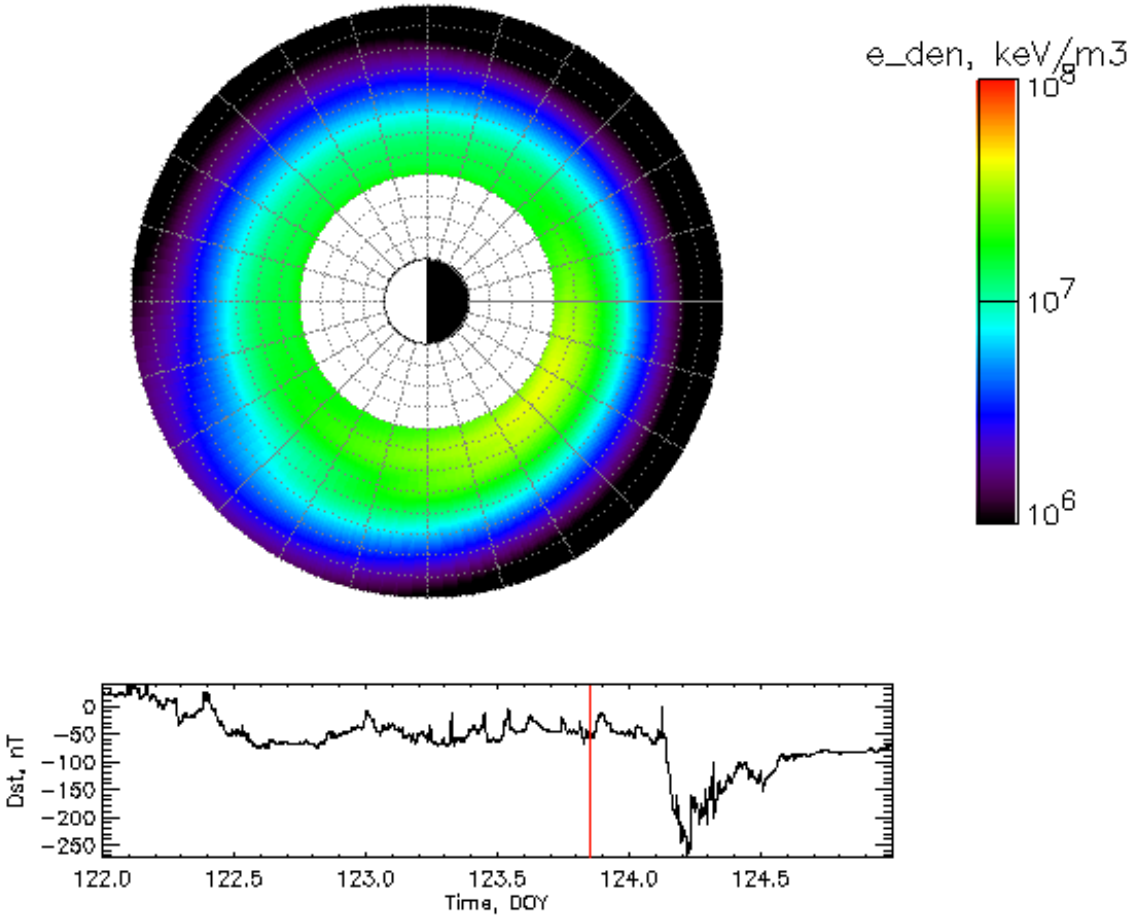
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



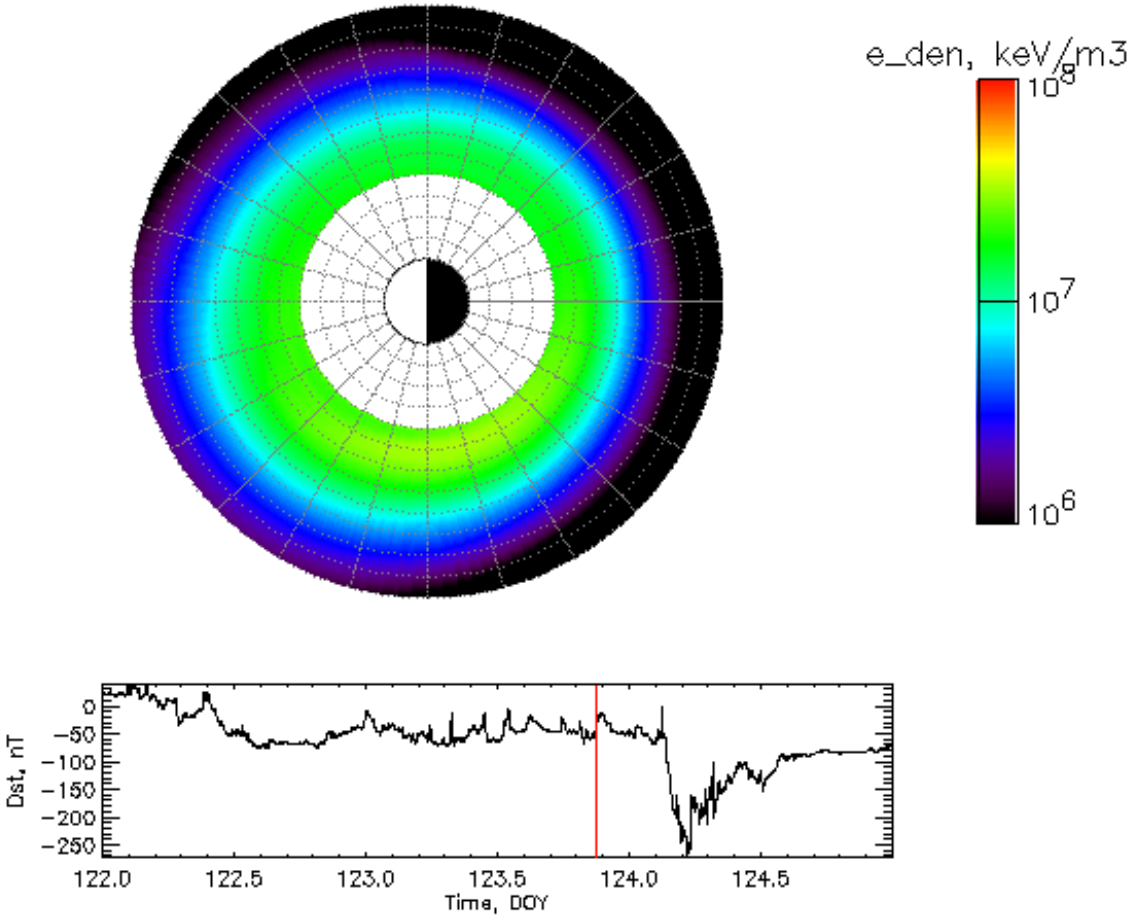
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



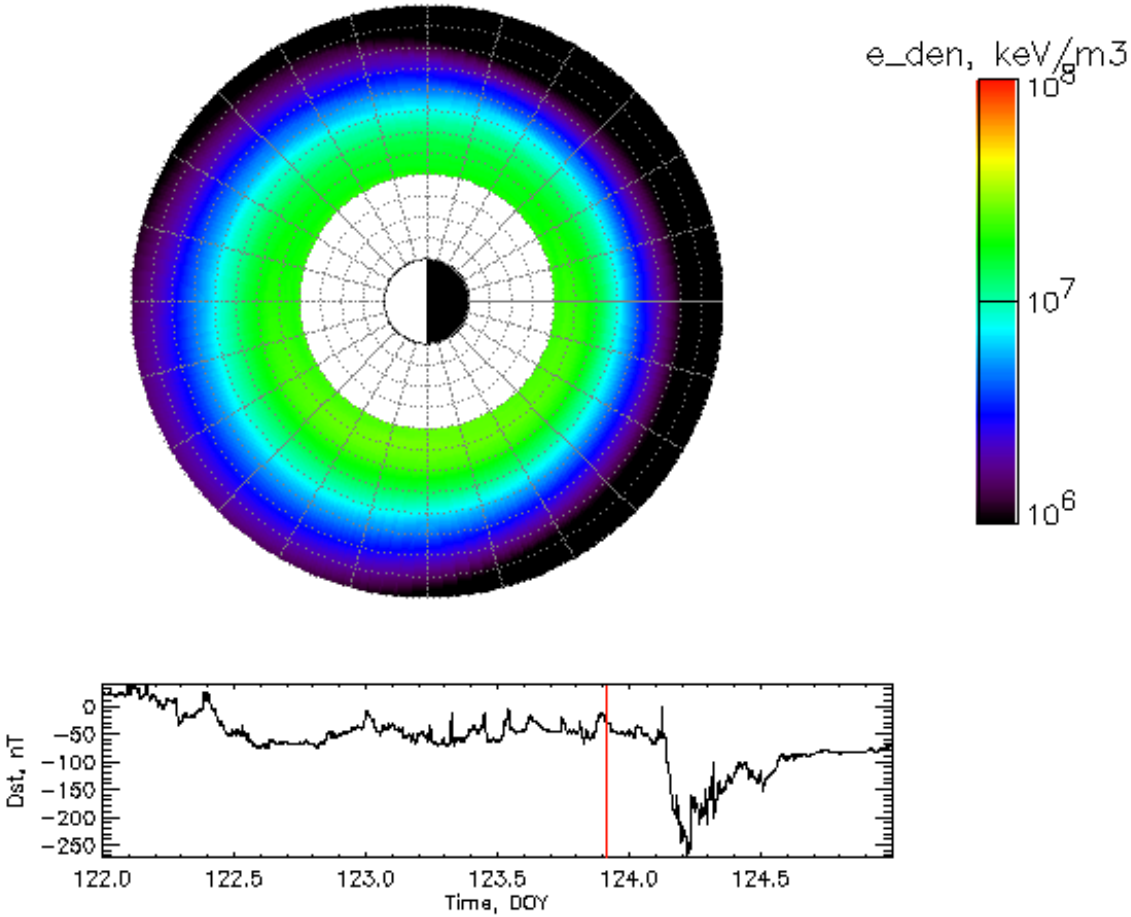
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



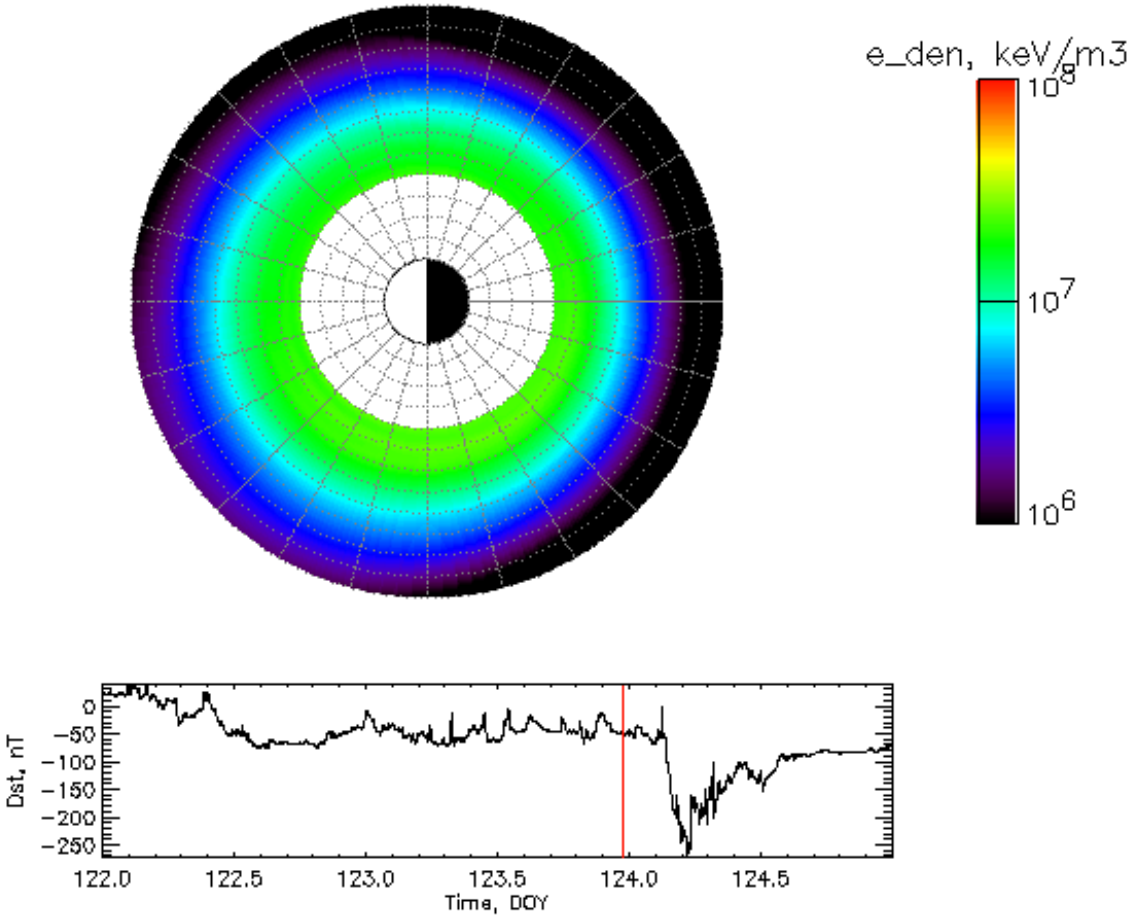
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



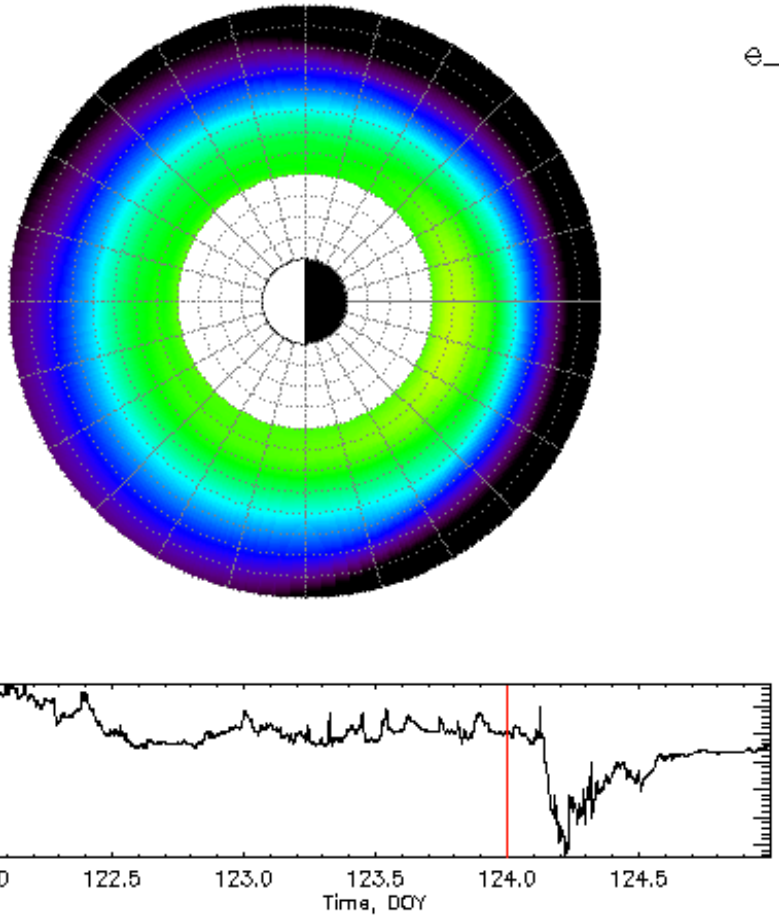
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



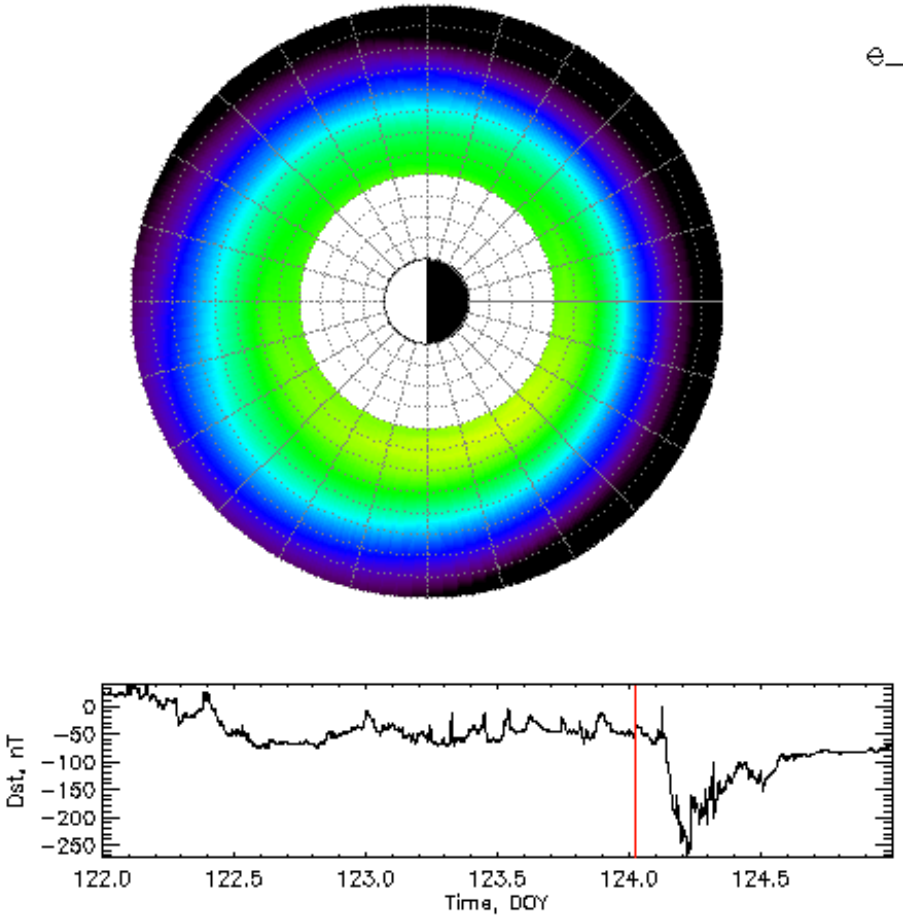
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



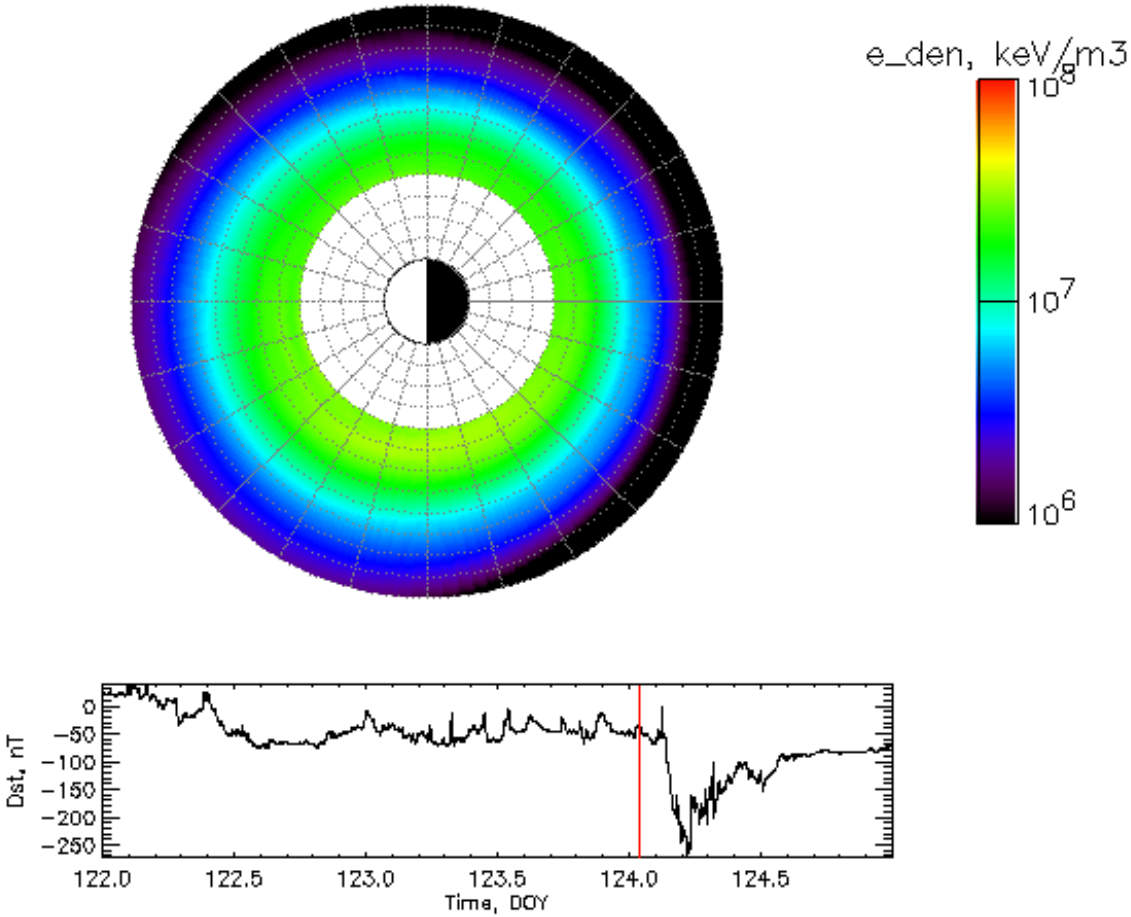
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



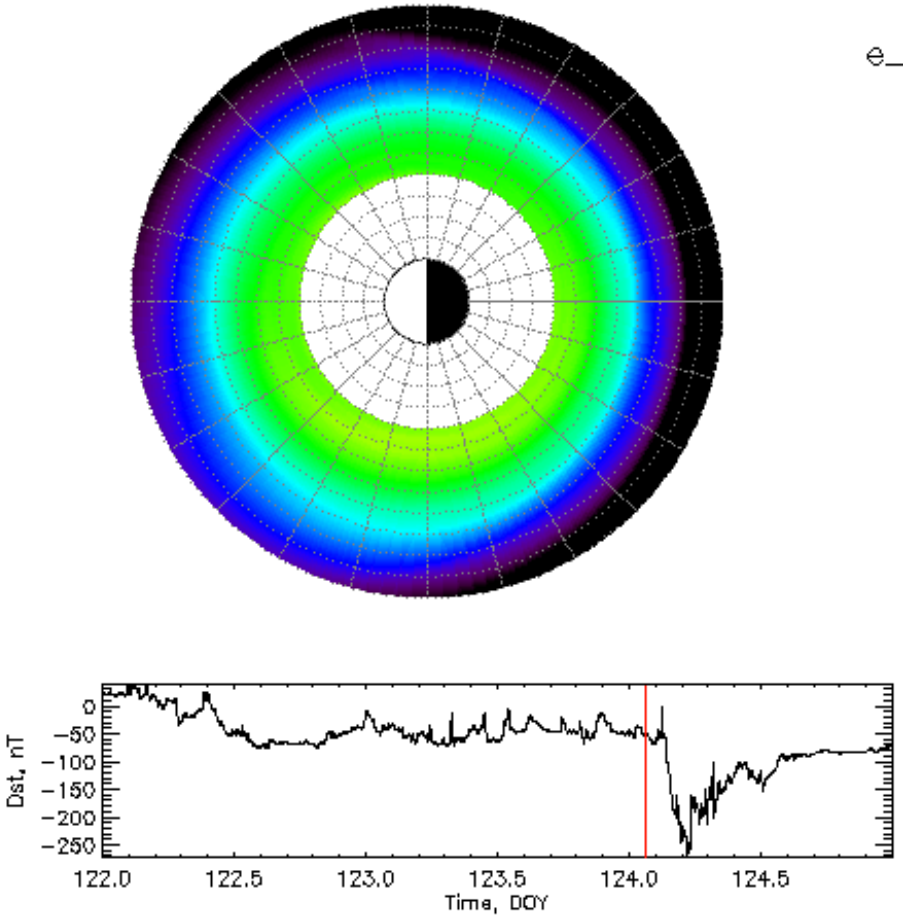
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



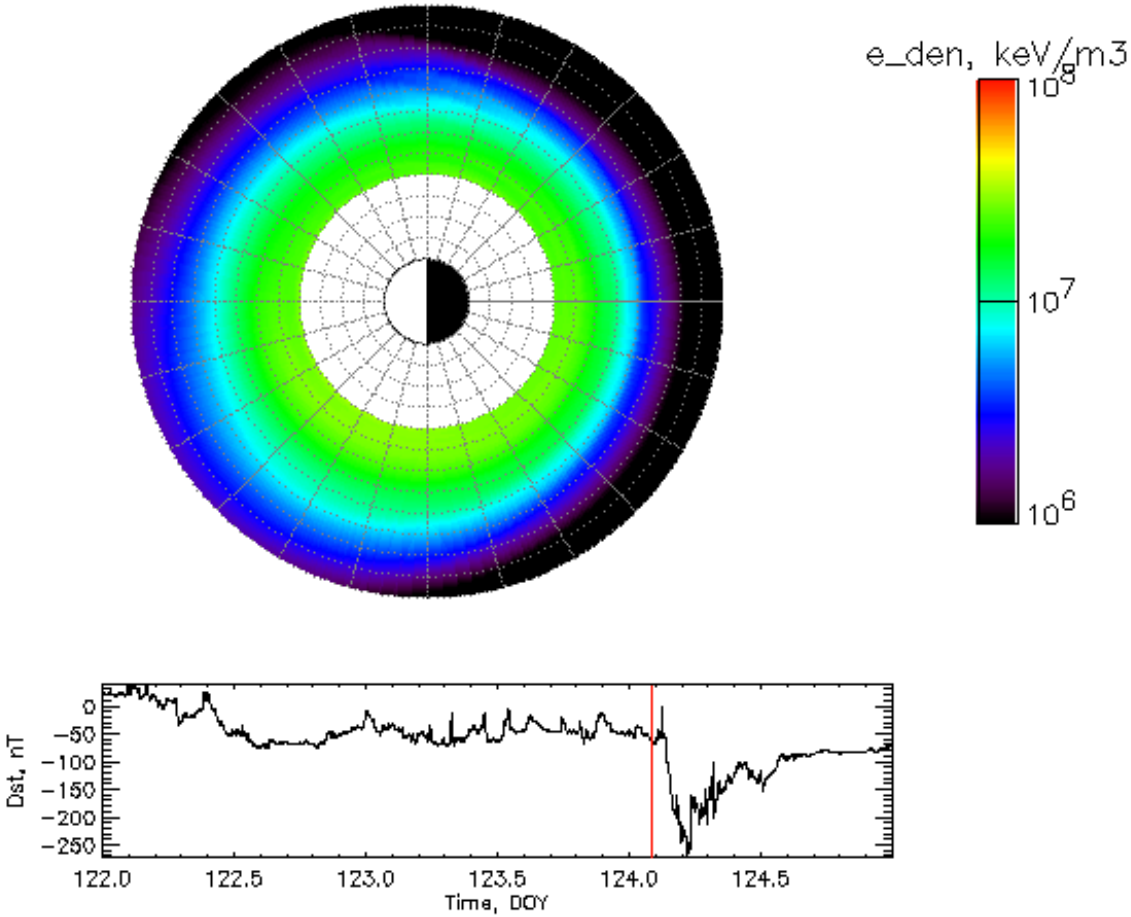
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



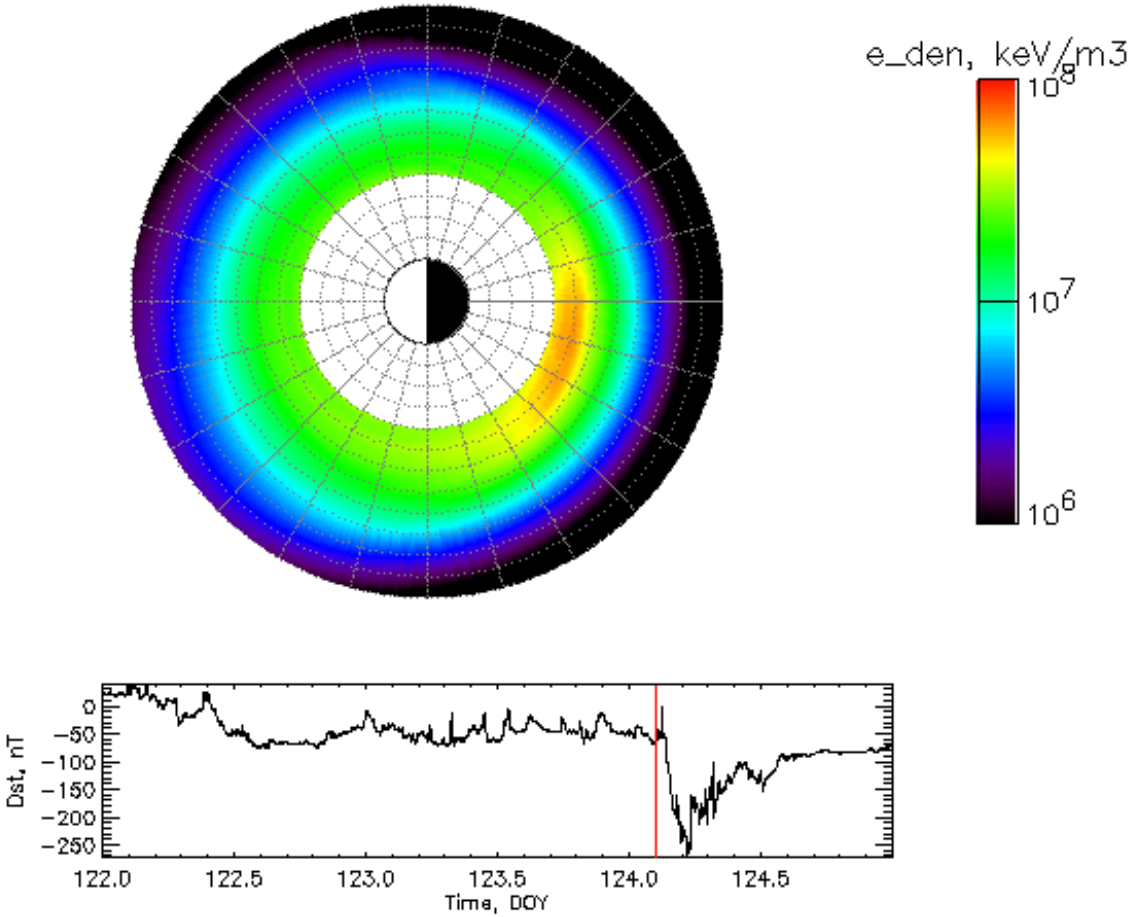
Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
3 days, May 2–4, 1998

Ring Current Protons



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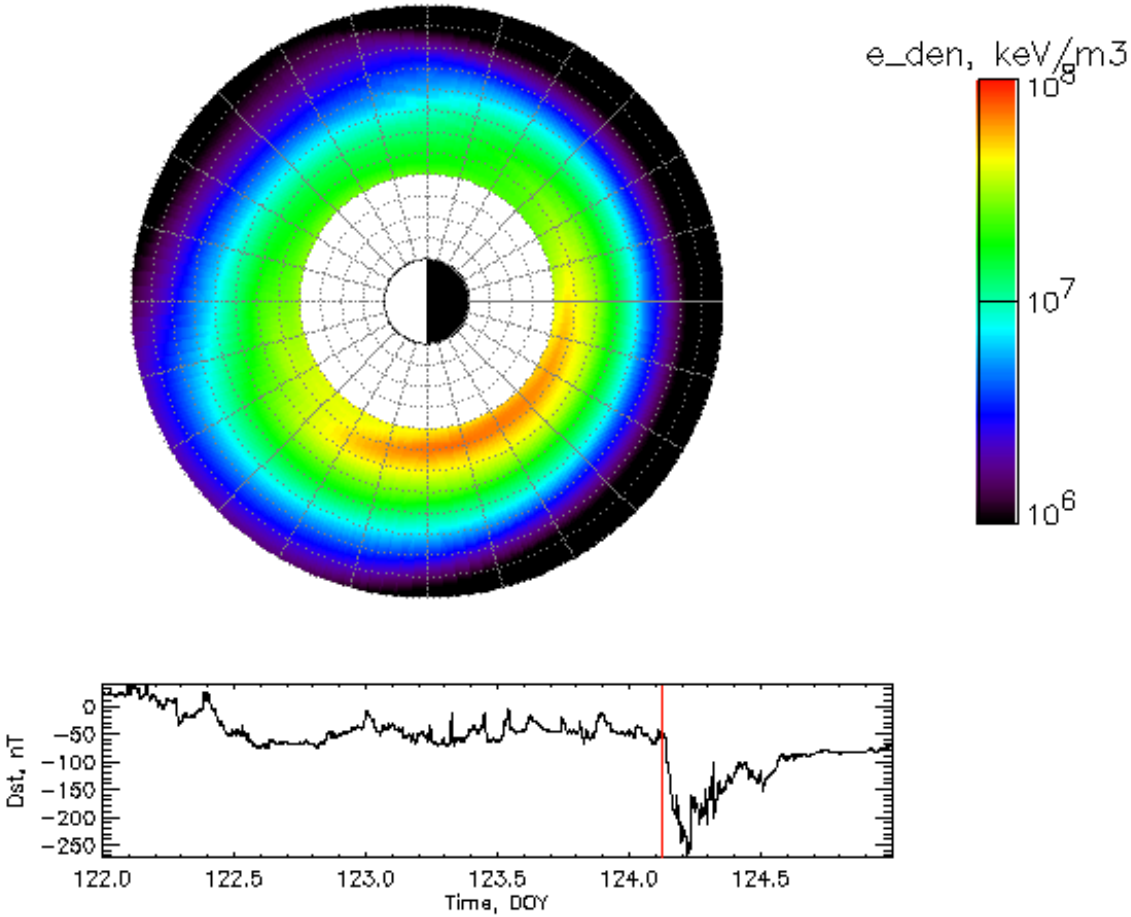

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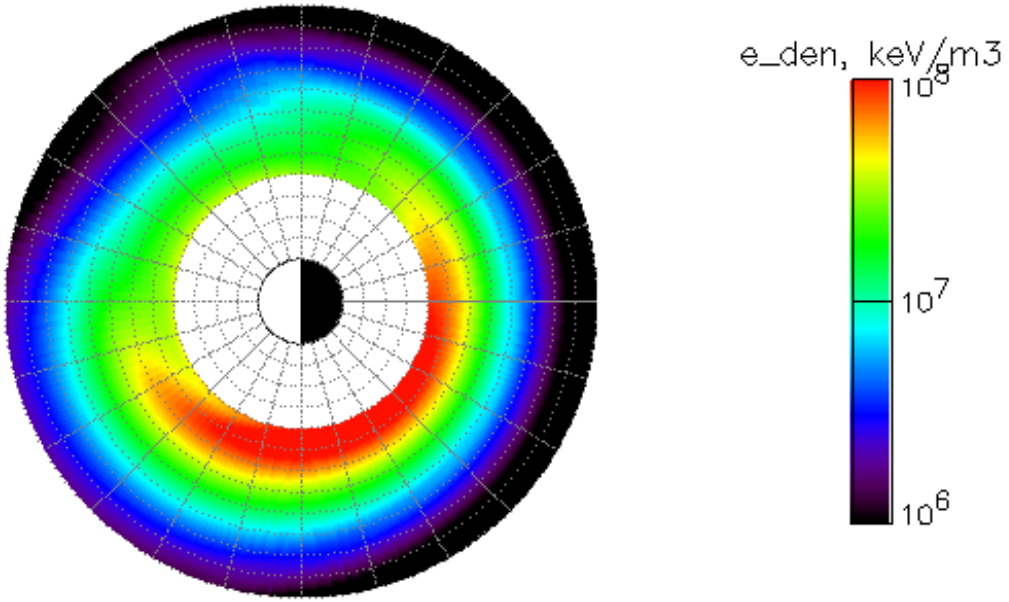

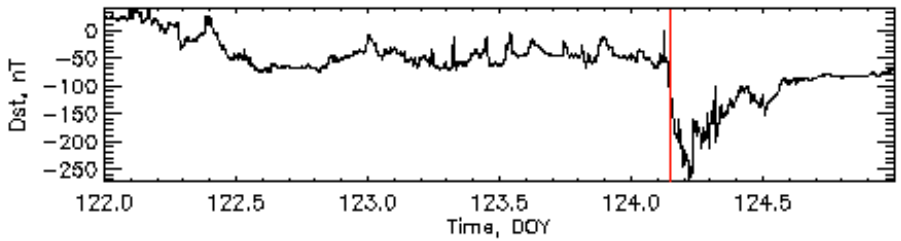

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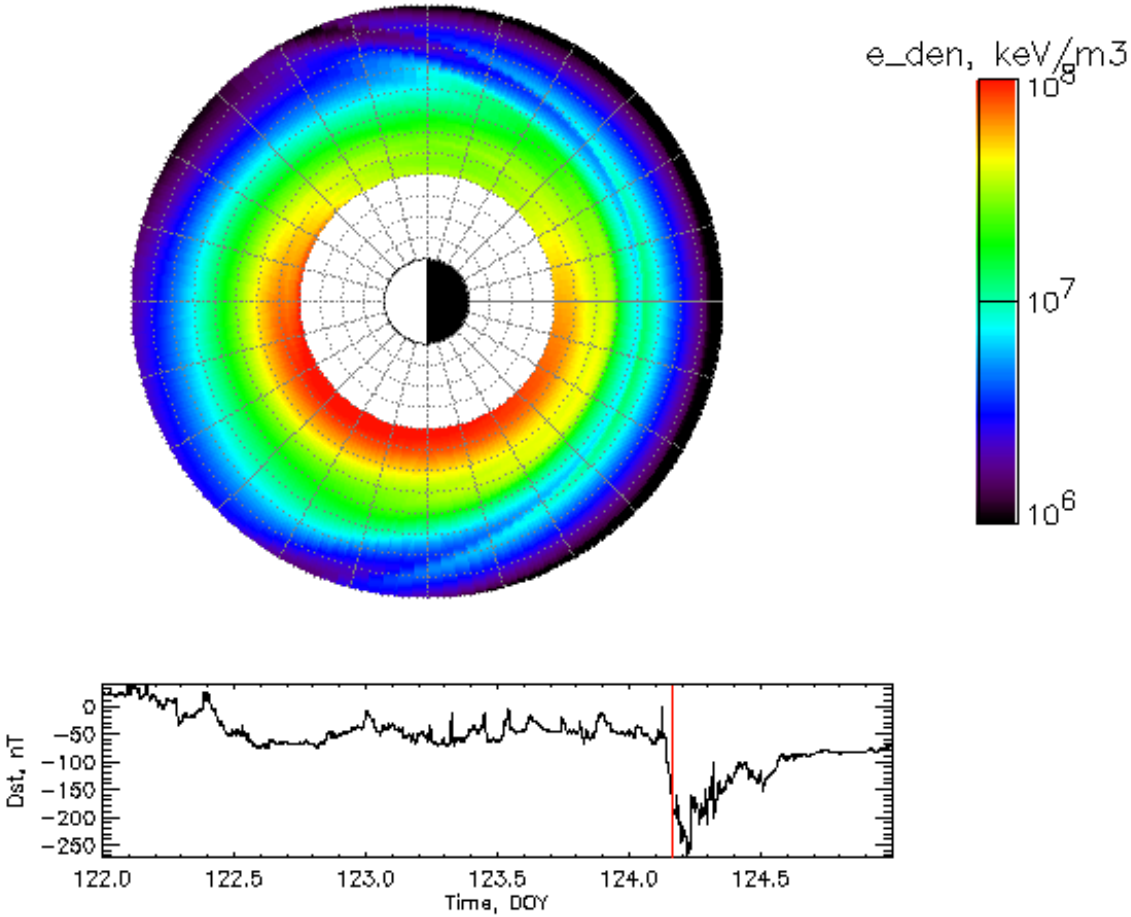

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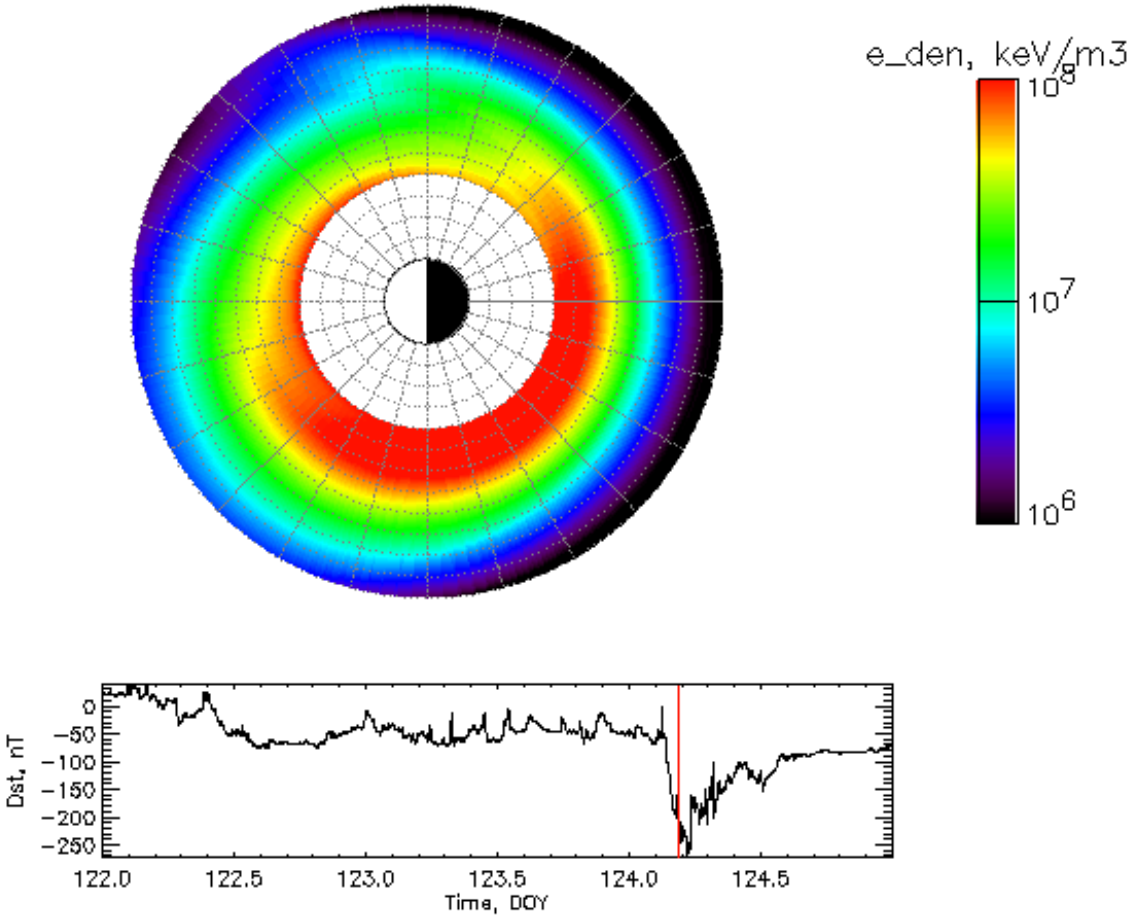

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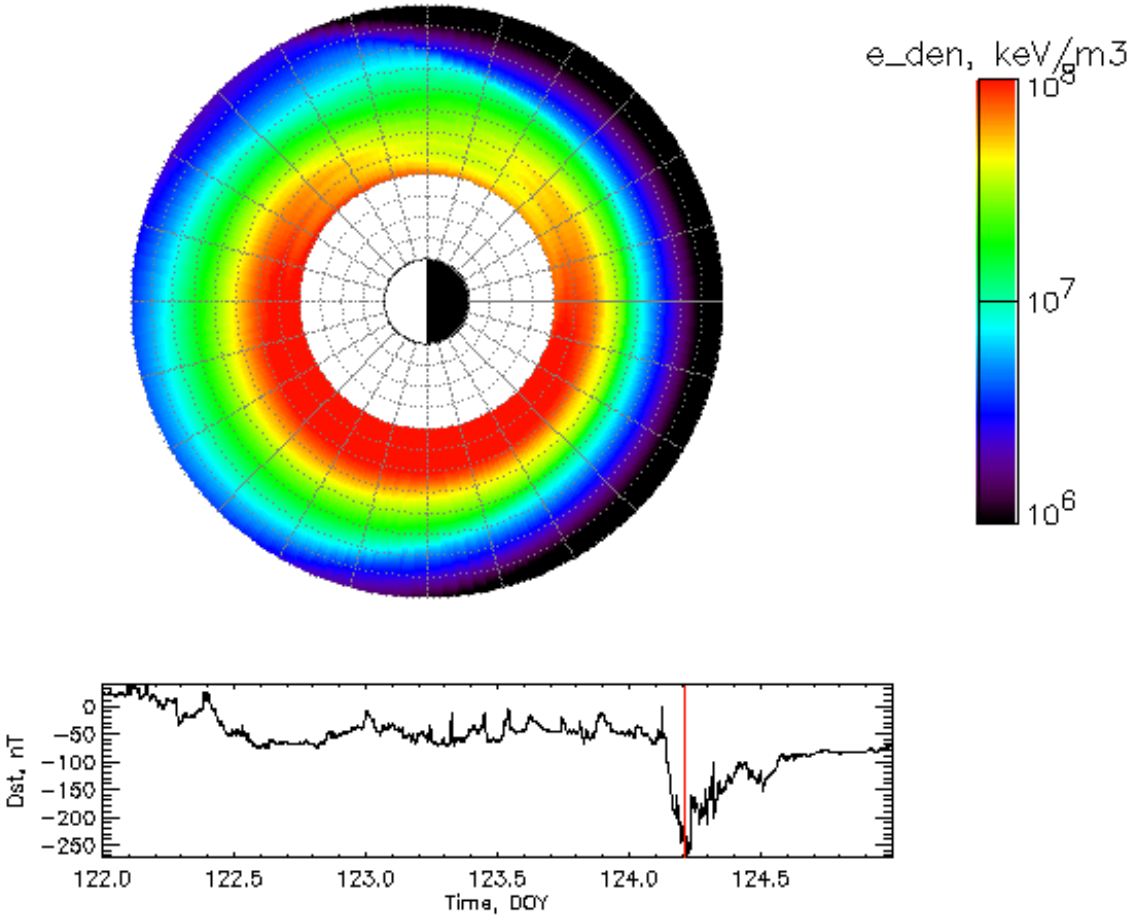

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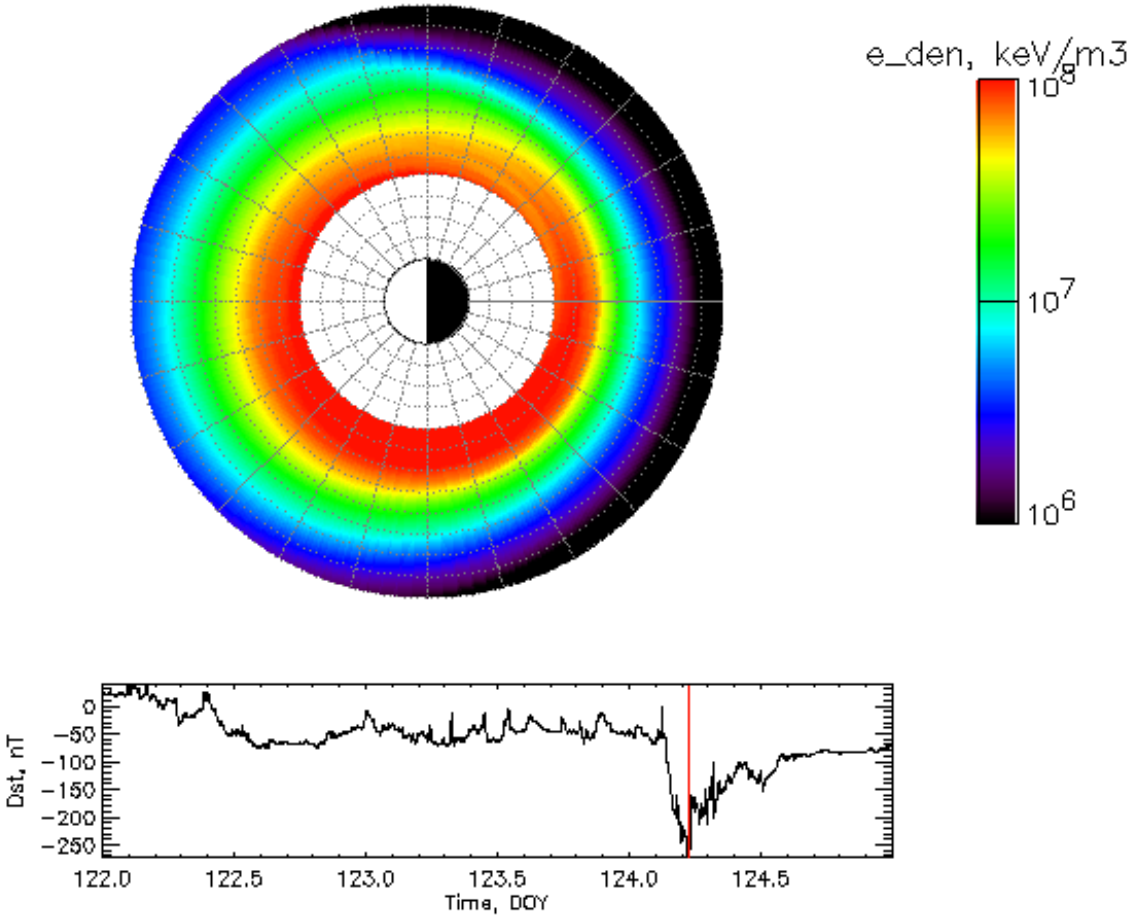

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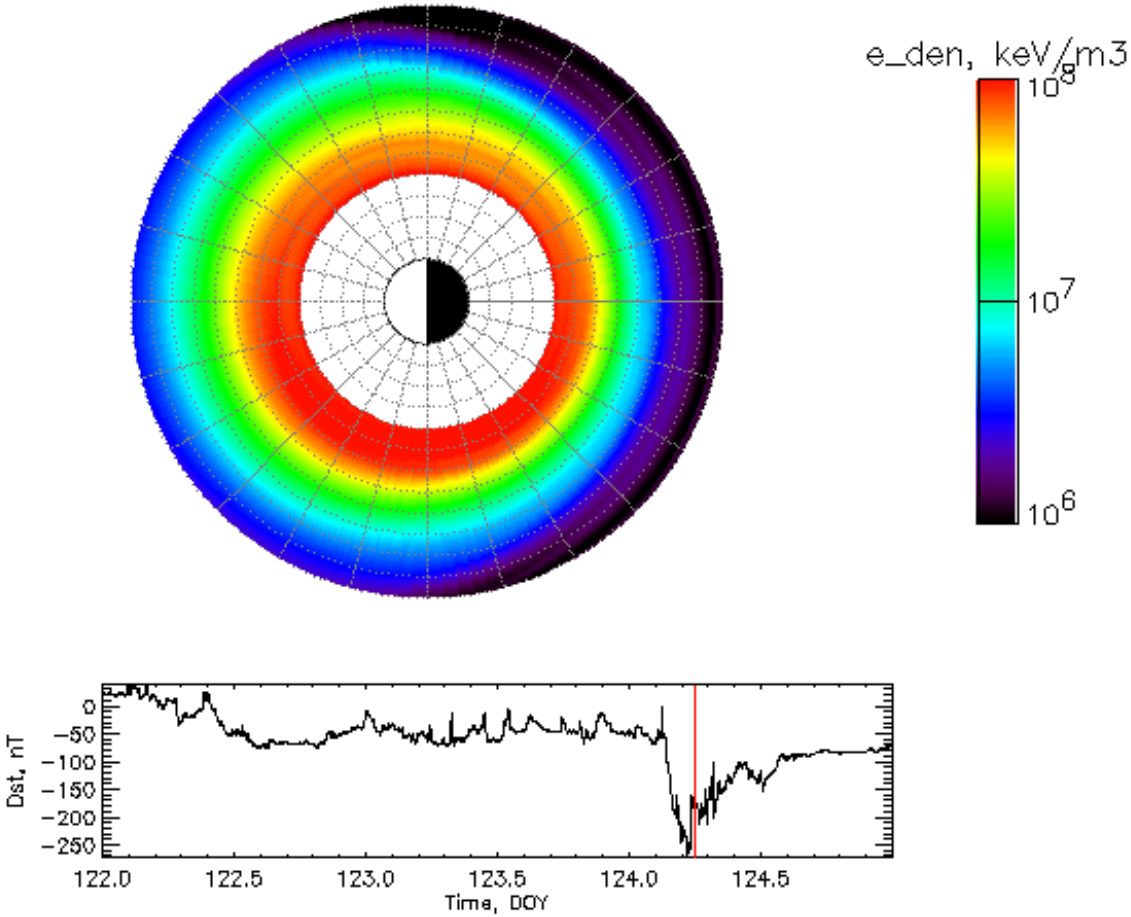

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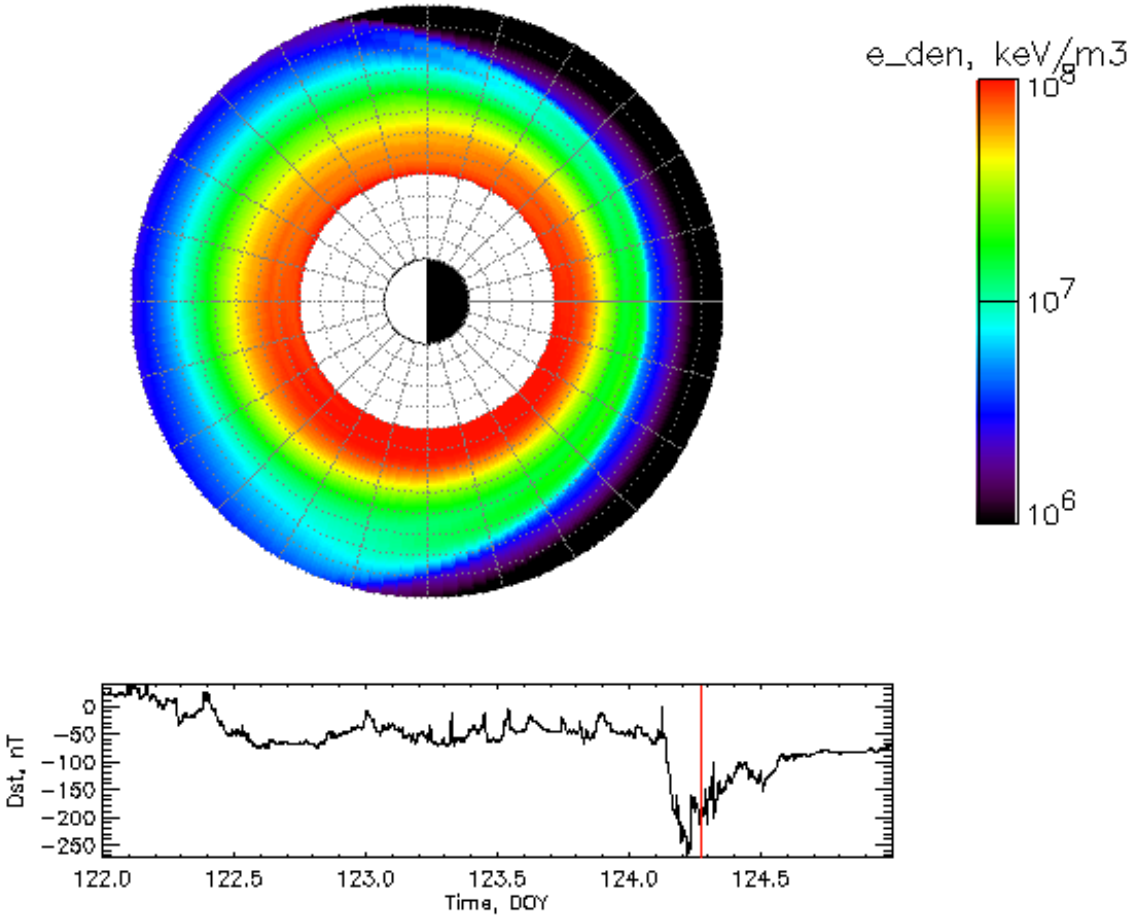

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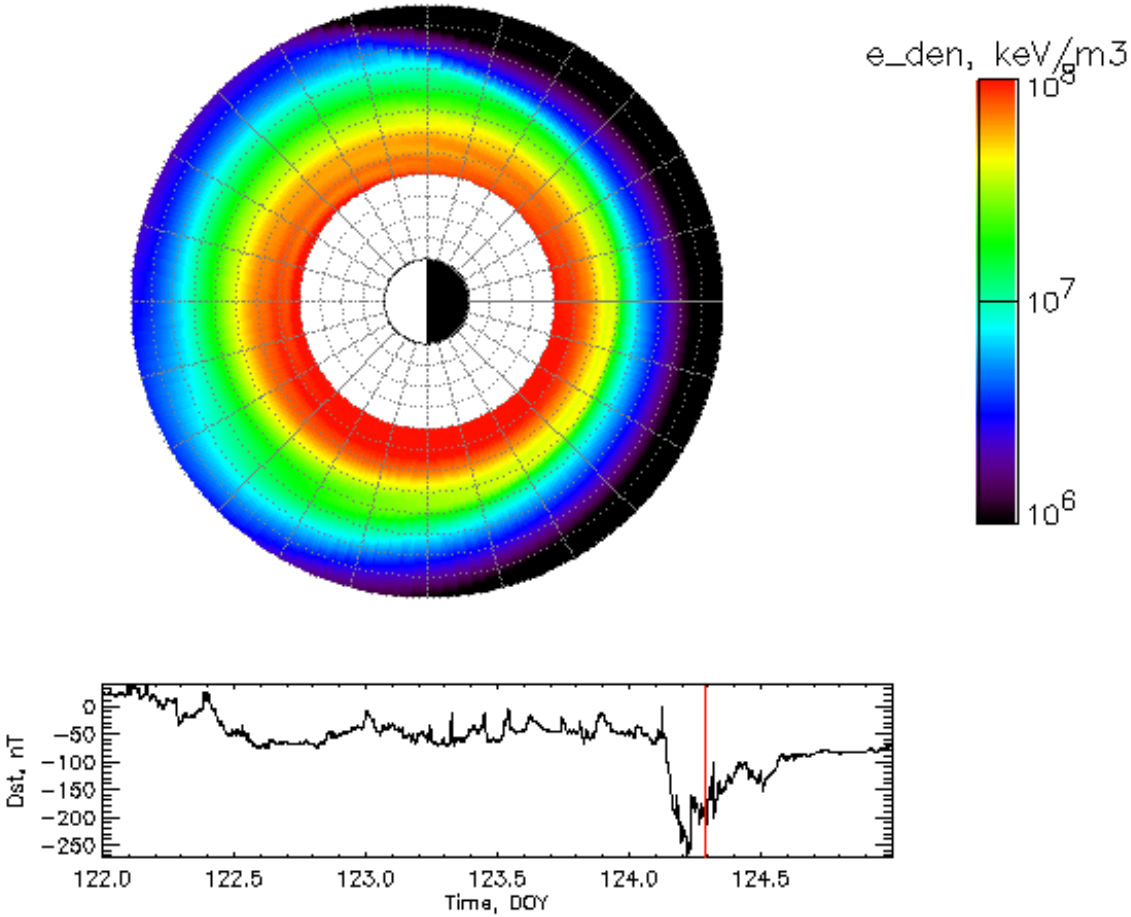

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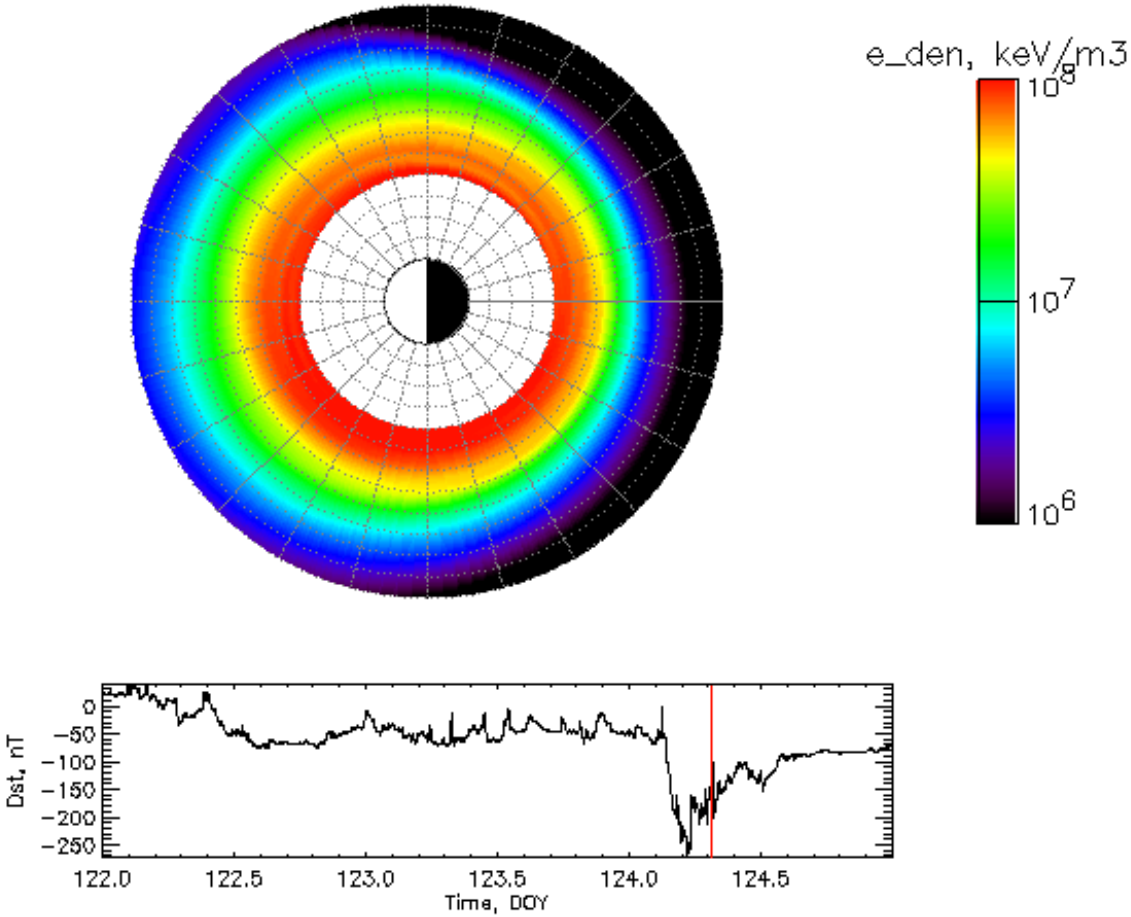

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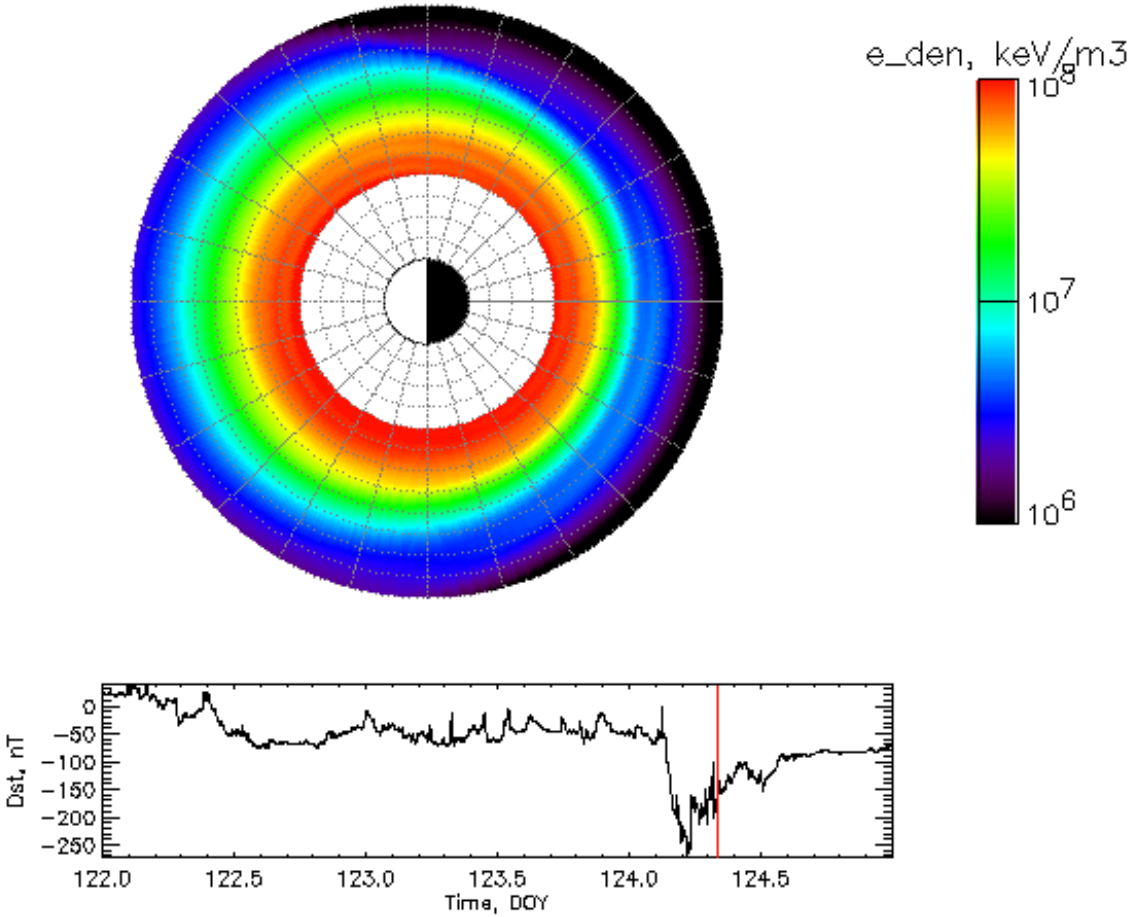

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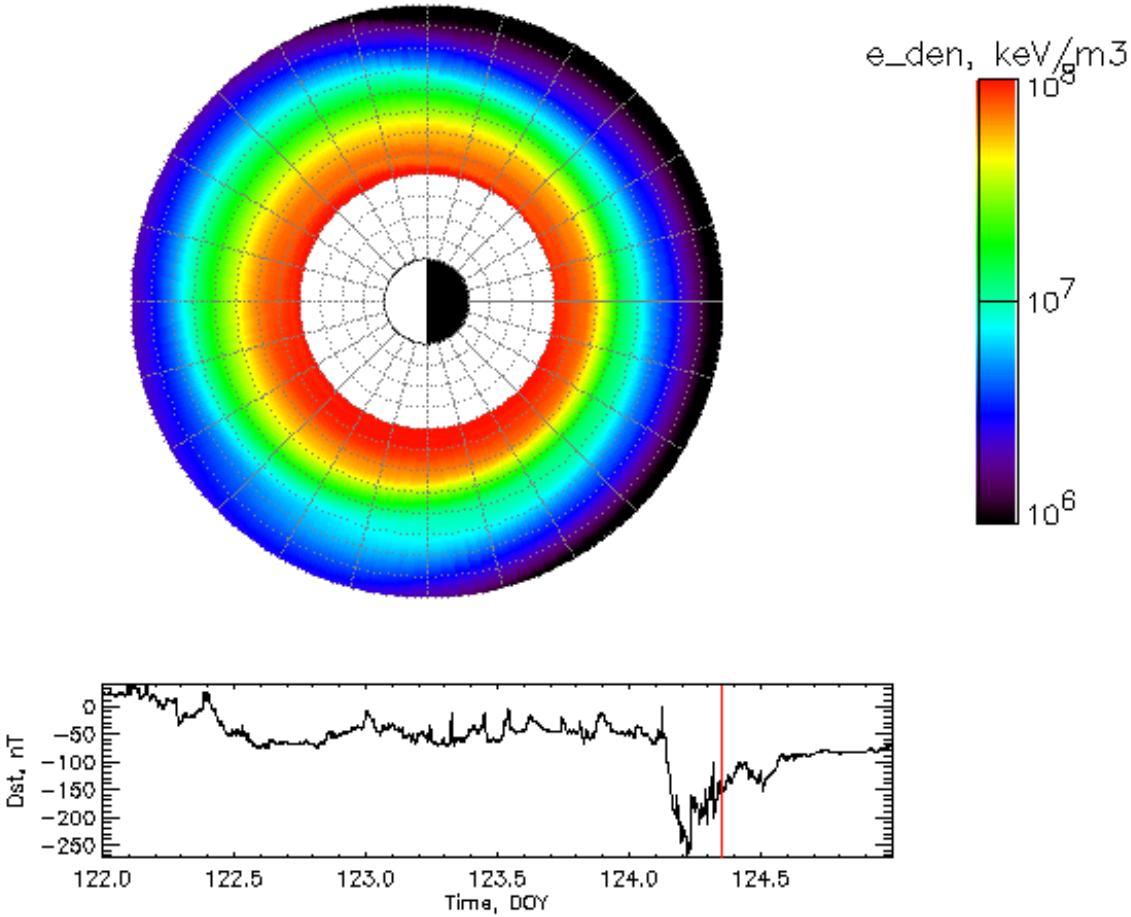

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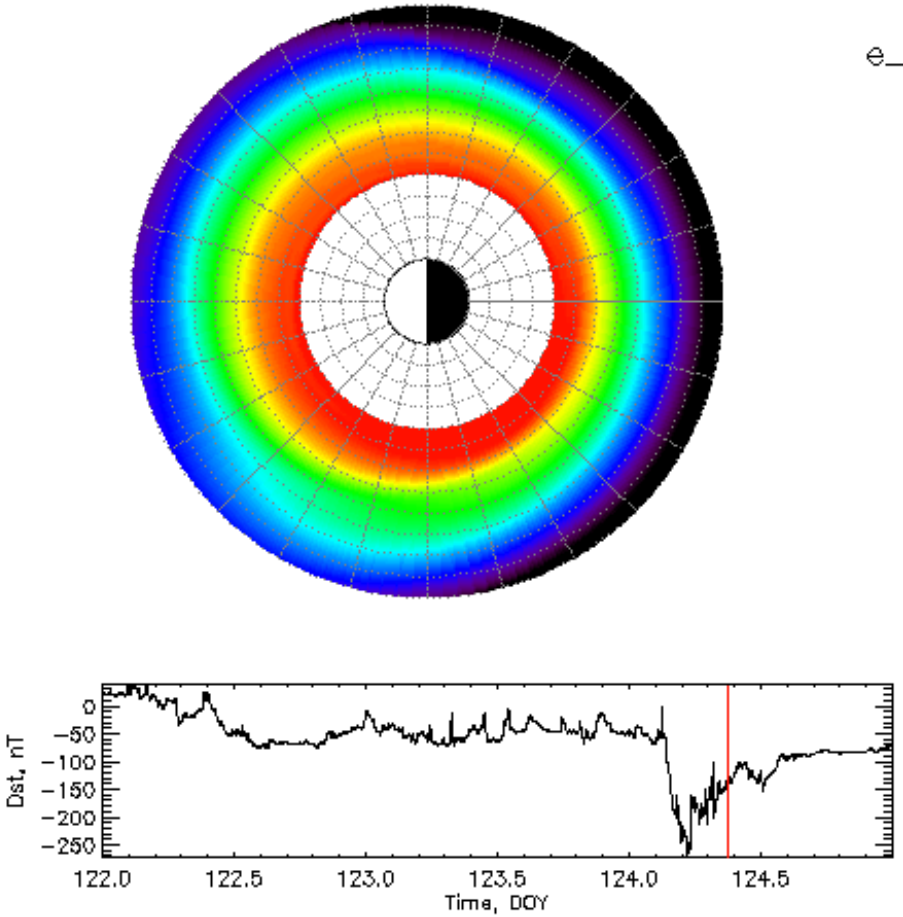

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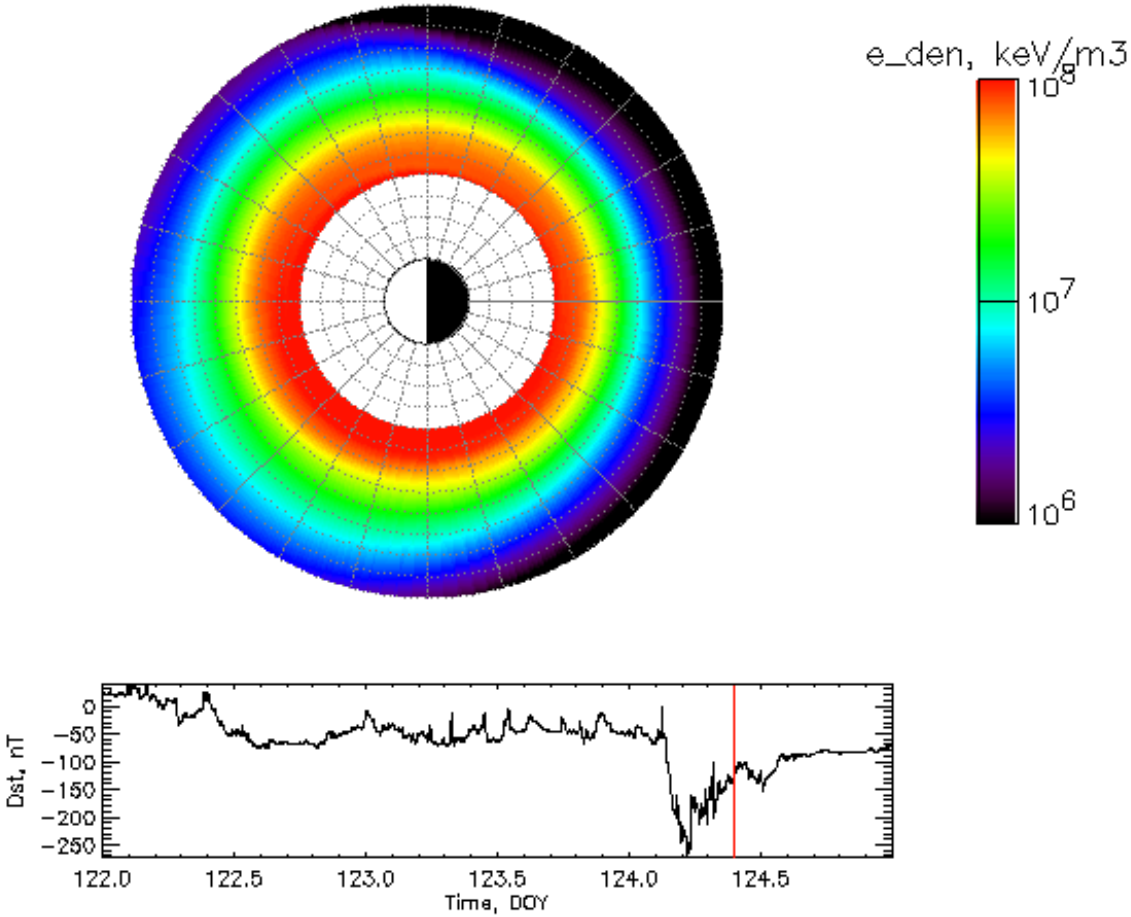

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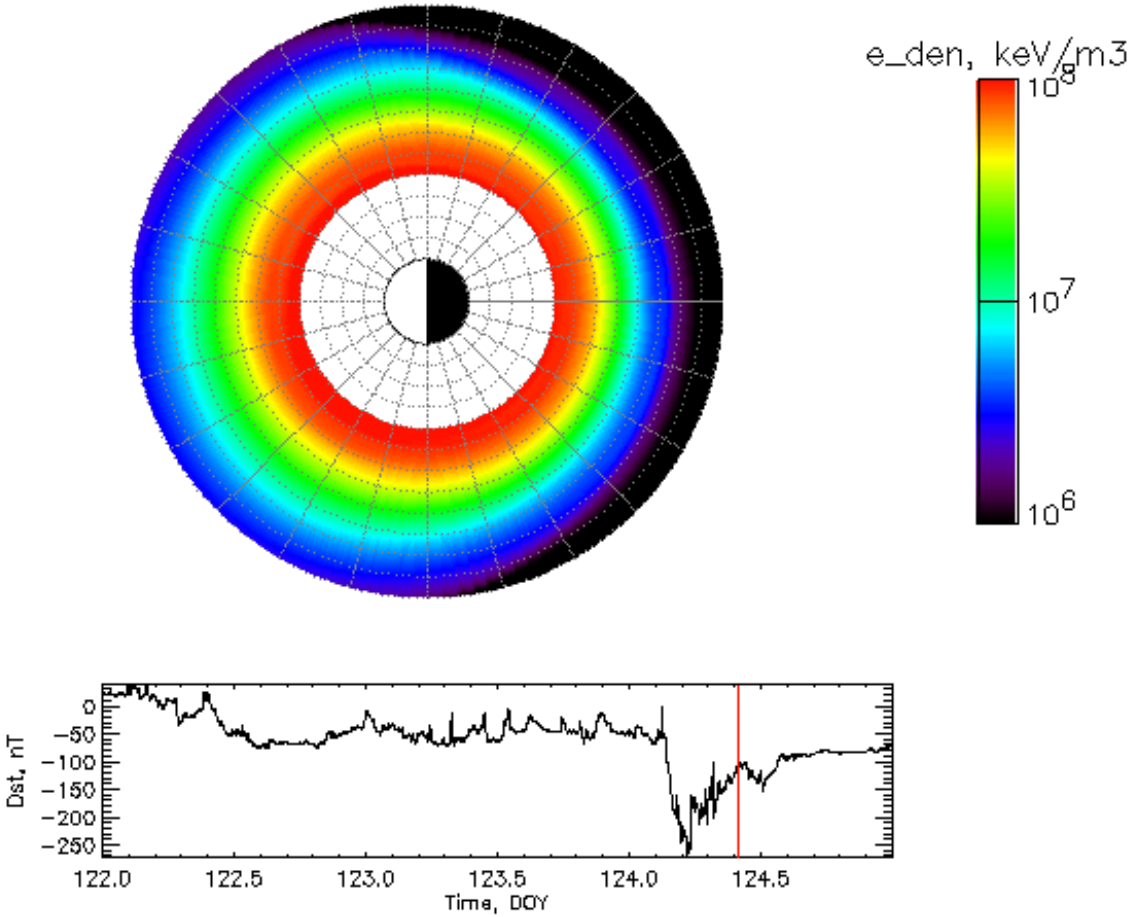

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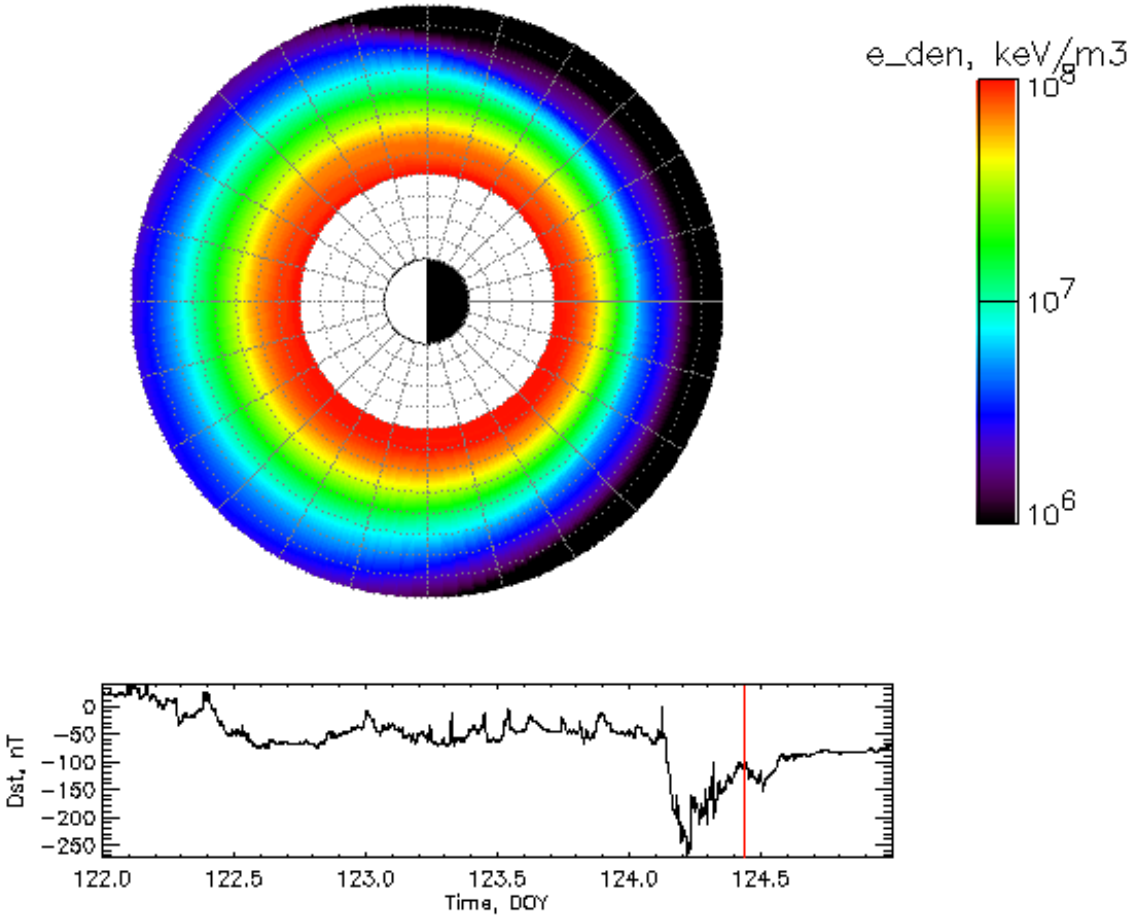

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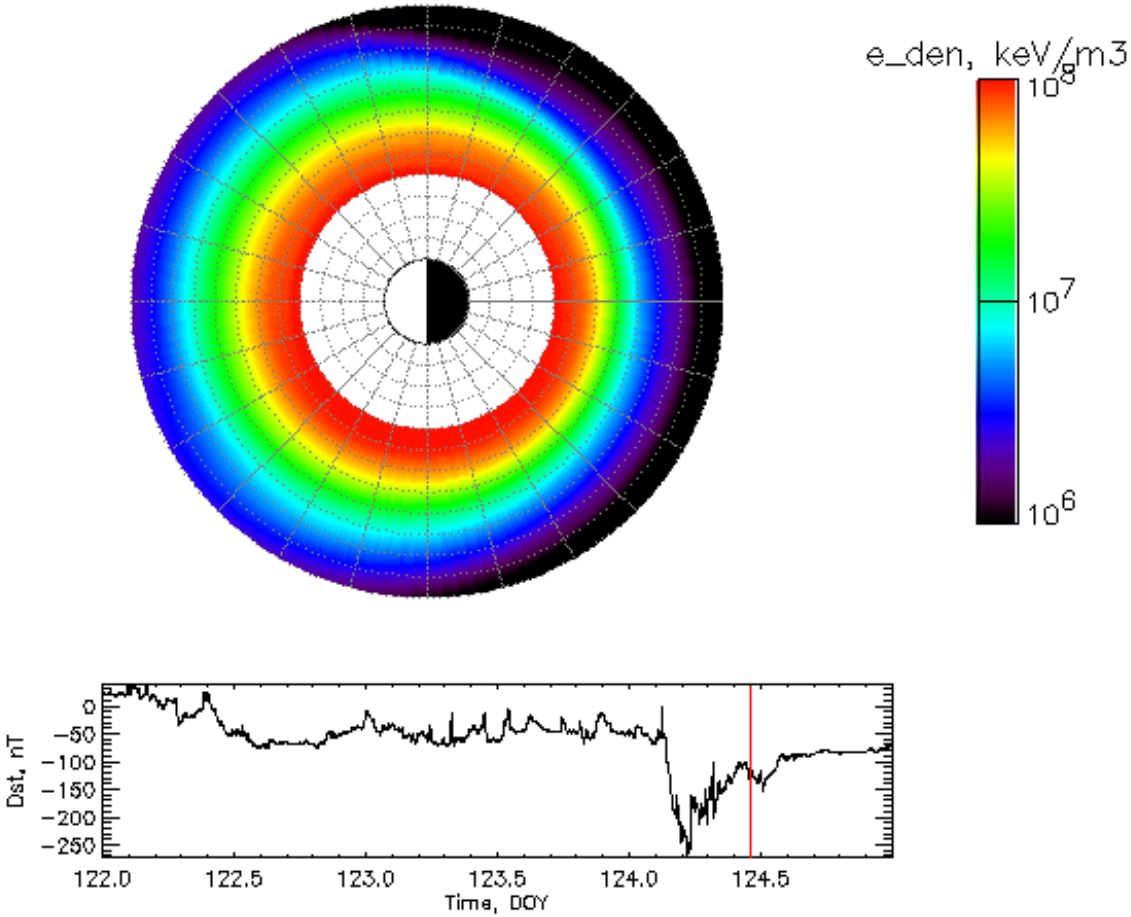

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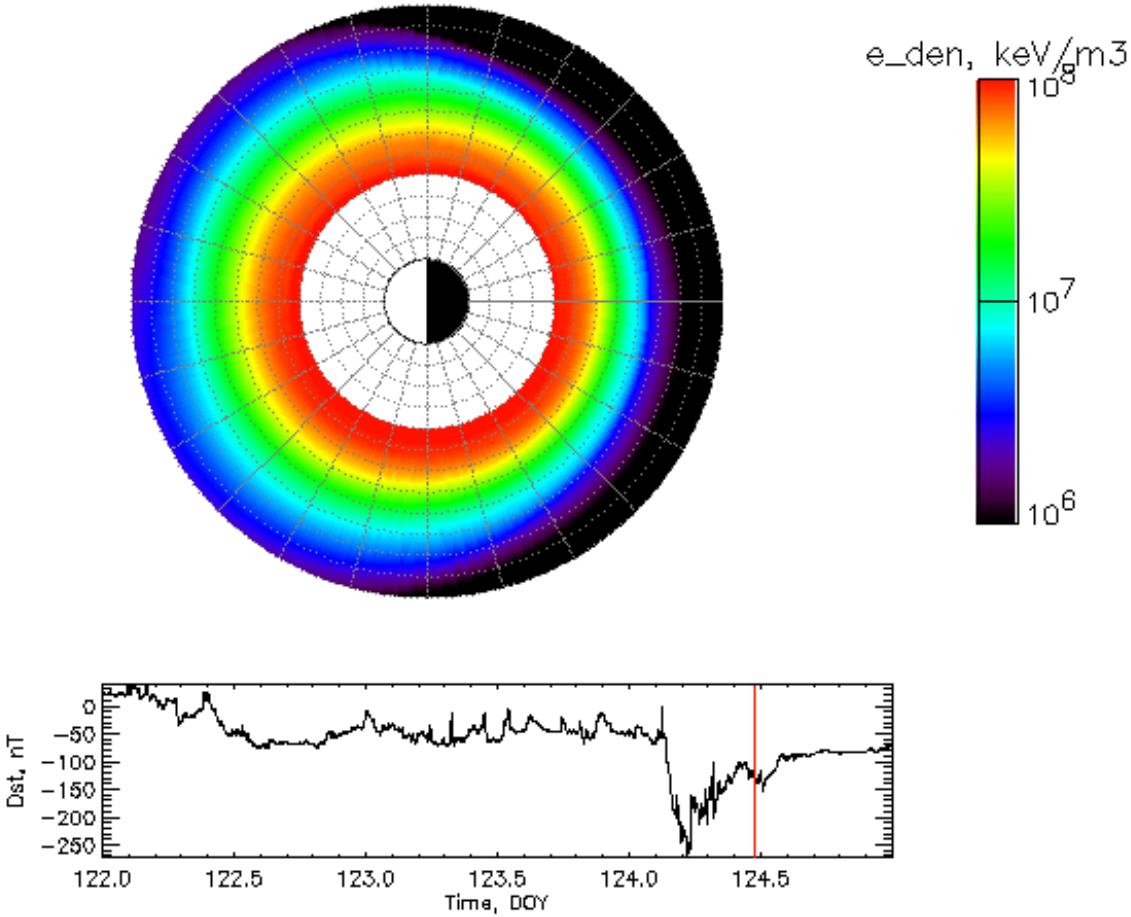

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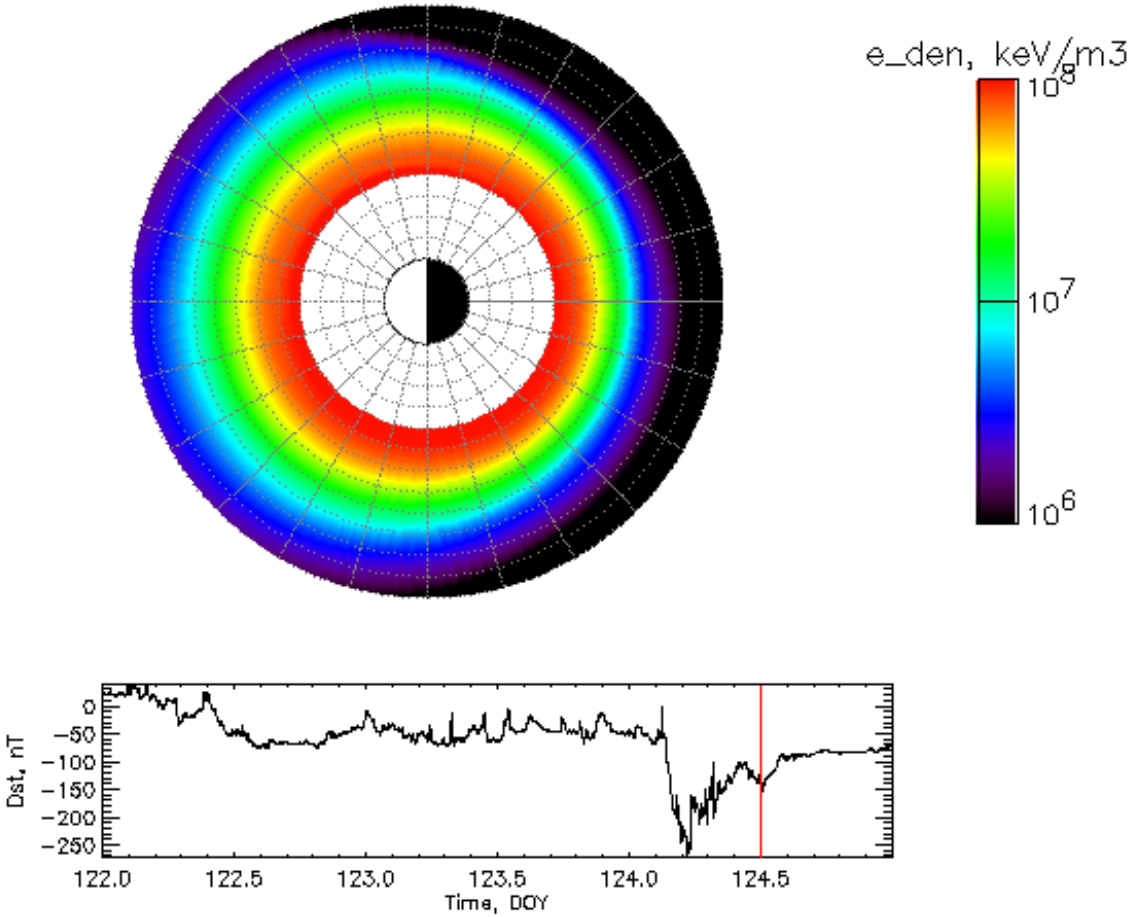

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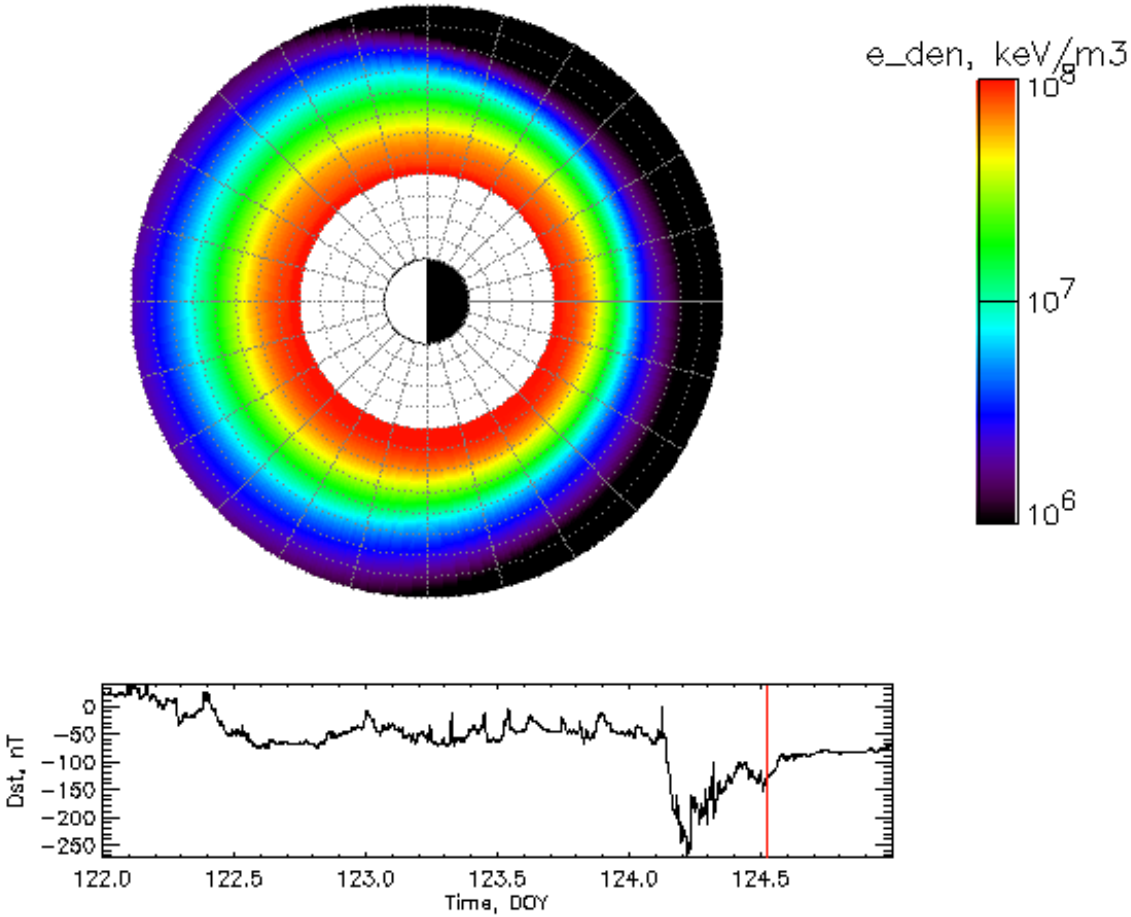

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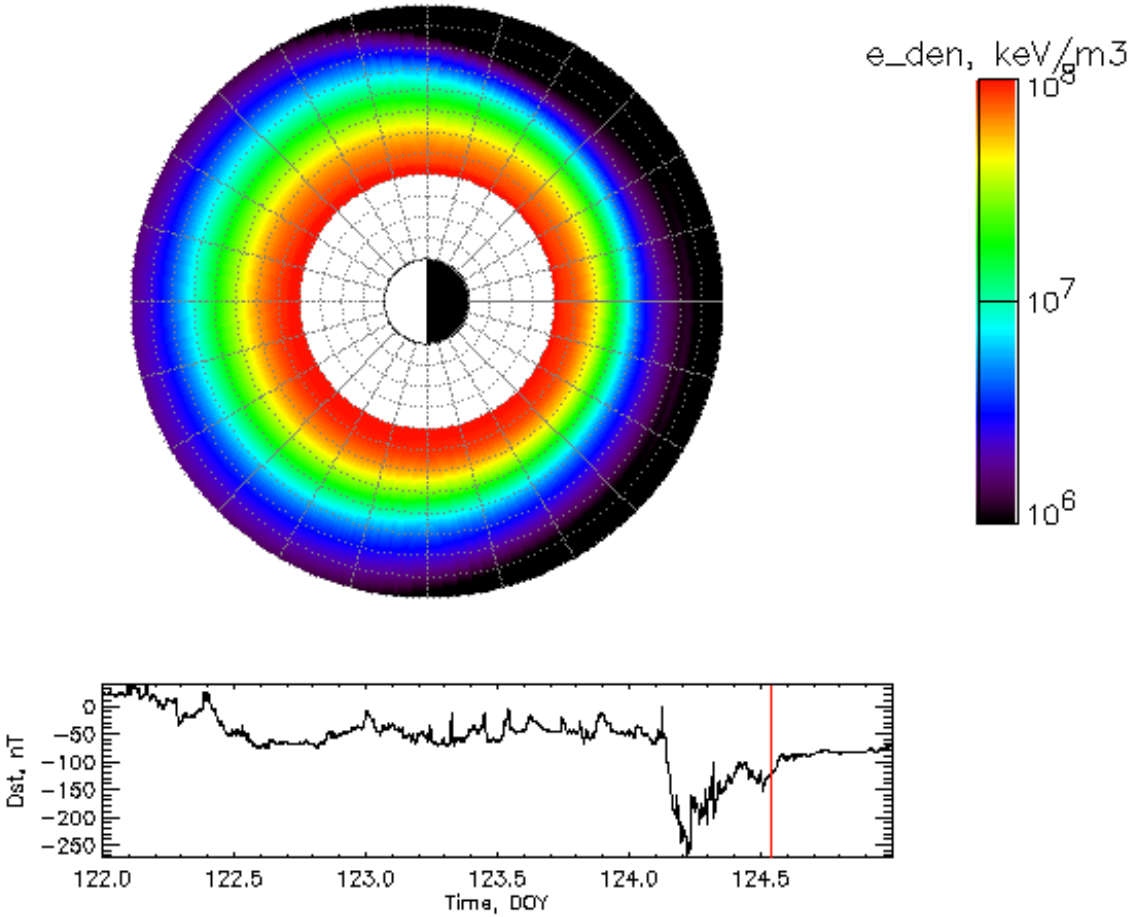

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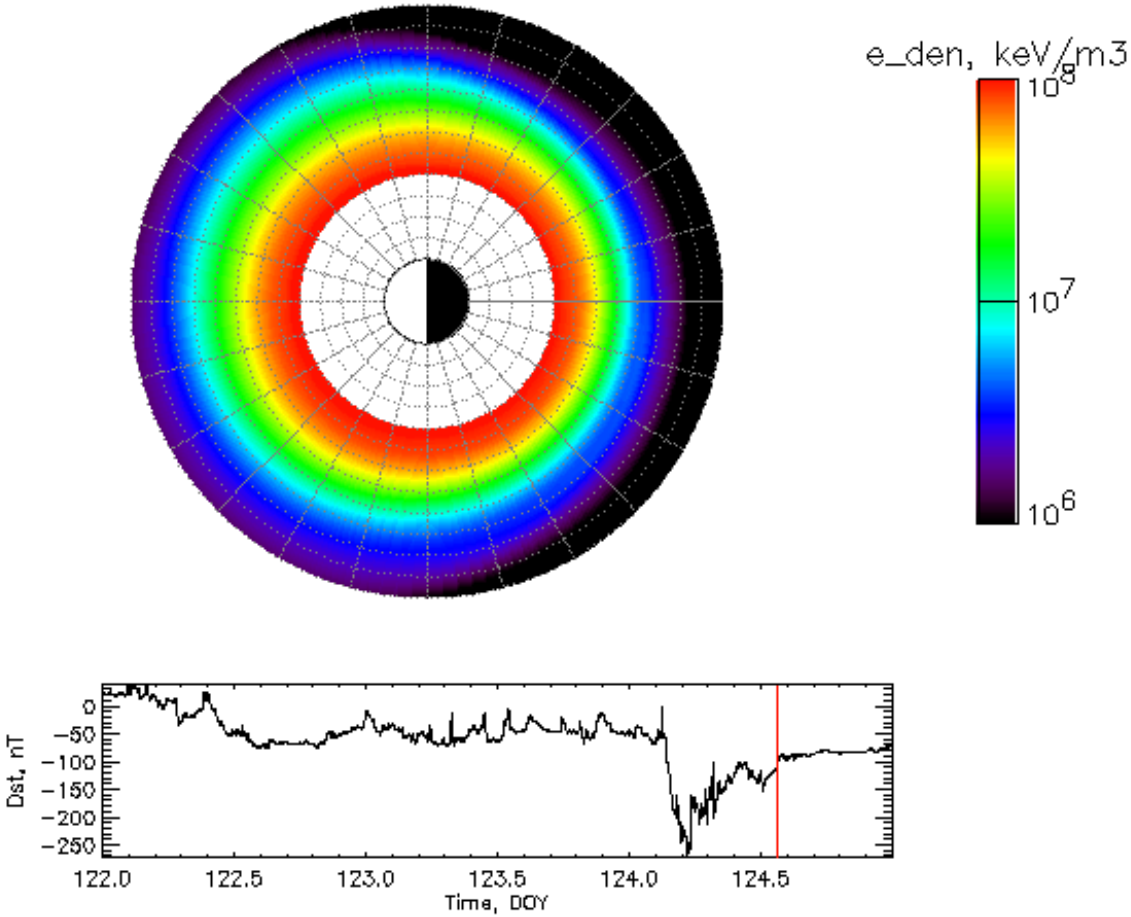

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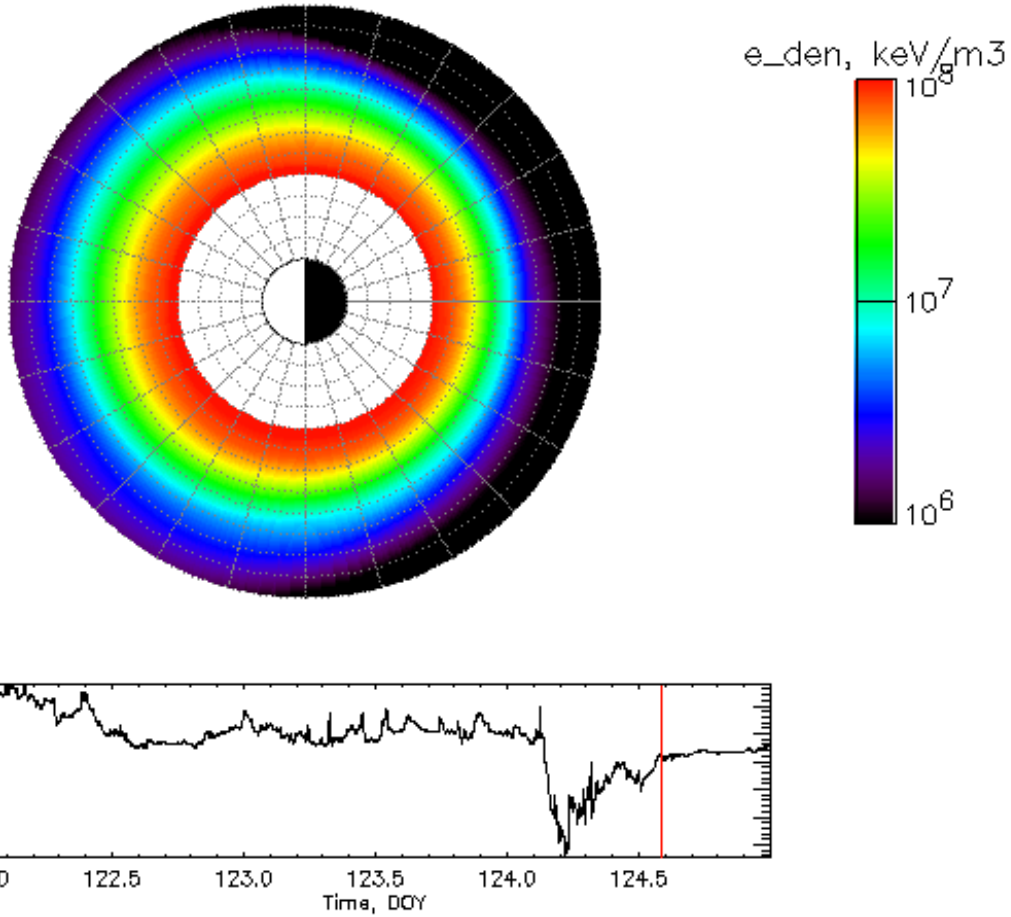

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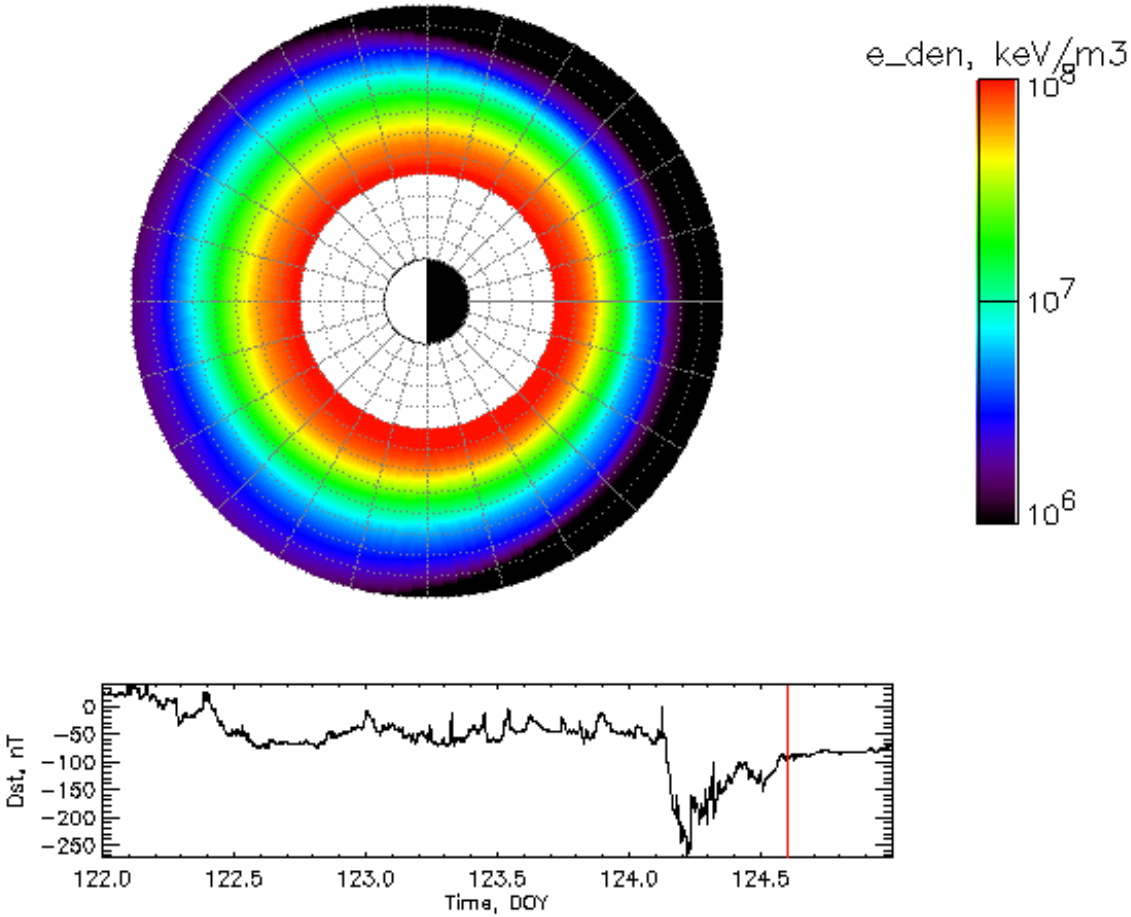

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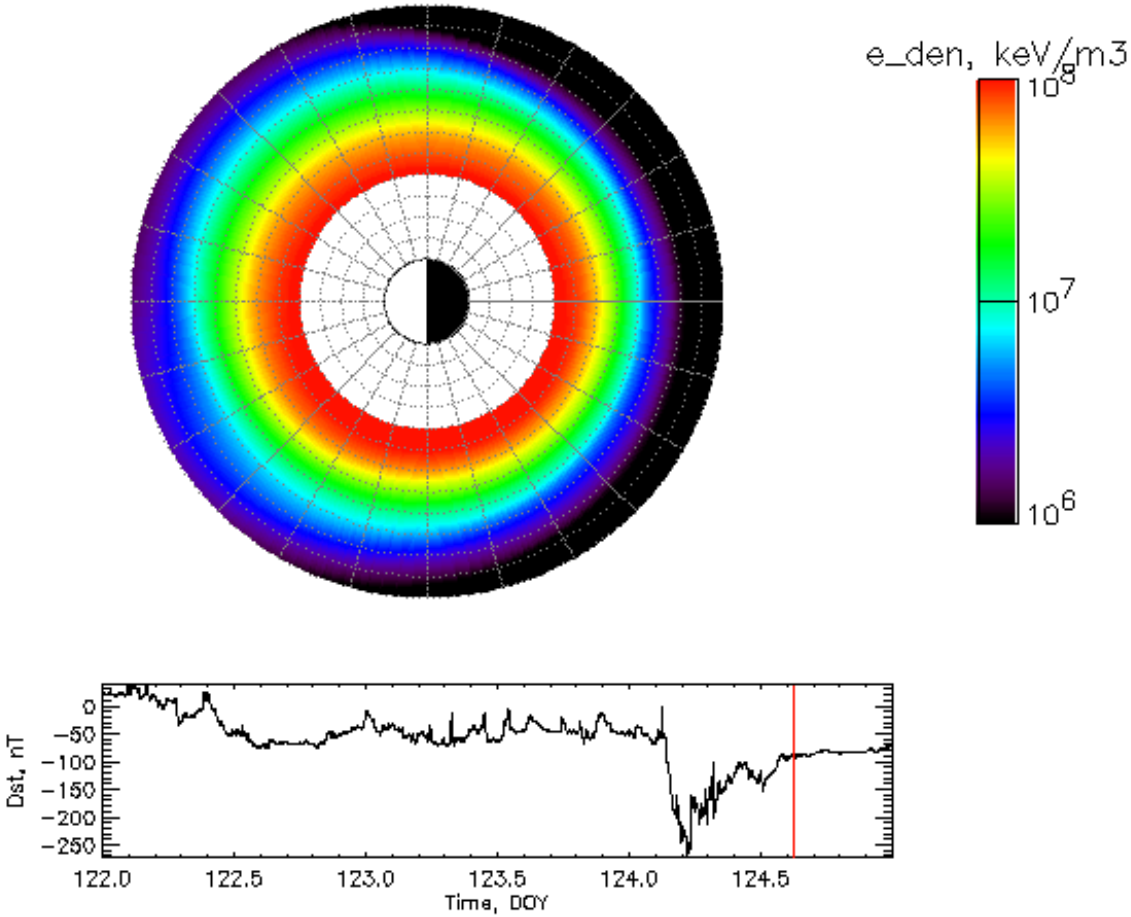

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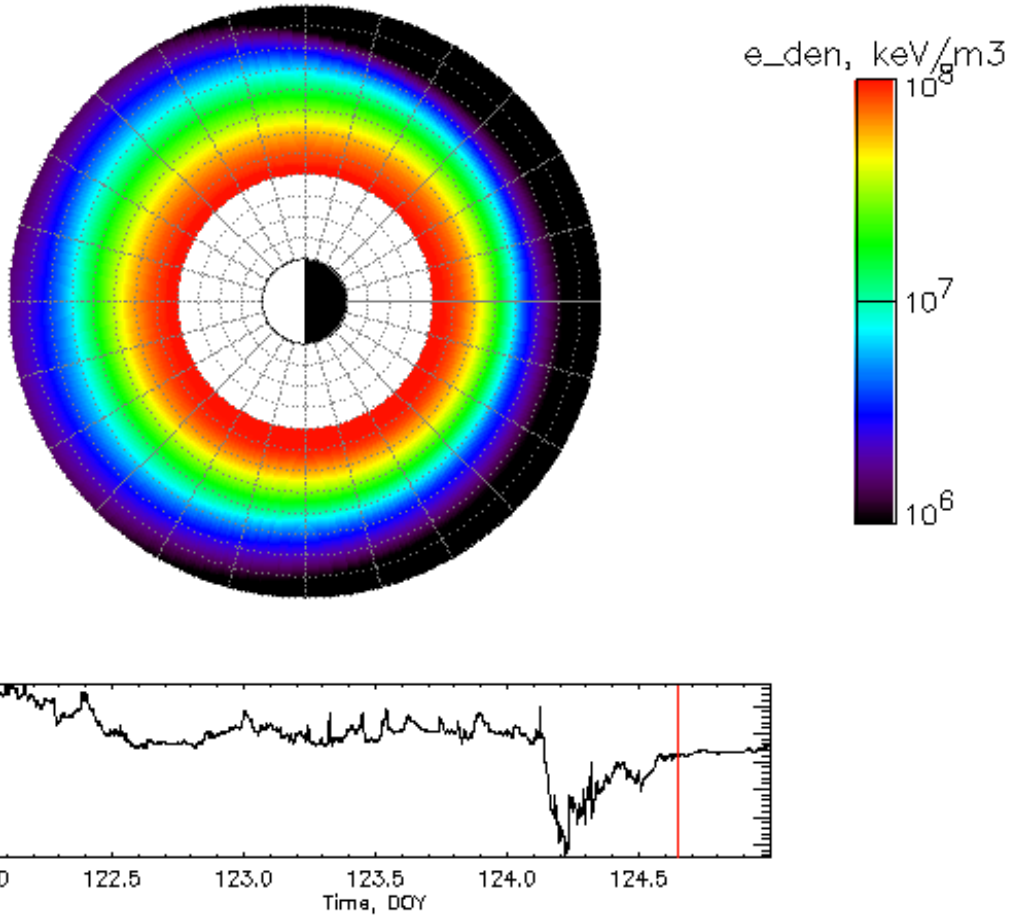

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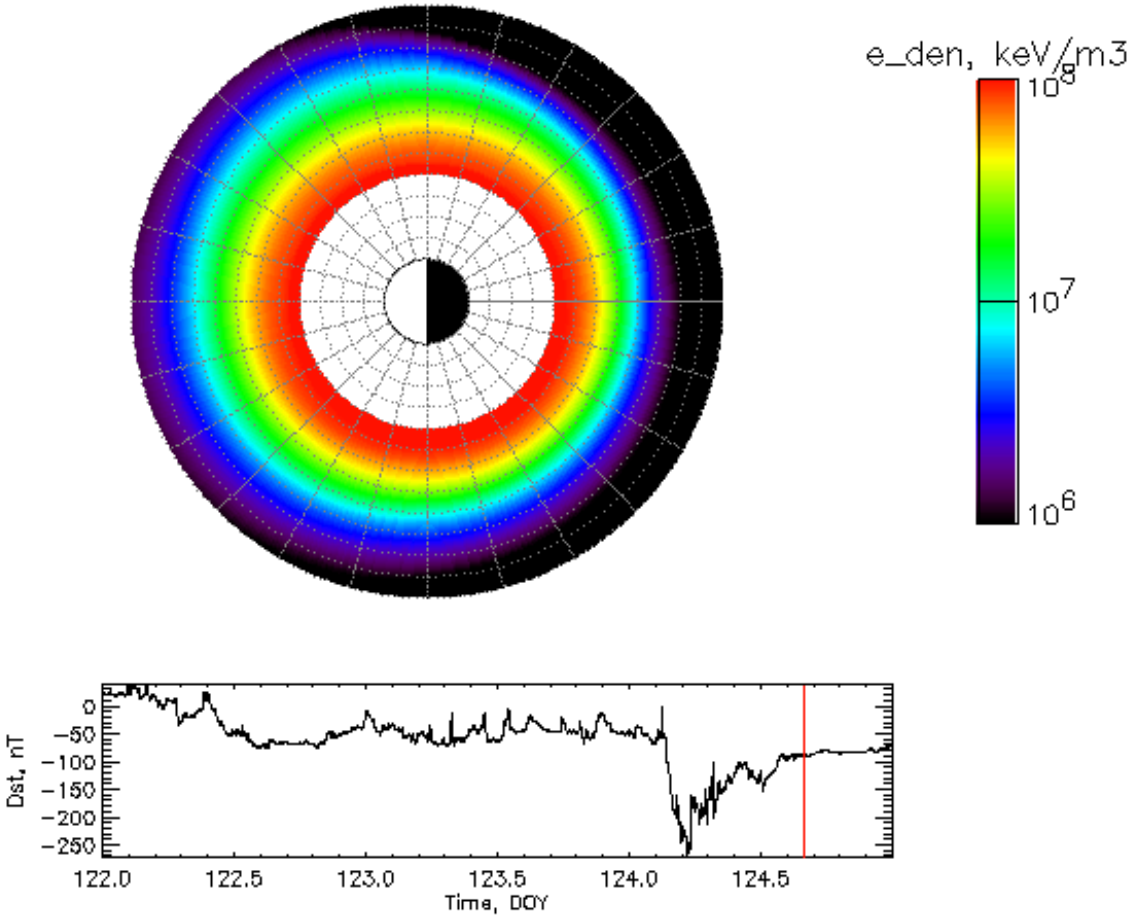

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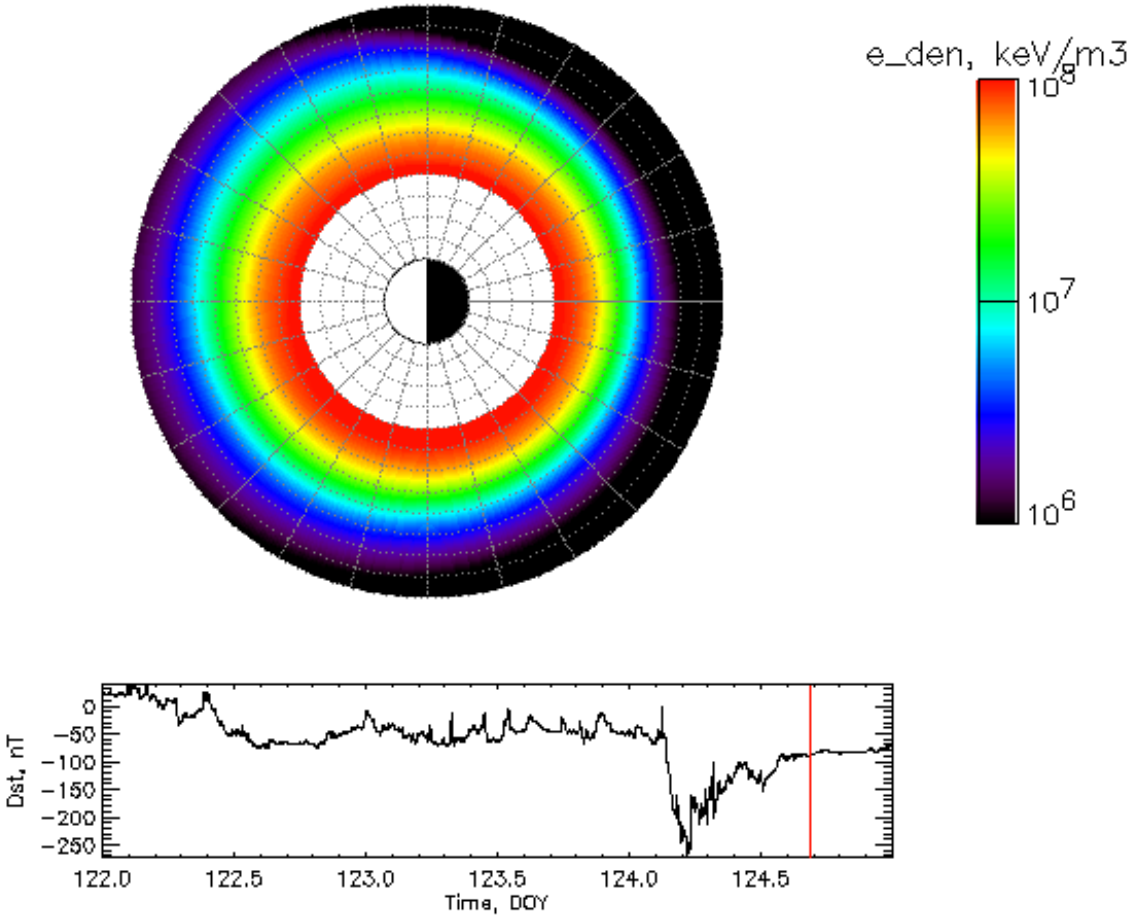

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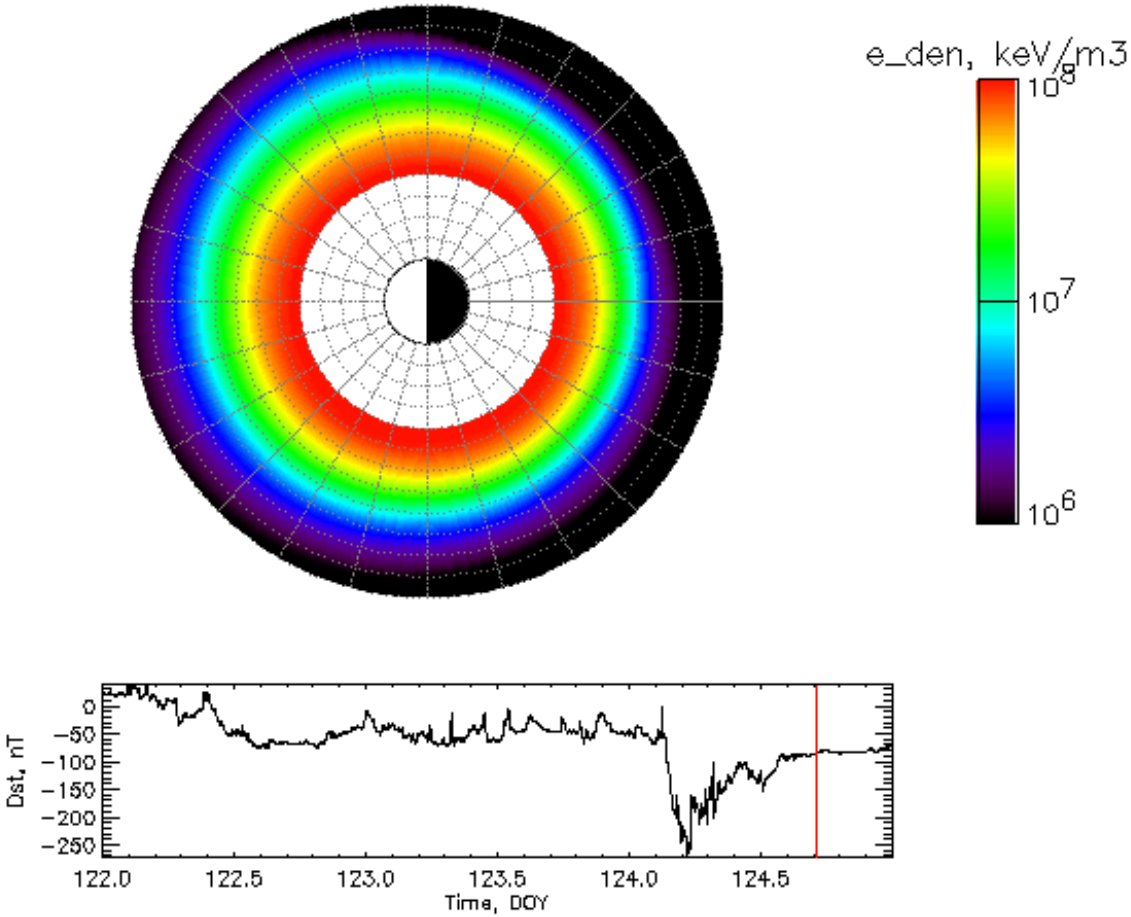

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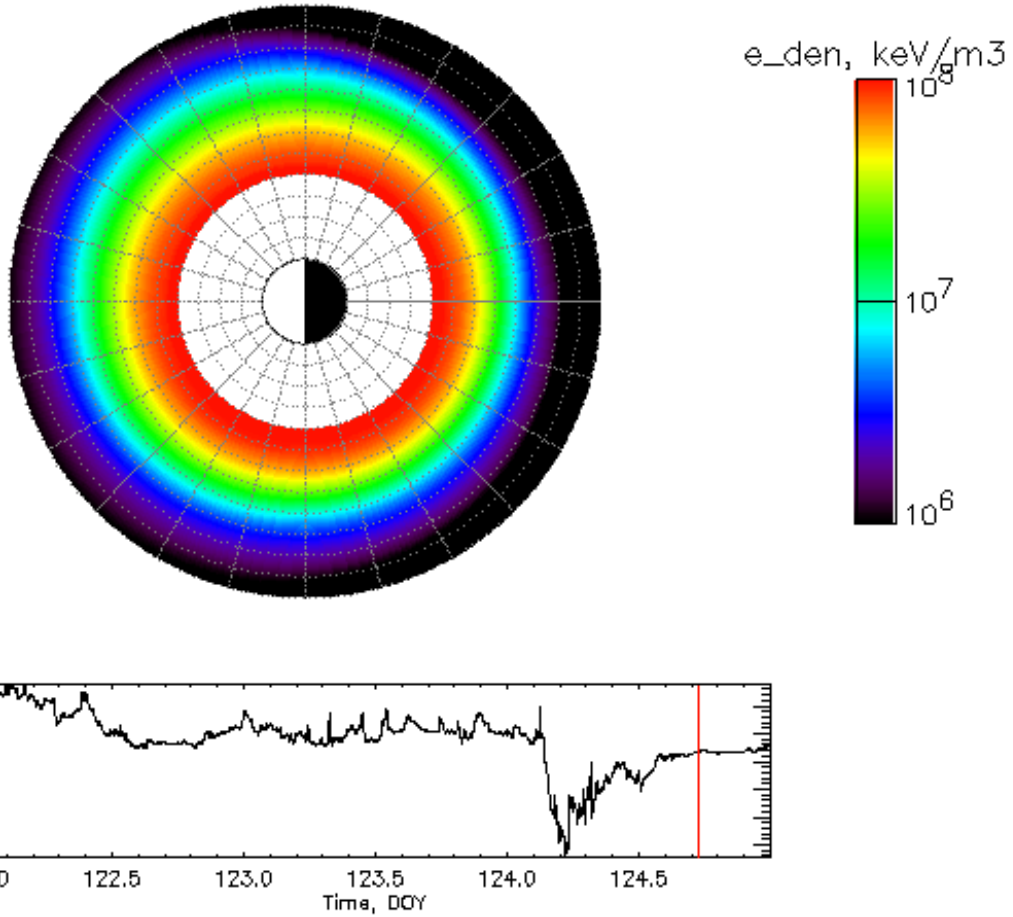

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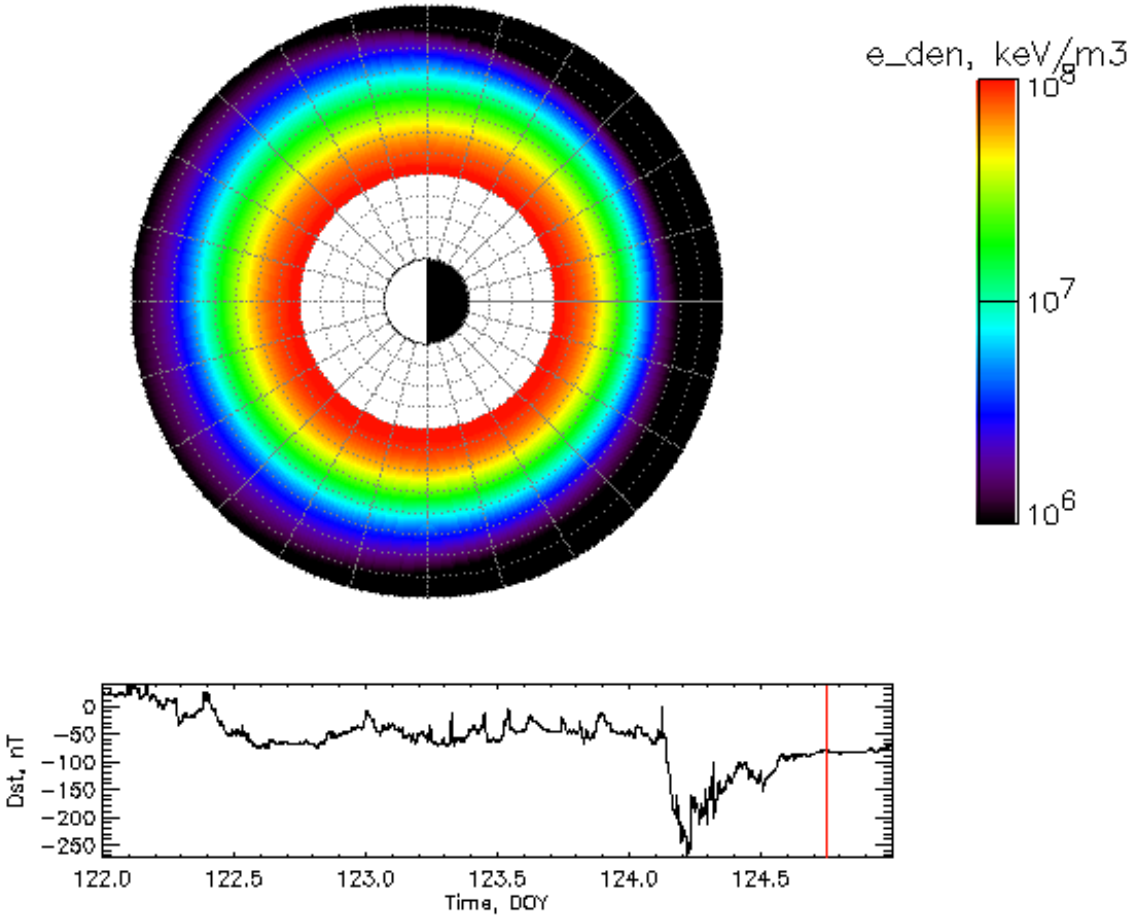

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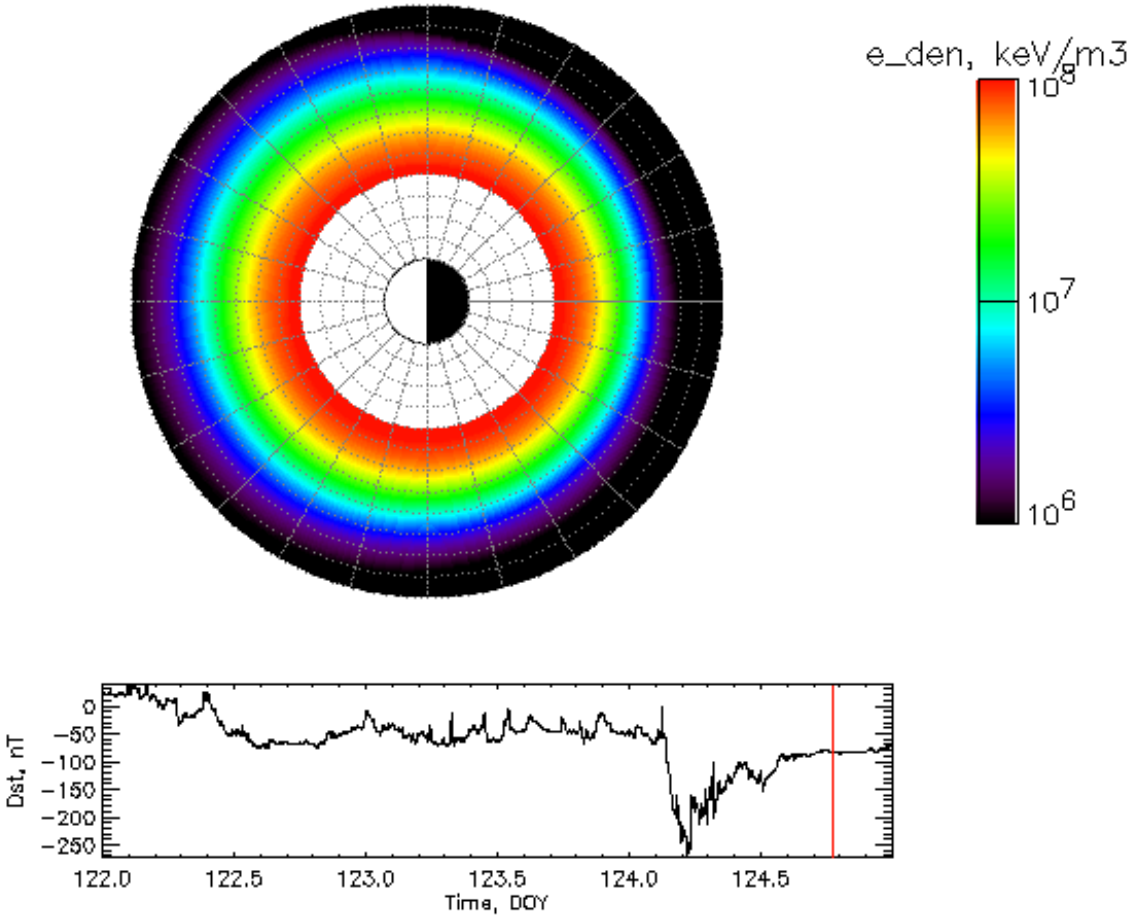

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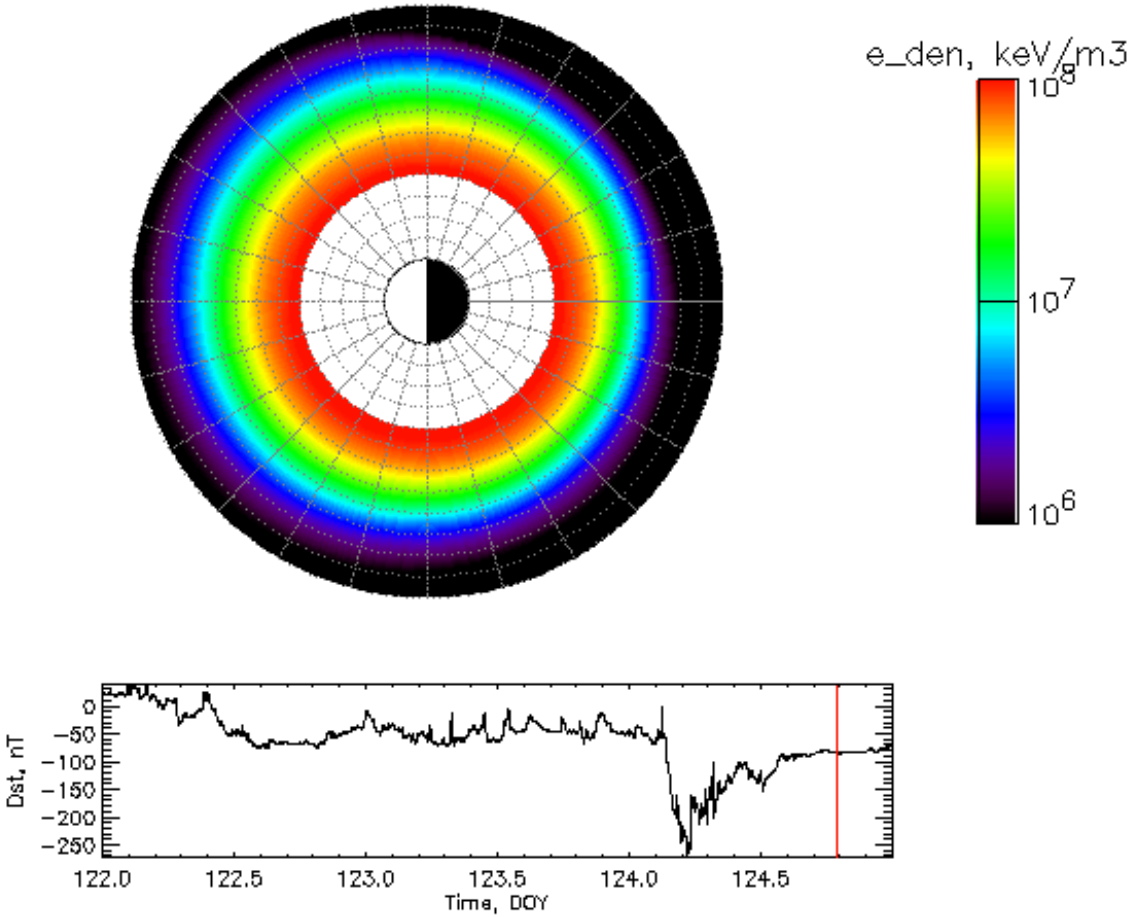

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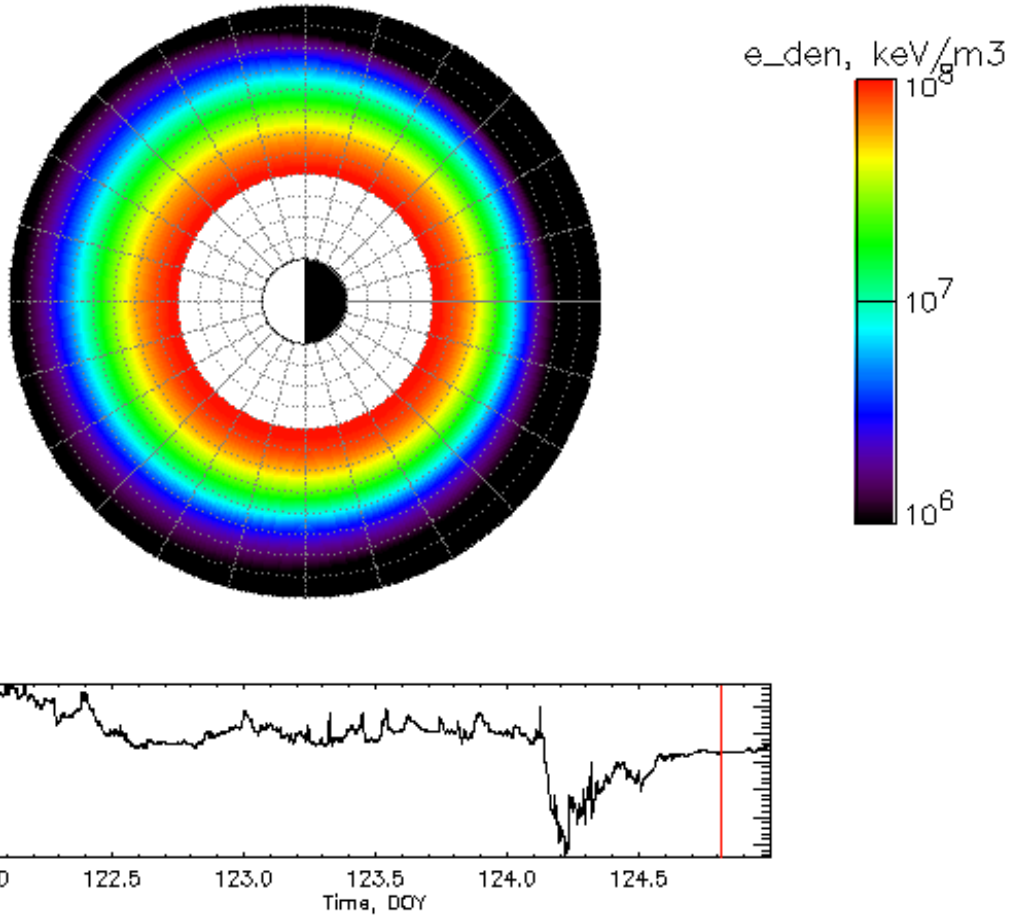

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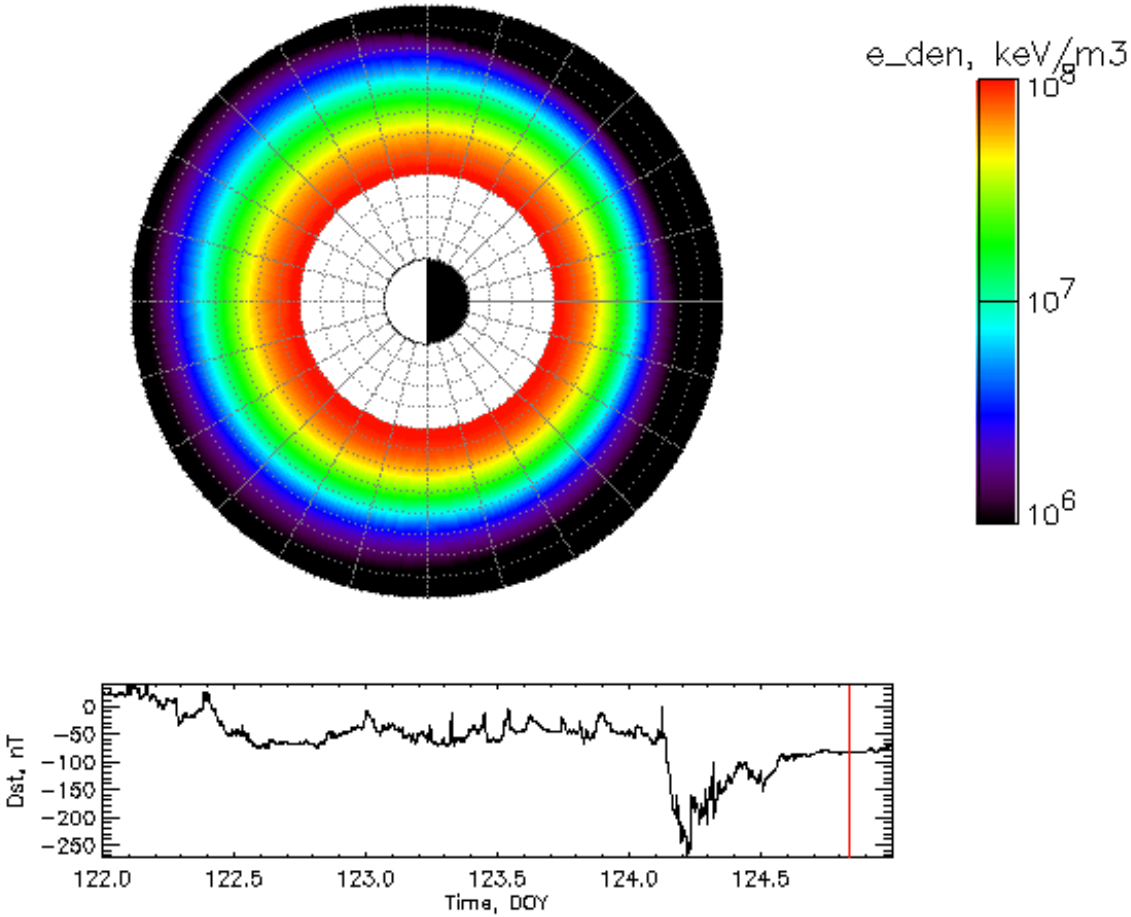

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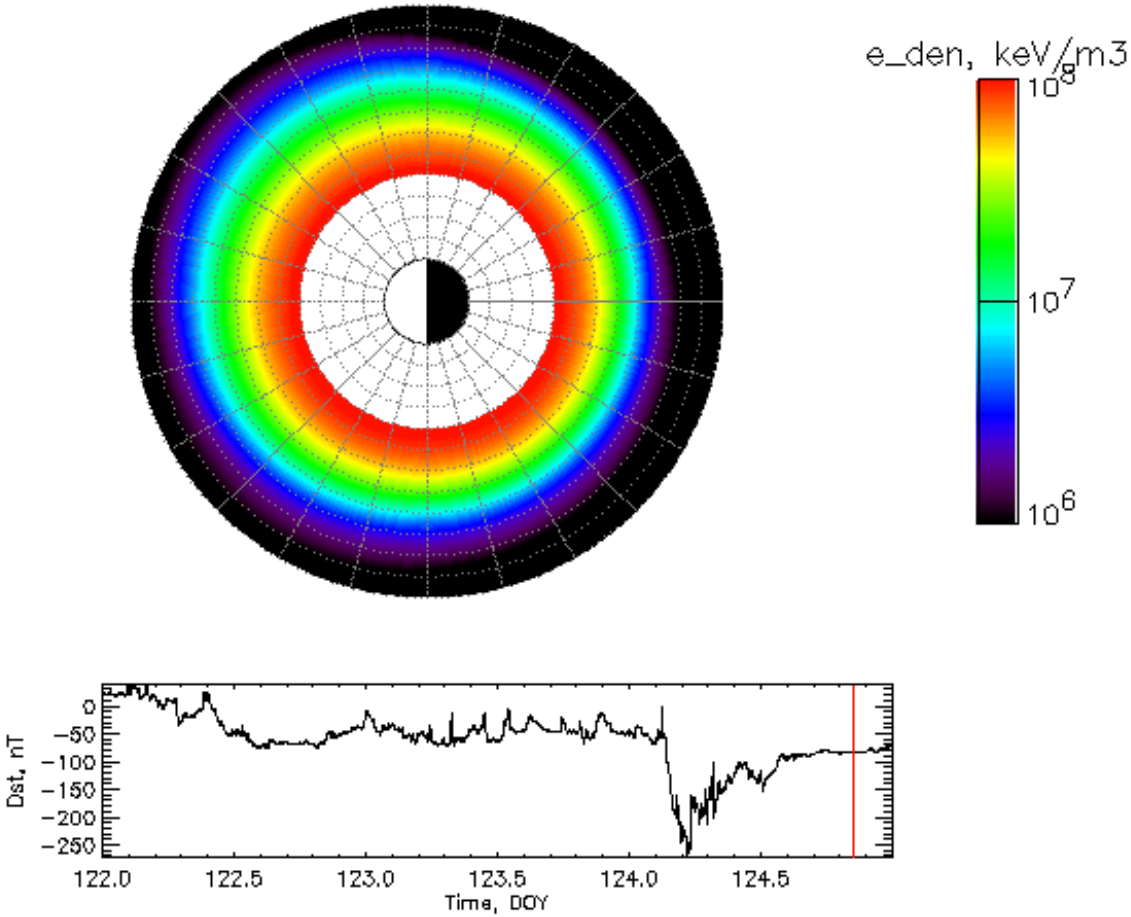

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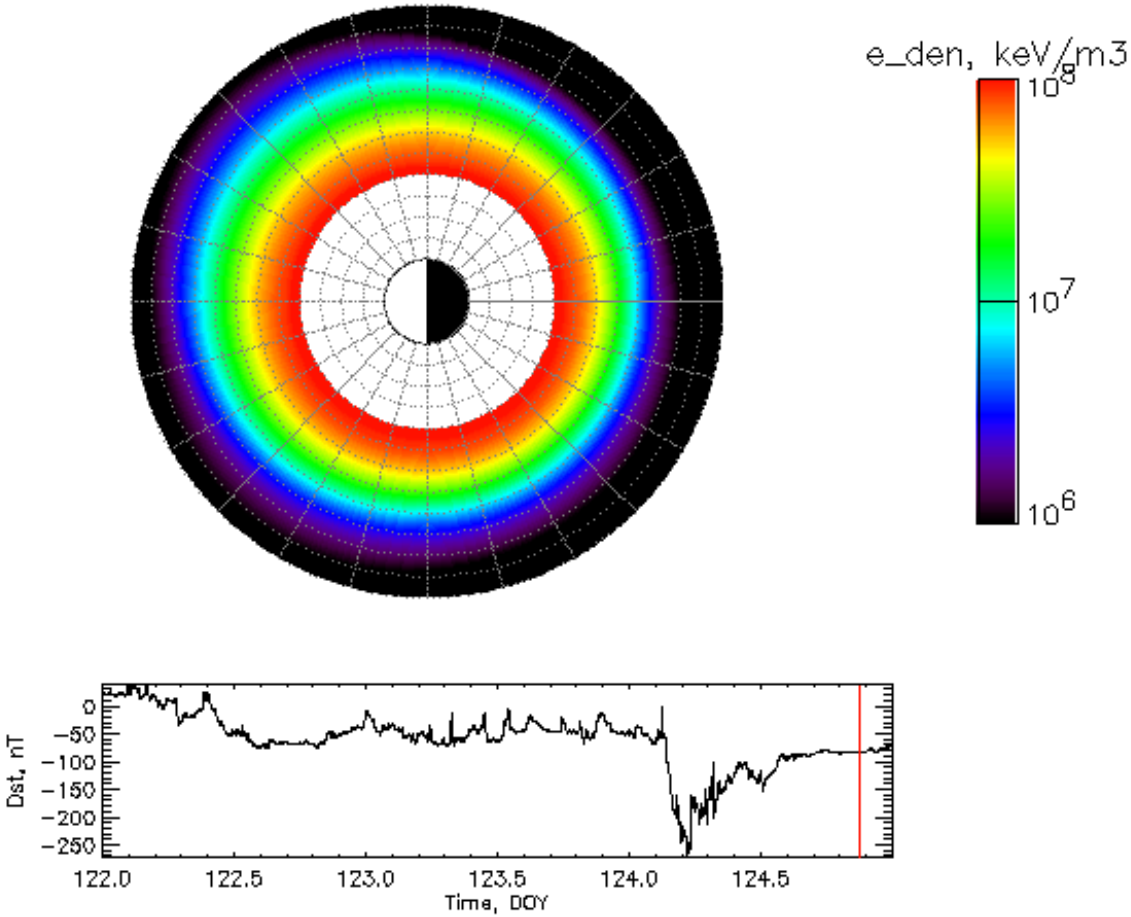

Inner Magnetosphere Particle Transport and Acceleration Model (IMPTAM)
Energy density,
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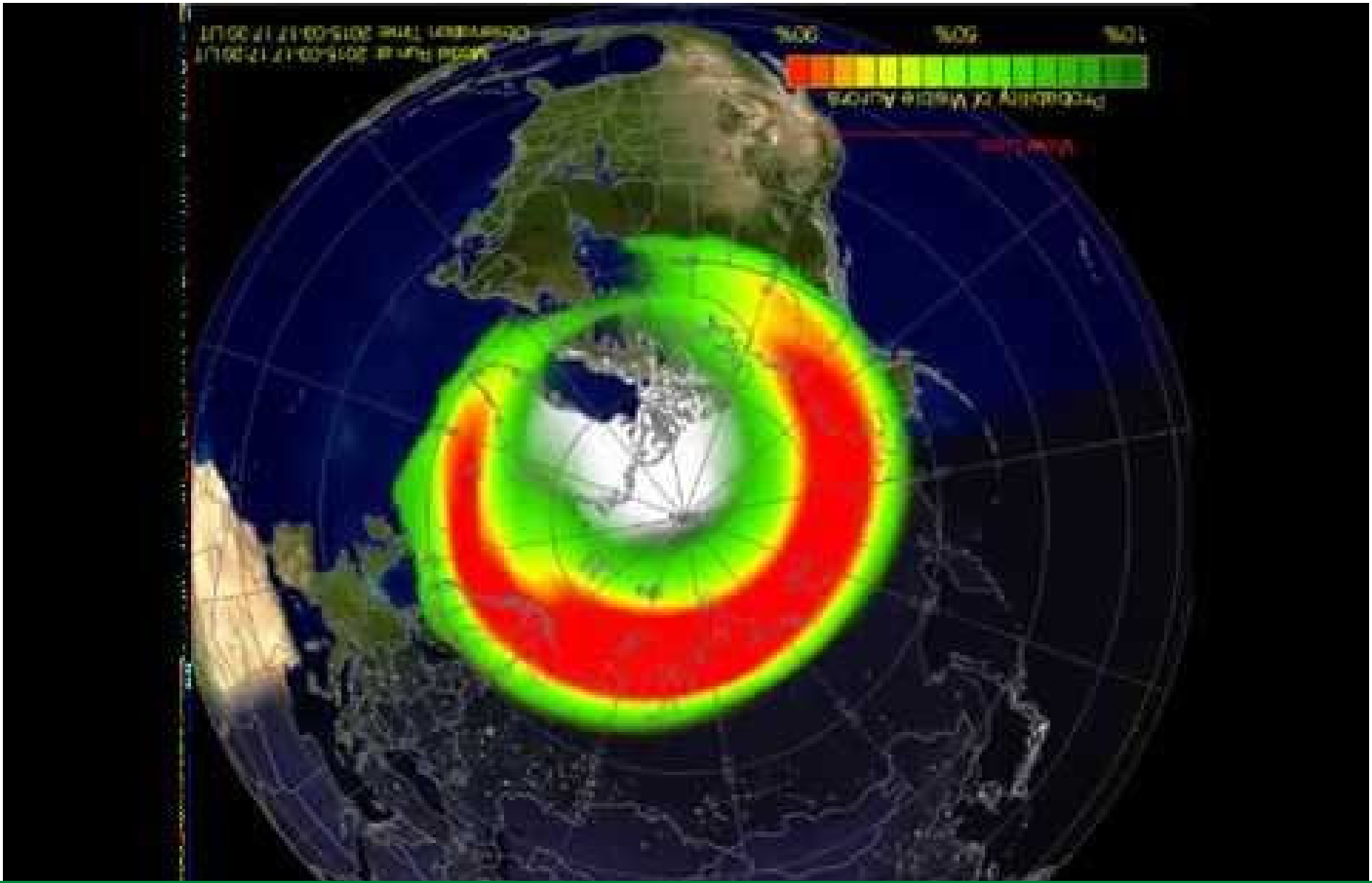
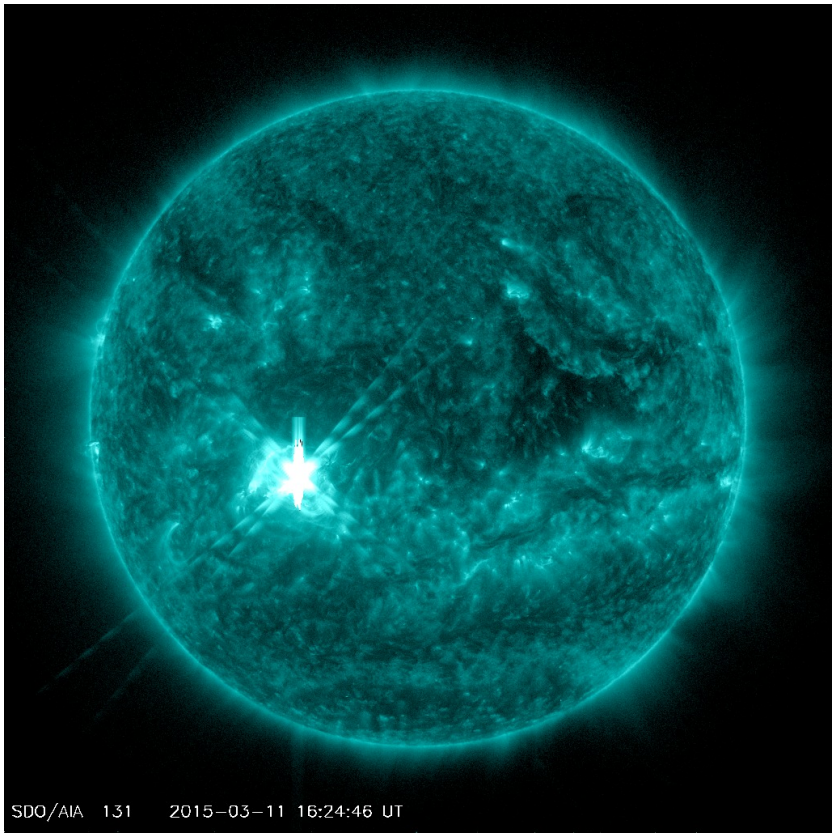
Aurora during magnetic storm

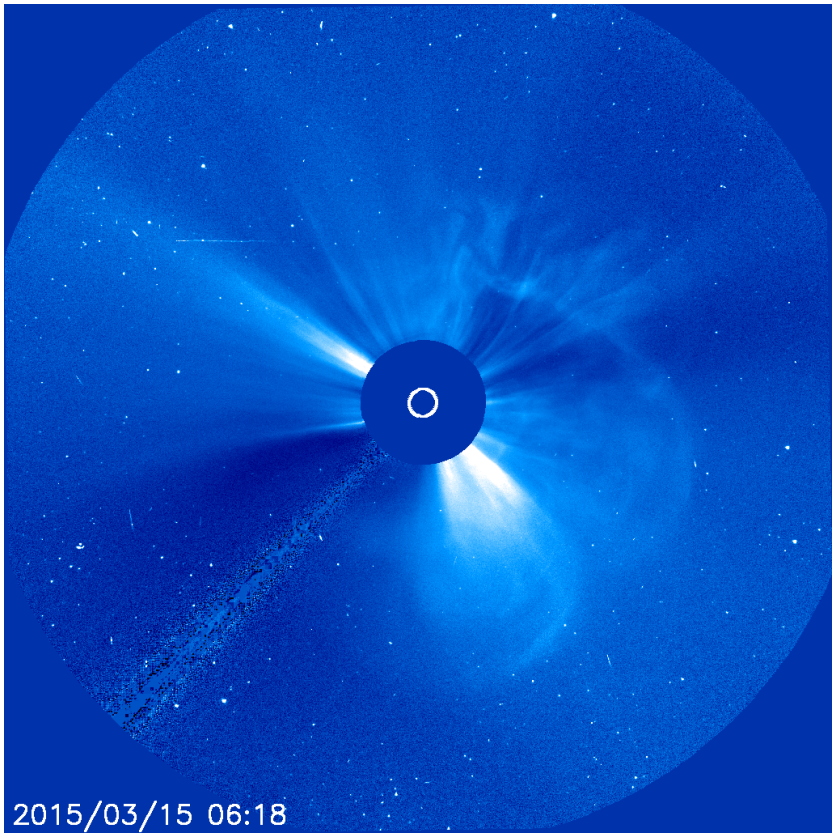


Magnetic storm: space weather preconditions

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.

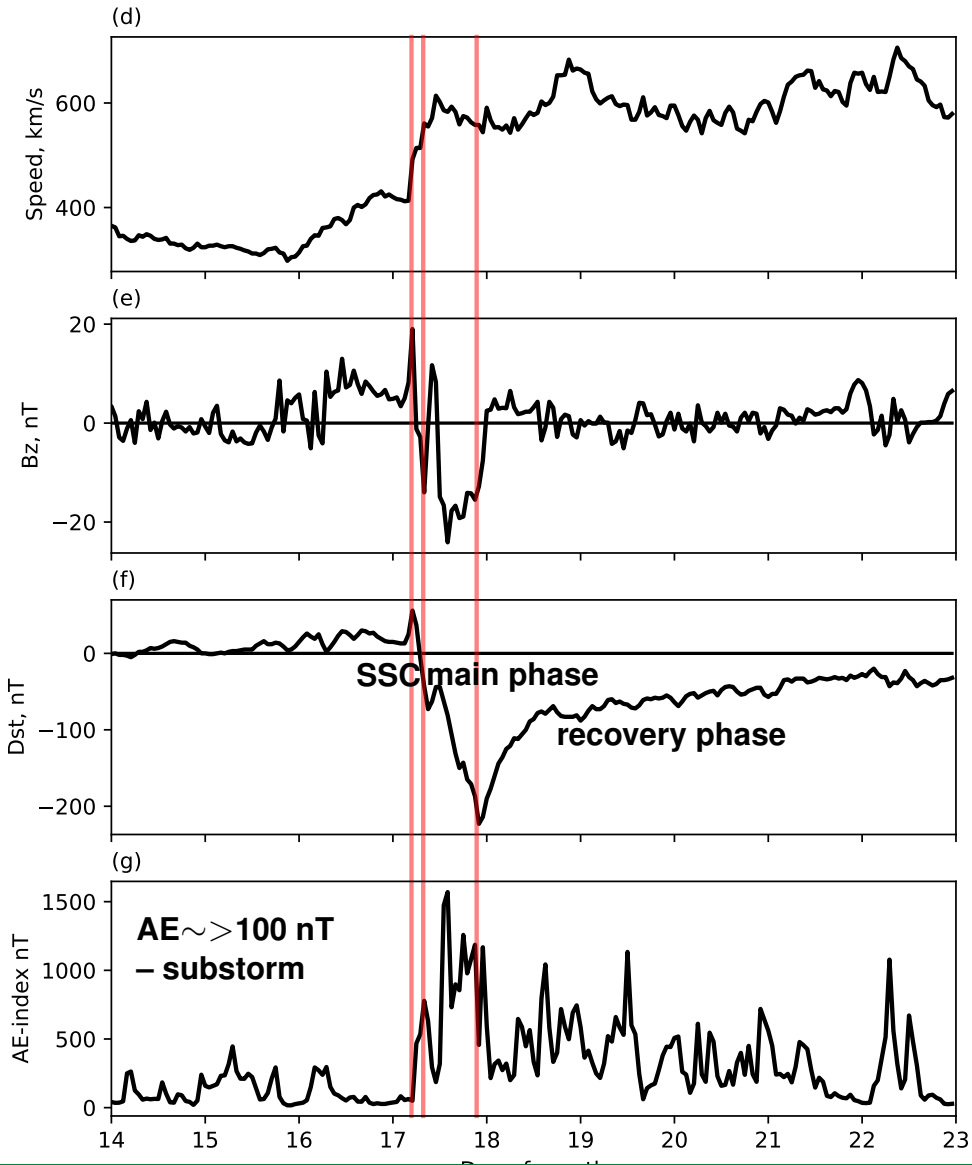




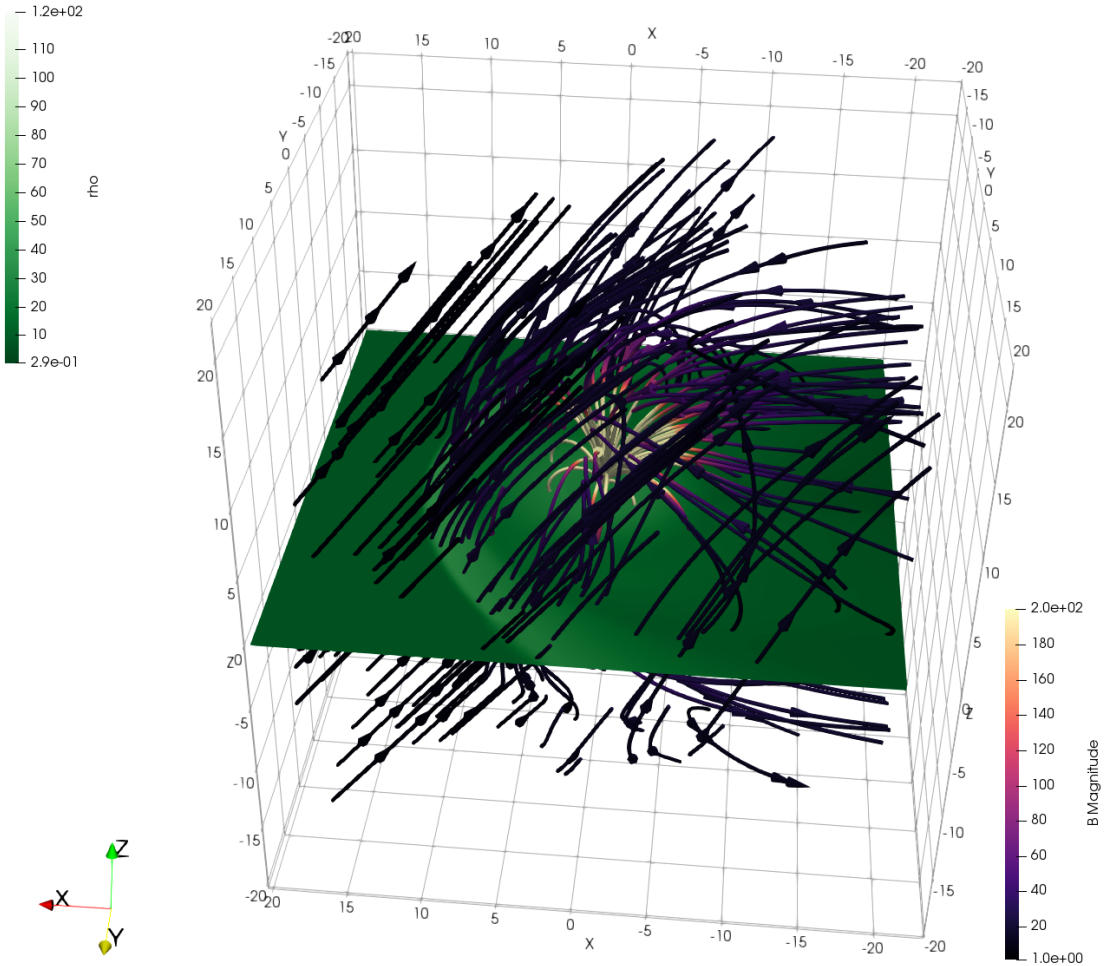
Magnetic storm: observations

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

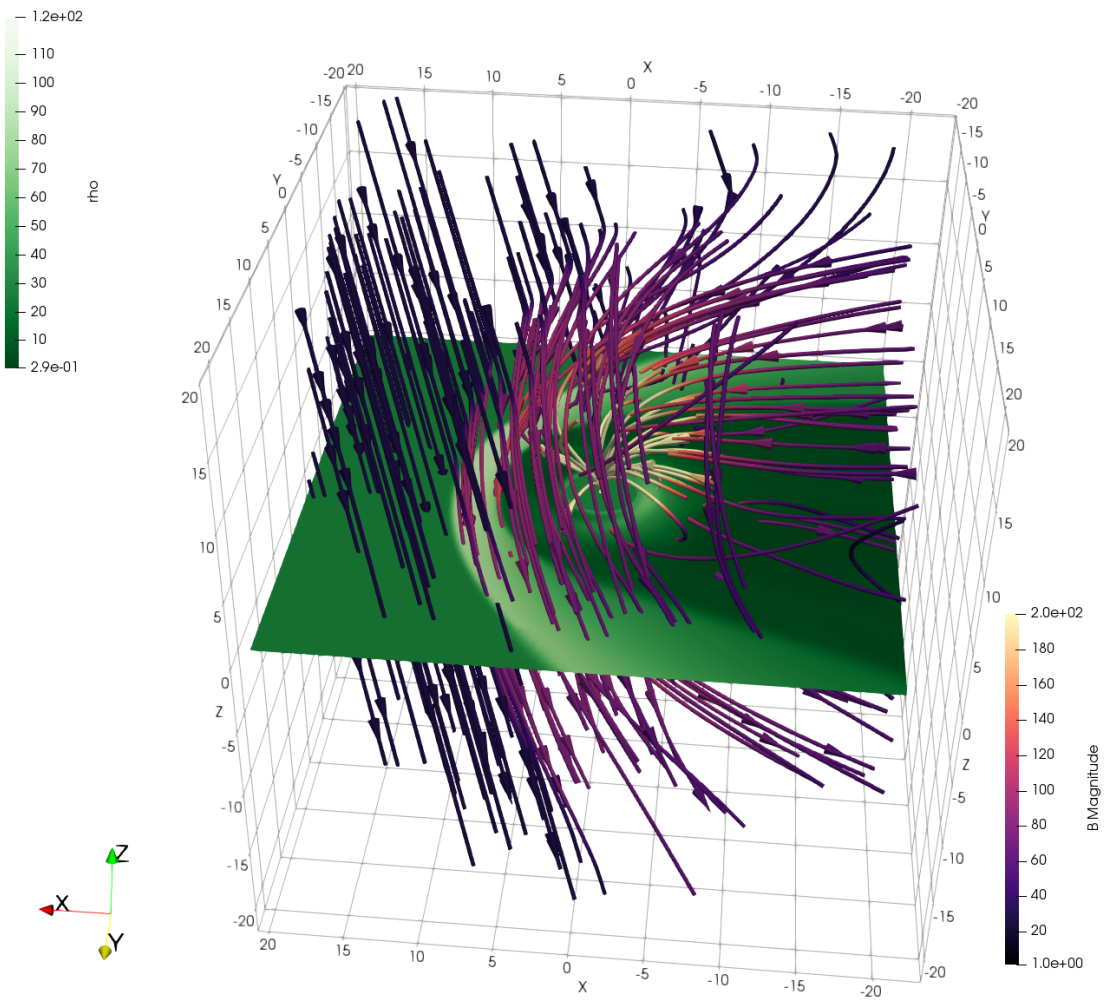


Magnetosphere: during northward IMF, 02:00 UT



Space Weather Modeling
Framework, data from R. Ilie

Magnetosphere: during southward IMF, 16:00 UT



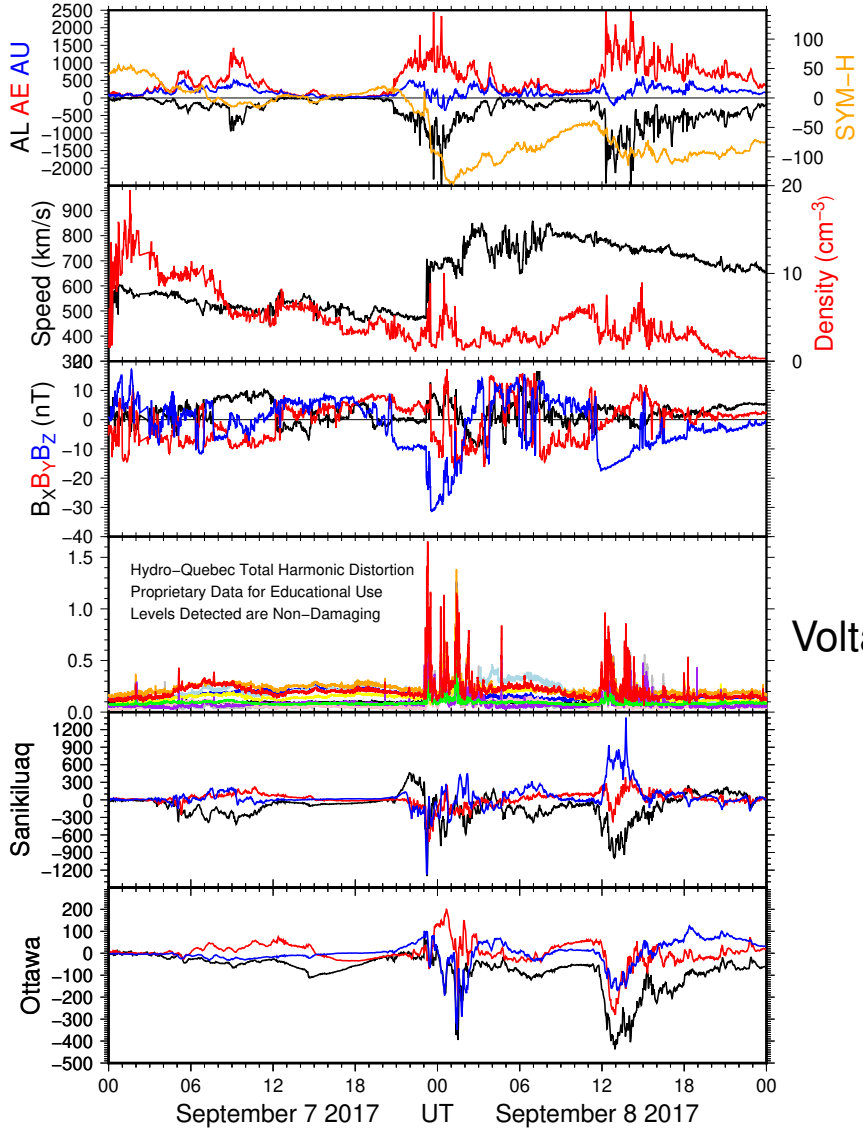
Space Weather Modeling Framework, data from R. Ilie

- During a prolongated 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

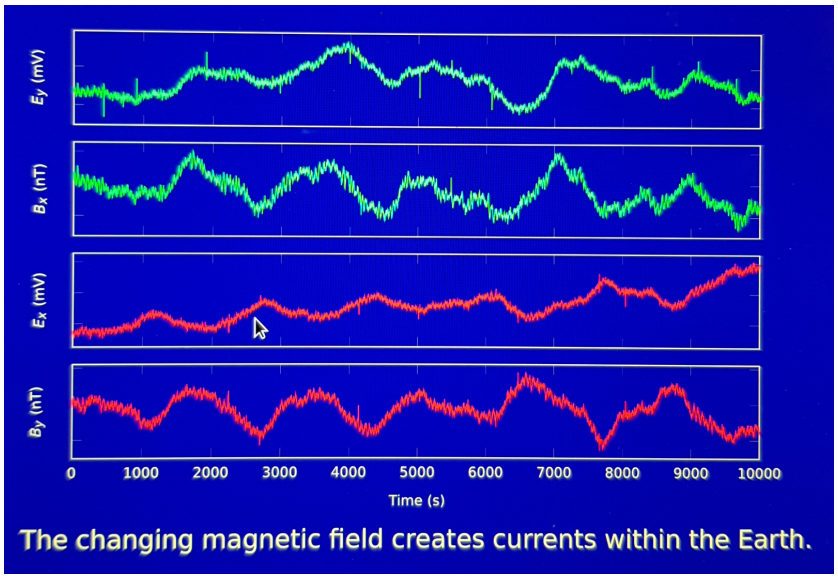
Credit: Martin Connors

Storm and GIC Sep 7–8 2017



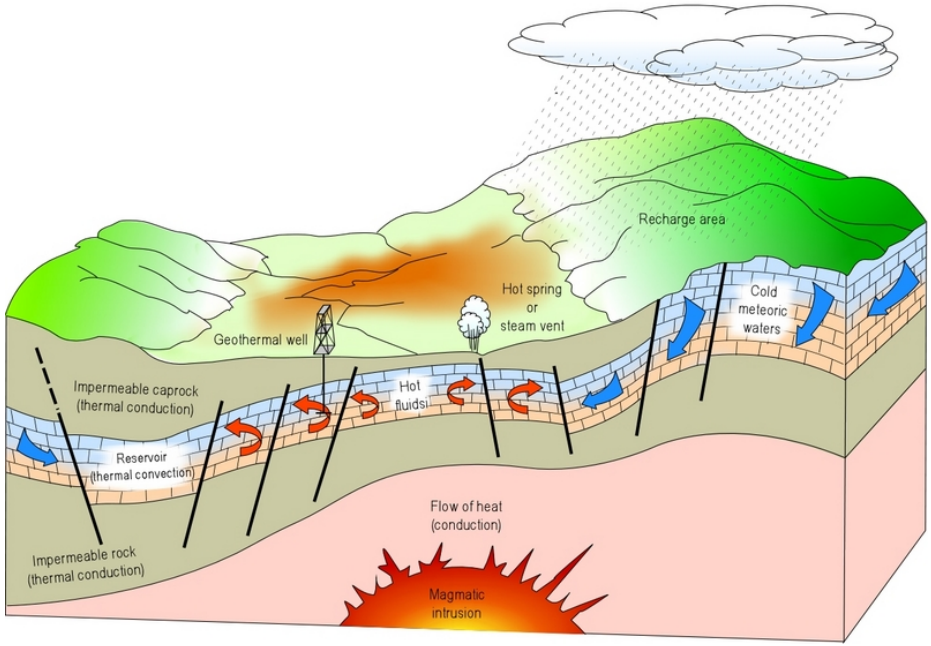
Voltage variation

Space Weather application: Investigation of conductivity



Credit: Max Moorkamp

Measuring in New Mexico



Taken from www.geothermal-energy.org

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.*

Literature

- 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