The Earth's Ring Current:
How much do we know about it?

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Terms and Definitions
The Sun- A Variable Star

- Sun is a magnetically active star. It supports a strong, changing magnetic field that varies year-to-year and reverses direction about every eleven years around solar maximum.
- The Sun's magnetic field leads to many effects that are collectively called solar activity, including sunspots on the surface of the Sun, solar flares, and variations in solar wind that carry material through the Solar System.
- Sunspots
- Solar Cycle

Solar Cycle Variations

[Graph showing solar irradiance variations from 1975 to 2005]
Solar Minimum and Maximum
Earth’s Magnetosphere

- Internal Source: In a first order approximation, the earth’s internal magnetic field can be approximated a tilted dipole. Fairly constant, at least in the time scales that we are interested in.

- External Sources: Currents in the magnetosphere. Highly variable depending on the state of the solar wind.

Tsyganenko1998
The ionosphere is a part of the upper atmosphere, comprising portions of the mesosphere, thermosphere and exosphere, distinguished because it is ionized by solar radiation.

- The D layer is the innermost layer, 60 km to 90 km above the surface of the Earth.
- Ultraviolet (UV), X-Ray and shorter wavelengths of solar radiation are ionizing, since photons at these frequencies contain sufficient energy to dislodge an electron from a neutral gas atom or molecule upon absorption.
- Ionization depends primarily on the Sun and its activity.

Earth’s atmosphere and ionosphere.
Contents

1. Space Weather.

2. Ring Current (Theory).

3. Enhancement of Ring Current during a geomagnetic storm.

4. Ring Current (Measurement).

5. Ring Current (Modeling).
1. Space weather
Space Weather: What is it?

Space Weather refers to conditions in space that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.

Sun:
• Energy released in the form of photons, particles, and magnetic fields

• Sources of major disturbances:
  • Coronal Holes
  • Solar Flares
  • Coronal Mass Ejections
  • Solar Particle Events
Solar Activity/Events

- Solar Flare is a localized explosive release of energy that appears as a sudden, short-lived brightening of an area in the chromosphere.

- Solar flares release their energy mainly in the form of electromagnetic radiation and energetic particles. (Video on the right.)

- CMEs is a massive burst of solar wind, other light isotope plasma, and magnetic fields rising above the solar corona or being released into space.

- CIRs are Solar wind fast streams emanating from solar coronal holes cause recurrent, moderate intensity geomagnetic activity at Earth. Intense magnetic field regions called Corotating Interaction Regions or CIRs are created by the interaction of fast streams with upstream slow streams.
Coronal Mass Ejections (CMEs)
Corotating Interaction Regions (CIRs)

Below: Fast Solar wind near the poles and slow wind close to the equator.

Top Figure: Coronal hole near the poles.
Sun to Earth

- A sequence of space weather event as it starts at the sun and ends up at Earth
  - Solar Flare
    - Light
    - Particles
  - CME/CIR
    - Particles and Fields
  - Magnetosphere
    - Deflects the solar wind
    - Energy transfer from solar wind to magnetosphere when interplanetary field opposite direction of Earth’s field
    - Accelerates particles
  - Ionosphere
    - Accelerated particles collide with the atmosphere producing the aurora
Examples of Concerns

The advent of new long range aircraft such as the A340-500/600, B777-300ER and B777-200LR

Next 6 Years:
Airlines operating China-US routes go from 4 to 9
Number of weekly flights from 54 to 249

Next 12 Years:
1.8 million polar route passengers by 2018

Global Positioning System

- Airborne Survey Data Collection: $50,000 per day
- Marine Seismic Data Collection: $80,000-$200,000 per day
- Offshore Oil Rig Operation: $300,000-$1,000,000 per day (Courtesy R. Barker)

GPS Global Production Value—expected growth:
2003 - $13 billion
2008 - $21.5 billion
2017 - $757 billion

Industrial Technology Research Institute (ITRI) – Mar 2005
Geomagnetically Induced Currents (GICs):

A time-varying magnetic field external to the Earth induces *telluric currents* -- electric currents in the conducting ground. These currents create a secondary (internal) magnetic field. As a consequence of *Faraday's law of induction*, an electric field at the surface of the Earth is induced associated with time variations of the magnetic field. The surface electric field causes electrical currents, known as geomagnetically induced currents (GIC), to flow in any conducting structure.

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \n\]
Geomagnetic Storm Effects
March 1989
Hydro Quebec Loses Electric Power for 9 Hours

Transformer Damage

Electric Power Transformer
Energetic Particle Effects
High Latitude HF Communications
Polar airline routes loose ground communications

- Alternate routes required
- Uses more fuel
- Flight delays

Sample of Flights Affected:
- 10/26/00: Lost of HF prior to 75N, re-route off Polar route with Tokyo fuel stop. 15:00 flight now 20:30
- 11/10/00: Due to poor HF, ORD to HKG flown non-polar at 47 minute penalty
- 3/30/01-4/21/01: 25 flights operated on less than optimum polar routes due to HF disturbances resulting in time penalties ranging from 6 to 48 minutes
- 11/25/00: Polar flight re-route at 75N due to Solar Radiation, needed Tokyo fuel stop
- 11/26/00: Operated non-polar at 37 minute penalty due to solar radiation
- 11/27/00: Operated non-polar at 32 minute penalty due to solar radiation.
- 11/28/00: Operated non-polar at 35 minute penalty due to solar radiation
Cosmic Ray and Solar Proton Radiation Effects on Airline

ACREM Measurements during GLE60 on 15. April 2001
10 h 25 min

Latitude in Degrees

Dose Equivalent Rate in μSv/h
NM Moscow % deviation

- Moscow Neutron Monitor (5min)
- ACREM (5min)
- ACREM (30s)
- Altitude

ACREM: 59.9 μSv
EPCARD (without GLE): H*(10)=42.0 μSv; E=49.4 μSv

Time in UTC

Dr. Peter Beck

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Health Hazards from Energetic Particles

• Humans in space
  – Space Shuttle, International Space Station, missions to Mars
• Crew/Passengers in high-flying jets
  – Concorde carries radiation detectors
  – Exposure limits set for European flight crews
Energetic Particle Effects: Spacecraft Systems

- **Systems affected**
  - Spacecraft electronics
    - Surface Charging and Discharge
    - Single Event Upsets (SEU)
    - Deep Dielectric Charging
    - USAF attributes 35% of SEU to space weather
  - Spacecraft imaging and attitude systems
2. Ring Current (Theory)
Earth’s Radiation Belts:

- Radiation belts comprise energetic charged particles trapped by the Earth’s magnetic field. (from keV to MeV).

- A given field line is described by its L value (radial location, in R_E, of its intersection with magnetic equator).

- **Inner belt region:**
  - Located at L~1.5-2. R_E
  - Contains electrons, high energy protons, and ions.
  - Very stable.

- **Outer belt region:**
  - Located at L~3-6.
  - Contains electrons and ions.
  - Very dynamic.
The Ring Current

- Collection of charged particles that drift around the Earth at a distance from about 2 to 8 Earth radii at magnetic equator
- Composed of free electrons and ions (mainly H\(^+\) and O\(^+\)) in the few keV to few hundred keV energy range
- Due to geometry of Earth’s magnetic field, ions travel westward and electrons travel eastward
- Charge separation and movement result in southward magnetic field at the equator on the Earth’s surface (can be measured by magnetometers; \(D_{st}\) is most commonly used index)
The ring current is carried by 80% of ions and 20% of electrons.

We can neglect the gyromotion and the bounce motion if the first two invariants are conserved.
Single particle motion basics:

$$\frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) + \vec{F}_{\text{non-EM}}$$  \quad \text{Newton’s second law.}

$$\vec{p} = mv$$

For uniform Electrostatic field

$$\vec{a} = \frac{qE}{m}$$

Uniform B field ($E = 0$)

$$m \frac{d\vec{v}}{dt} \cdot \vec{v} = \frac{d}{dt} \left( \frac{mv^2}{2} \right) = 0$$

B is uniform, then $u_z$ is constant; taking the second derivative yields:

$$\ddot{v}_x = -\omega_g^2 v_x$$
$$\ddot{v}_y = -\omega_g^2 v_y$$

With parallel velocity, the motion becomes a helix.

$$x - x_0 = r_g \sin \omega_gt$$
$$y - y_0 = r_g \cos \omega_gt$$
Motion in uniform Electromagnetic field:

\[
\begin{align*}
\dot{v}_x &= \omega_g v_y + \frac{q}{m} E_x \\
\dot{v}_y &= -\omega_g v_x \\
\dot{v}_y &= -\omega_g^2 \left( v_y + \frac{E_x}{B} \right)
\end{align*}
\]

\[
\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}
\]

The $\mathbf{E} \times \mathbf{B}$ drift does not depend on the charge, thus electrons and ions drift in the same direction!
Nonuniform magnetic fields in space

Shear, twist

Curvature

Divergence

Gradient

**Gradient Drift:**

\[
v_\nabla = \frac{m v_\parallel^2}{2q B^3} (\mathbf{B} \times \nabla B)
\]

**Curvature Drift:**

\[
v_R = \frac{m v_\parallel^2}{q R_c^2 B^2} (\mathbf{R}_c \times \mathbf{B})
\]

\[
j_\nabla = \frac{n_e (\mu_i + \mu_e)}{B^2} (\mathbf{B} \times \nabla B)
\]

\[
j_R = \frac{2n_e (W_{i\parallel} + W_{e\parallel})}{R_c^2 B^2} (\mathbf{R}_c \times \mathbf{B})
\]
**First Adiabatic invariant:**

As a particle moves into regions of converging or diverging $B$ its cyclotron radius changes, but the magnetic moment remains constant. *Magnetic moment* - The first adiabatic invariant.

$$\mu = \frac{W_\perp}{B} = \frac{1}{2}mv_\perp^2 = \text{constant}$$

This constancy of the particle magnetic moment holds only when the spatial variation of $B$ inside the particle orbit is small compared to the magnitude of $B$. 
Note that the drift is in the azimuthal direction. A positive drift velocity corresponds to eastward motion, whereas a negative velocity corresponds to westward motion. It is clear that, in addition to their gyromotion and periodic bouncing motion along field-lines, charged particles trapped in the magnetosphere also slowly *precess* around the Earth. The ions drift westwards and the electrons drift eastwards, giving rise to a net westward current circulating around the Earth. This current is known as the *ring current*. 

\[
v_{\perp} = \frac{E \times B}{B^2} + \frac{\mu}{m \Omega} \mathbf{b} \times \nabla B + \frac{v_{\parallel}^2}{\Omega} \mathbf{b} \times (\mathbf{b} \cdot \nabla) \mathbf{b}.
\]
3. Enhancement of Ring Current during a Geomagnetic Storm
Geoeffective Conditions for Geomagnetic Storm

- IMF magnetic field (B) orientation opposite to planetary B direction.
- Reconnection and the flux transfer rate.
- The rate of reconnection depends on many other factors like the dynamic pressure, the individual components of B-fields and their magnitudes, and mach numbers.
Magnetic reconnection is a physical process in highly conducting plasmas in which the magnetic topology is rearranged and magnetic energy is converted to kinetic energy, thermal energy, and particle acceleration.

- Magnetic reconnection or magnetic merging is a process in which several existing magnetic field lines are cut in the region of reconnection and the free ends are reconnected to other field lines.
- This process locally changes the magnetic topology.
- Models (Sweet Parker, Petschek)
- Rates.

Magnetic Reconnection: This view is a cross-section through four magnetic domains undergoing separator reconnection. Two separatrices (see text) divide space into four magnetic domains with a separator at the center of the figure. Field lines (and associated plasma) flow inward from above and below the separator, reconnect, and spring outward horizontally. A current sheet (as shown) may be present but is not required for reconnection to occur. This process is not well understood: once started, it proceeds many orders of magnitude faster than predicted by standard models.
\[ \nabla \times \mathbf{B} = \mu \mathbf{J} + \mu \varepsilon \frac{\partial \mathbf{E}}{\partial t}. \] \quad \text{Ampere’s Law}

Assuming slow time scales (MHD), the displacement current term can be neglected. Taking the curl of the above ampere’s law and using resistive Ohm’s law, and faraday’s law we obtain.

\[ \mathbf{E} + \nu \times \mathbf{B} = \frac{j}{\sigma} \quad \text{Ohm’s Law} \]

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \text{Faraday’s law of Induction} \]

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\nu \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \]

The ratio of the first term to the second term on the RHS of the induction equation is called the magnetic Reynolds number. If the first term is negligible (like if there is no plasma flow), then the equation reduces to simple diffusion equation.

\[ \frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} \]
Convection in the magnetosphere opened by reconnection. The lower picture illustrates the motion of the ionospheric end of the magnetic field line assuming that plasma and magnetic field are frozen-in to each other. Note that the tail in this picture is strongly compressed in the horizontal direction. In reality the far-tail neutral line is located somewhere at 100 RE or even further. (Adapted from the textbook of Kivelson and Russell [1995].)
Equipotential lines of convection (E cross B drift) and corotation electric fields in the equatorial plane. The numbers at the faces of the panels give the local times.

Orbits of low-energy particles (i.e, magnetic moment $\mu \approx 0$) in the equatorial plane assuming $E_0 = 0.3$ mV m$^-1$. The distance between consecutive points is 10 min. (Adapted from Kavanagh et al[1968].)

(a)  

(b)  

(c)  

(d)
Ring Current Losses

Major loss processes:

• Drift loss at dayside magnetopause.
• Charge exchange with neutral atmosphere.
• Coulomb Collision in the plasmasphere.
• Loss-cone loss.
• Pitch-angle diffusion by wave-particle interactions.
4. Modeling of Ring Current
Modeling of Ring Current:

**Empirical:**

Requires studying of massive amount of data. Model involves, curve fitting regression analysis. Examples—Temerin and Li (2002, 2006), Asikainen’s work (2010). E.g. Temerin and Li’s 2002 model is:

$$\text{Dst} = \text{dst}_1 + \text{dst}_2 + \text{dst}_3 + (\text{pressure term}) + (\text{direct IMF b z term}) + (\text{offset terms that do not depend on solar wind}).$$

$$\text{dst}_1(t + dt) = \text{dst}_1(t) + \left\{ a_1 \cdot [-\text{dst}_1(t)]^{a_2} + \text{fe}_1(t) \right\} dt$$

$$\cdot \left\{ 1 + \frac{\text{a}_3 \cdot \text{dst}_1(t - \tau_1) + \text{a}_4 \cdot \text{dst}_2(t - \tau_1)}{1 - \text{a}_5 \cdot \text{dst}_1(t - \tau_1) - \text{a}_6 \cdot \text{dst}_2(t - \tau_1)} \right\}$$

$$\text{dst}_2(t + dt) = \text{dst}_2(t) + \left\{ b_1 \cdot [-\text{dst}_2(t)]^{b_2} + \text{fe}_2(t) \right\} dt$$

$$\cdot \left\{ 1 + \frac{\text{b}_3 \cdot \text{dst}_1(t - \tau_2)}{1 - \text{b}_3 \cdot \text{dst}_1(t - \tau_2)} \right\}$$

$$\text{dst}_3(t + dt) = \text{dst}_3(t) + \left\{ c_1 \cdot \text{dst}_3(t) + \text{fe}_3(t) \right\} dt$$

$$\cdot \left\{ 1 + \frac{\text{c}_2 \cdot \text{dst}_3(t - \tau_3)}{1 - \text{c}_2 \cdot \text{dst}_3(t - \tau_3)} \right\}$$

where $a_1 = 6.51 \cdot 10^{-2}$, $a_2 = 1.370$, $a_3 = 8.4 \cdot 10^{-3}$, $a_4 = 6.053 \cdot 10^{-3}$, $a_5 = 1.21 \cdot 10^{-3}$, $a_6 = 1.55 \cdot 10^{-3}$, $\tau_1 = 0.14$ days, $b_1 = 0.792$, $b_2 = 1.326$, $b_3 = 1.29 \cdot 10^{-2}$, $\tau_2 = 0.18$ days, $c_1 = -24.3$, $c_2 = 5.2 \cdot 10^{-2}$, $\tau_3 = 9 \cdot 10^{-2}$ days, $\text{fe}_1 = -4.96 \cdot 10^{-3} (1 + 0.28 \cdot \text{dh})[2 \cdot \text{exx} + \text{abs} (\text{exx} - \tau_1) + \text{abs} (\text{exx} - \text{th}2 - \text{th}1 - \text{th}2)]$, $\text{fe}_2 = 2.02 \cdot 10^3 \cdot \sin^{0.49}(\phi)$, $\text{fe}_3 = 3.45 \cdot 10^3 \cdot \sin^{0.9}(\phi)$, $\text{df}_2/(1 - \text{df}_2)$, $\text{df}_2 = -3.85 \cdot 10^{-5}$, $\text{exx} = 10.1$, $\text{b}_1 = 1.16 \cdot n^{0.24}(1 + \text{dh})$, $\text{exx} = 10^{-3} \cdot \text{v}_x \cdot \text{b}_1 \cdot \sin^{0.1}(\phi)$, $\text{exx} = (\text{acosh}(b_{\text{x}}/b)) - \pi/2$, $b_{\text{y}} = b_{\text{z}}^2$, $\text{th}1 = 0.725 \cdot \sin^{-1.46}(\phi)$, $\text{th}2 = 1.83 \cdot \sin^{-1.46}(\phi)$, $\text{dh} = \text{b}_p \cdot \cos(\text{atan}(b_{\text{x}}, b_{\text{y}}) + 6.10(3.59 \cdot 10^{-2} \cos(2\pi t/\text{yr} + 0.04) - 2.18 \cdot 10^{-2} \sin(2\pi t - 1.60)))$, and $b_p = (b_{\text{y}}^2 + b_{\text{z}}^2)^{1/2}$. 
Neural Network

Machine learning based algorithms used to predict the Dst values. Eg. Bala et al, 2010

Energy Balance

Assume that the ring current energy charges and decays at certain time scales. The energy is then related to the Dst index using the Dessler Parker Schopke relation. E.g. Burton 1975, McPherron 2000, and the **WINDMI model**.

\[
\frac{dW_{rc}}{dt} = R_{prc} I_2^2 + \frac{pVA_{eff}}{B_{tr}L_y} - \frac{W_{rc}}{\tau_{rc}}
\]

**Dessler Parker Schopke relation**: Relating ring current energy to Dst

\[
D_{st} = \frac{\mu_0 W_{rc}(t)}{2\pi B E R^3_E}
\]
Phase space representation:

A particle can be represented by a single point in the six-dimensional phase space \(x, y, z, v_x, v_y, v_z\). The phase-space distribution function, \(F(r,v)\), characterizes the number of particles in a six-dimensional infinitesimal volume element, \(d^3r \, d^3v\).

This is the Boltzmann equation, which describes the evolution of the phase-space distribution function, \(F(t, r, v)\).

\[
\frac{\partial F(t, r, v)}{\partial t} + (\mathbf{v} \cdot \nabla) F(t, r, v) + (\mathbf{a} \cdot \nabla_v) F(t, r, v) = \frac{\delta F(t, r, v)}{\delta t}.
\]

Bounce averaged particle solvers like the Fok kinetic model calculates the temporal variation of the phase space density of a particle species \(s\), by solving the following bounce-averaged Boltzmann transport equation.

\[
\frac{\partial \bar{f}_s}{\partial t} + \left\langle i_i \right\rangle \frac{\partial \bar{f}_s}{\partial l_i} + \left\langle \phi_i \right\rangle \frac{\partial \bar{f}_s}{\partial \phi_i} = -\nu \sigma_s \left\langle n_H \right\rangle \bar{f}_s - \left( \frac{\bar{f}_s}{0.5 \tau_b} \right) \text{loss cone}
\]
Bounce-averaged approximation

The first two invariants are conserved

Bounce-averaged approximation is valid

$f(X,Y,Z,Vx,Vy,Vz)$

$f(L,\phi,E,\alpha_0)$

Full particle trajectory

Bounce-averaged drift trajectory
Multi scale problem:

Which technique to use?

Depends on what you are looking for…. Examples,
1. Prediction Efficiency.
2. Faster Physics based Prediction and modeling.
5. Ring Current Measurements
Ring Current Measurement Techniques:

- In-Situ measurements using particle detectors on-board satellites.

- Remote sensing using images taken by satellites like energetic neutral atom (ENA) imaging.

- Remote sensing/ guessing using ground measurements by magnetometers spread across the globe.
Charge-Exchange Loss of Ring Current Ions

\[ \frac{\partial f}{\partial t} = - f \frac{1}{\tau}, \quad \tau = \frac{1}{v \sigma n_H} \]

At \( L \sim 3 \), ♦ in hours for 10 keV H\(^+\) and days for 100 keV H\(^+\)
♦ in days for 10 keV O\(^+\) and hours for 100 keV O\(^+\)
ENA: Energetic Neutral Atoms

- Created in charge-exchange collisions between high-energy ions (H\(^+\) and O\(^+\) in ring current) and low-energy neutrals (primarily H in exosphere)
- Can be used to infer ring current ion populations
- Advantages: global view of the entire ring current region at one point in time, relatively free from outside influences
- Disadvantage: difficulty in determining the source location of neutral atoms and subsequently the ring current ion flux (requires complicated inversion process involving models and manual input)
**Dst measurement (Ground Based)**

- Magnetospheric storm activity generates magnetic fields that can be detected with ground-based magnetometers.

- By removing the Earth’s magnetic field contribution and normal daily variations, magnetic disturbances can be determined.

- A global picture can be formed by using a number of different magnetometer stations located strategically around the Earth at mid-latitudes.

- Dst is calculated as a hourly average of the magnetic disturbance in the Earth’s dipole direction.
Known Issues:--

• Magnetometer-derived ring current information is that magnetometers cannot distinguish between the different magnetospheric current systems.

• Difficulty in estimating daily variations accurately.

• RC asymmetry difficult to resolve.

• Removal of quiet time values is not perfect.

• Problems with Dessler Parker Schopke relationship.

• Uncertainty over the contribution of ground induced currents.
Space Weather Modeling at CSE-USU.

At Center for Space Engineering (CSE):
(Dr. E. Spencer, T. Andriyas, S. Patra, A. Raj, P. Kasturi)

http://ccmc.gsfc.nasa.gov/models/models_at_glance.php
http://ccmc.gsfc.nasa.gov/cgi-bin/WINDMlpred.cgi

Recent Publications:
Conventional empirical geomagnetic field models: Structure

\[ \mathbf{B}_E = \mathbf{B}_{CF} + \mathbf{B}_T + \mathbf{B}_{SRC} + \mathbf{B}_{PRC} + \mathbf{B}_{FAC} + \mathbf{B}_{INT} \]
WINDMI Model

\[
L \frac{dl}{dt} = V_{sw}(t) - V + M \frac{dl_1}{dt} \tag{1}
\]

\[
C \frac{dV}{dt} = l - l_1 - l_{ps} - \Sigma V \tag{2}
\]

\[
\frac{3}{2} \frac{dp}{dt} = \frac{\Sigma V^2}{\Omega_{cps}} - u_0 p K_{||}^{1/2} \Theta(u) - \frac{pVA_{eff}}{\Omega_{cps} B_{tr} L_y} - \frac{3p}{2\tau_E} \tag{3}
\]

\[
\frac{dK_{||}}{dt} = l_{ps} V - \frac{K_{||}}{\tau_{||}} \tag{4}
\]

\[
L_1 \frac{dl_1}{dt} = V - V_1 + M \frac{dl}{dt} \tag{5}
\]

\[
C_l \frac{dV_l}{dt} = l_1 - l_2 - \Sigma_l V_l \tag{6}
\]

\[
L_2 \frac{dl_2}{dt} = V_l - (R_{pre} + R_{A2}) l_2 \tag{7}
\]

\[
\frac{dW_{rc}}{dt} = R_{pre} l_2^2 + \frac{pVA_{eff}}{B_{tr} L_y} - \frac{W_{rc}}{\tau_{rc}} \tag{8}
\]
ARV AL = 0.45

AL Index Comparison 2002

Comparison of Tail current contribution to Dst from MT index and WINDMI

\[ \tau_{rc} = 33.4 \text{ Hrs} \]
Extended Dst forecasting using Solar Images:

Work Done by Tushar Andriyas and A. Raj.

• To improve the space weather prediction model lead time from 1 Hr currently to possible 3 days.

• Solar wind parameters will be deduced from Images of the Sun, which when incorporated with the WINDMI model will give a 3-day advanced forecast for the intensity of geomagnetic events.
Solar Minimum 1996
Low solar activity
- Comparable sunspot numbers

Narrow equatorward extensions from polar coronal holes

Disorganized short-duration energy flows into the Earth's atmosphere.

Weak radiation environment

Solar Minimum 2008

Multiple broad low-latitude coronal holes

Periodic long-duration energy flows into the Earth's atmosphere. Atmosphere ringing with solar wind periodicities.

Enhanced radiation environment
Dst from ACE satellite data (green) against ground $D_{st}$ (black)
Accurate Prediction of the Auroral Oval:
This will help in improving the AL model.
Work done by Ashish Raj and T. Andriyas.
We have started to understand space weather better, but there are many outstanding questions still remaining.

- What triggers a CME or Flare?
- What is the contribution of other magnetospheric currents to the Dst index?
- Is the AL index a true indicator of the auroral electrojets?
- What is the cause of acceleration of particles in the inner heliosphere to relativistic velocities?
- How much is the contribution of the substorm to the enhancement of the ring current?
- What is the relative contribution of the competitive loss mechanisms of the ring current?

We may be more vulnerable now, but with improved understanding of space weather and associated phenomenon, we have never been better prepared.