Geomagnetic activity: Structure and Variability of Particle Precipitation

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Change in Surface Air Temperature with Geomagnetic Activity

- \( \Delta T \) for (high – low) geomagnetic activity
- What is the mechanism?

Seppala et al., JGR [2009]
Particle Precipitation - Importance

- Largest energy input to the polar atmosphere at night and polar winter
- Major loss process for radiation belts
- Space weather effects – ionisation - aviation, GPS, satellite charging
- Changes atmospheric chemistry
  - Affects heating and cooling rates – winds
- Transmits solar variability to the atmosphere
  - Dynamic coupling through the atmosphere?
  - Climate link?
Sunspot Cycle – Geomagnetic Activity

- Magnetic activity (mag storms) peaks 1-2 years after sunspot max.
Magnetic Activity Peaks After Sunspot Max

Figure 8. Sunspot number versus aa index from 1950 to 1999. The solid curve is the sunspot number, and the dashed curve is the geomagnetic activity.

- Feynman and Gabriel [2000]
Types of Precipitation

- Cosmic Rays
- Solar energetic particles (protons)
- Radiation belt electrons
  - \(~100\) keV – several MeV
- Discrete auroral electrons
  - \(~1 – 10\) keV
- Diffuse auroral electrons
  - \(~0.1 – 10\) keV
- Ring current protons
  - \(~10 – 200\) keV
Solar Energetic Particle Events

- Protons accelerated by interplanetary shocks
- Access the Earth’s magnetic field in the polar regions
- >10 MeV protons measured by POES
- >~500 MeV protons can reach the ground in polar regions
- 10 largest since 1976 occur up to 2 years after sunspot max [Odenwald et al. [2006]]
- Climate link uncertain
Cosmic rays and Solar Energetic Particle Events

- Cosmic rays from neutron monitors at Colorado (>3 GV rigidity)
- SEP events > 60 MeV
- Cosmic ray background

- SEPs tend to be anti-correlated with cosmic rays – generated by CMEs
- Lockwood and Hapgood [2007]
Radiation Belts

- Electrons up to several MeV
- Mostly trapped inside the magnetic field
- >2 MeV electron flux can change by 5 orders of magnitude on timescales of hours – days
- Precipitation into the atmosphere is a major loss process
Radiation Belts – South Atlantic Anomaly
Particle Motion – Trapped Particles

- Particle motion > ~100 keV
  - Cyclotron motion around B (kHz)
  - Bounce between mirror points (Hz)
  - Drift around the Earth (mHz)
The loss cone angle at the equator is about
- 2° at L=6.6 (geostationary orbit)
- 16° at L=2

Particles with $\alpha > \alpha_{LC}$ are trapped in space

Particles with $\alpha \leq \alpha_{LC}$ are lost to the atmosphere

Wave-particle interactions in space scatter (diffuse) electrons into the loss cone which results in precipitation
Example - Chorus Waves - Precipitation

- Whistler mode chorus waves \( L \approx 4 \) occur in bursts
- Burst precipitation >1 MeV measured by SAMPEX is associated with chorus
- Chorus also associated with precipitation of \( \sim 10 \text{ keV} \) to \( \sim 1 \text{ MeV} \) electrons
- Lightning generated waves can also cause bursts of precipitation

Lorentzen et al. GRL [2001]
DE1, CRRES, Cluster 1, TC1 and THEMIS
MLT Coverage: 06–15 MLT

Field: Olson Pfitzer Quiet + IGRF
L* Coverage: Outside Plasmapause

Wave Magnetic Field Intensity (0.5fce \( < f \) \( < 1.0fce \))

AE (100 nT)

100 (AE (300 nT)

AE (300 nT)

Wave Magnetic Field Intensity (0.1fce \( < f \) \( < 0.5fce \))

AE (100 nT)

100 (AE (300 nT)

AE (300 nT)
DE1, CRRES, Cluster 1, TC1 and THEMIS
Latitude Coverage: $-15^\circ \lesssim \lambda_m \lesssim 15^\circ$
Field: Olson Pfitzer Quiet + IGRF
$L^*$ Coverage: Outside Plasmapause

Wave Magnetic Field Intensity ($0.5\text{ fce} \lesssim f < 1.0\text{ fce}$)

- AE ($100 \text{ nT}$)
- $100 < \text{AE} \lesssim 300 \text{ nT}$
- $\text{AE} > 300 \text{ nT}$

Wave Magnetic Field Intensity ($0.1\text{ fce} \lesssim f < 0.5\text{ fce}$)

- AE ($100 \text{ nT}$)
- $100 < \text{AE} \lesssim 300 \text{ nT}$
- $\text{AE} > 300 \text{ nT}$
>30 keV Precipitation

- MLT dependence of chorus waves and electron precipitation
- Geomagnetic control
- Chorus waves responsible for >30 keV electron precipitation
- Lam et al., JGR [2010]
Weak and Strong Diffusion

- Weak diffusion
  - Loss cone is almost empty
  - Trapped flux is much higher

- Strong diffusion
  - Loss cone almost full
  - Trapped flux \sim \text{loss cone flux}

- Strong diffusion never lasts long – otherwise we would not have radiation belts

- Diffusion rate depends on wave power

- Measurement difficulties
Solar Wind Control

>1 MeV electrons

>300 keV

>100 keV

>30 keV

- Immediate precipitation at ~ 30 keV, but delayed at higher energies

- Meredith et al. JGR [2011]
>30 keV Precipitation - POES

- Diffusion into loss cone can occur at all longitudes
>1 MeV precipitation - POES

- Diffusion into loss cone is weaker, occurs mainly over SAA – drift loss cone
Whistler Mode Hiss

- Hiss
- Broad band waves
- Not bursty like chorus

Precipitate ~ 0.03 – few MeV electrons depending on location

Max power on the dayside implies more precipitation on dayside
Electromagnetic Ion Cyclotron Waves

- Precipitate > 1 MeV electrons
- Precipitate ring current ions 10 – 100 keV
- Max occurrence near dusk
- Observed during geomagnetic storms
Discrete Auroral Electron Precipitation 1-10 keV

- Beam of electrons between ~1 – 10 keV
- Accelerated along magnetic field line by E fields, Alfven waves, double layers, and many more ideas…….
- Source of bright auroral arcs
- Magnetic activity

Evans et al., JGR [1977]
Discrete and Diffuse Electron Precipitation 1-10 keV

- Diffuse aurora \( \sim 71\% \) energy input
- Note difference in magnetic local time

Newall et al., JGR [2009]
Difficulties with Measuring Precipitation

- POES satellites at ~ 800 km
- Detector has a width of +- 15° m
- Does not measure all the loss cone
- Drift and bounce averaged diffusion rate from whistler mode chorus at 1 MeV at L~4.5 is ~ 6 x 10^{-5} s^{-1} [Horne et al., JGR, 2005]
Summary

- Geomagnetic activity peaks 1-2 years after the sunspot cycle
- SEP events penetrate the polar cap, low altitudes, but are not very frequent
- Radiation belt electrons 100 keV – several MeV
  - Precipitation caused by wave-particle interactions – at varying energy/MLT
  - Wave properties modulated by solar wind – magnetosphere interaction
  - > 30 keV precipitation - mainly from 00:00 – through dawn to ~12:00 MLT
  - > 30 keV – ~ 800 keV – precipitate at any longitude
  - > ~800 keV mainly precipitate in south Atlantic anomaly region
- More precipitation in the southern hemisphere cf northern hemisphere
- Enhanced in declining phase of solar cycle – fast solar wind
- Measuring precipitation using satellites requires careful corrections
- Diffuse and discrete auroral electron precipitation ~ 1 – 10 keV
  - Discrete – mainly before midnight, diffuse – midnight till dawn
  - Discrete – depends on substorms and storms – highest 1-2 years after solar max