REPW 2007: Abstracts

Jay Albert
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Quasilinear Diffusion Calculations: Fast And/Or Accurate

Quasilinear diffusion by cyclotron-resonant plasma waves is likely a driver of radiation belt electron dynamics. Simulations require the diffusion coefficients to be evaluated quickly as well as accurately. The recently developed parallel propagation approximation replaces integration over the wavenormal distribution with a closed form expression.
This is very fast but not very accurate, as I will show. I will also present a modified version, based on a previously developed procedure for identifying wavenormal angles that are resonant with a given frequency distribution. Because this also requires evaluation at only a small number of WN values, it is also much faster to evaluate than the full integrals, while preserving contributions from oblique waves and all harmonic numbers. Finally, I will discuss progress in extending to 3D the change-of-variables method of eliminating cross terms for time-dependent diffusion simulations.

Jacob Bortnik
UCLA, Los Angeles, USA

Modeling the propagation characteristics of chorus and its effect on the radiation-belts

Whistler-mode chorus waves are amongst the most intense plasma waves in the near-Earth space environment, in the Very-Low-Frequency (VLF) range. It was shown in a number of recent studies, that chorus is closely associated with radiation-belt dynamics, serving a dual role: it can act as a loss mechanism for lower energy electrons (~100 keV), and as an acceleration mechanism for the high energy electrons (~1 MeV). In order to properly quantify the effect of chorus on the radiation-belts, it is necessary to accurately specify the wave characteristics that define chorus, such as power spectral density, wave normal angle spread, and bandwidth. Furthermore, it is necessary to understand the distribution of these quantities in 3-dimensional space (L-shell, MLT, and latitude), and evolution in time. In this talk, we will present extensive ray-tracing based modeling of chorus propagation, including the effects of Landau damping, and a realistic model of the cold-plasma density. The modeling is compared against statistical studies of chorus observations, and the possible relation to other wave types is discussed.

Anthony Chan
Rice University, Houston, USA

Recent Results from Theory and Modeling of Radiation Belt Electron Transport, Acceleration and Loss

Anthony A. Chan, Bin Yu, Xin Tao, Richard A. Wolf, Scot R. Elkington, Seth G. Claudepierre, Jay M. Albert, and Michael Wiltberger.

Understanding of the basic physical processes responsible for the transport, acceleration and loss of radiation belt particles is still incomplete, and further work is needed to build better physics-based models of radiation belt dynamics. Two classes of mechanisms are thought to be especially important for relativistic electrons: (1) Local acceleration and loss by cyclotron-resonant interaction with VLF/ELF waves, and (2) radial transport by drift-resonant interaction with electromagnetic perturbations in the ULF frequency range. In this work simulations of radial transport will be presented, including results from 1D (plus time) radial diffusion simulations and results from test-particle trajectories in fields obtained from LFM (Lyon-Fedder-Mobarry) global MHD simulations. The simulations are carried out for storms driven by high speed solar wind streams. These storms occur with 27-day periodicity during the declining phase of the solar cycle and they are especially interesting because they may contain very large, sustained electron flux increases. We will report on efforts to find radial diffusion coefficients which best describe the transport of MeV electrons between geosynchronous orbit and equatorial GPS locations (at 4.2 earth radii), two locations where simulated phase-space densities (for given first and second adiabatic invariants) can be compared with spacecraft measurements. Results will also be presented from a new method of solving radiation belt diffusion equations using stochastic differential equation (SDE) methods.

Scot Elkington
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Stormtime plasmasheet access to the inner magnetosphere

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Energetic particle fluxes in the inner magnetosphere vary as a result of a complex balance between transport, acceleration, and loss. During periods of strong Earthward convection in the tail, inward transport of energetic plasmasheet particles may lead to a boundary population of electrons that can be trapped and subsequently heated to MeV energies through a combination of diffusive radial transport and local heating. Conversely, during periods where plasmasheet particles do not have access to the inner magnetosphere, diffusive transport in the inner magnetosphere will act to deplete the radiation belts as particles move outward through the drift loss cone. In this effort, we use large-scale MHD/particle simulations of the geomagnetic system to calculate the effect of the coupling state between the radiation belts and plasmasheet during geomagnetic storms. By contrasting particle injection and trapping rates at different phases of storms of varying strength, we attempt to describe those conditions in the solar wind and plasmasheet where the outer boundary may significantly influence flux variation in the radiation belts. Calculations of the evolving particle phase space densities in the plasmasheet and inner magnetosphere are used to evaluate the overall influence of convective transport and heating on storm-time radiation belt dynamics.

Brian Fraser
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Electromagnetic Ion Cyclotron Waves in the Magnetosphere: Wave and Plasma Properties

Electromagnetic ion cyclotron (EMIC) waves play an important role in magnetosphere dynamics including ring current ion and radiation belt electron losses. In studying the wave-particle interaction important parameters include the particle phase space distribution function, wave frequency, wave normal angle, wave power and spectral energy density. The role of the cold/cool ambient background plasma and its constituents, including heavy ions need to be considered in wave generation and propagation. It has generally been assumed that the steep radial gradient in the density profile of the plasmapause is the favoured region for the generation and propagation of

electromagnetic ion cyclotron (EMIC) waves. This is the region of overlap between the expanding cold plasmasphere with the inner edge of the hot ring current during storm recovery, providing favourable conditions for EMIC instability. However, EMIC waves are seen more frequently outside the plasmapause, in extended radial plasma plumes attached to the plasmasphere. These provide enhanced radial plasma density and associated azimuthal gradients. This study will attempt to provide EMIC wave and plasma parameters of interest to modellers of ring current and radiation belt loss mechanisms. EMIC wave data from ATS-6 and GOES at geostationary orbit and CRRES at geostationary transfer orbit along with plasma and energetic particle data from FAST in a low altitude polar orbit and LANL at geostationary orbit will be used. The dependence of EMIC wave occurrence on geomagnetic activity and storm phase will also be considered.

Reiner Friedel
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Pitch angle evolution of energetic electrons at geosynchronous orbit during dropouts

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Pitch angle resolved data have been obtained for three of the Los Alamos geosynchronous energetic particle instruments for parts of the period 2001-2004. We first "remove" the geometric effects in the pitch angle distributions by sorting the data into pitch-angle dependent L^* coordinates and the re-assembling the pitch angle distribution adiabatically at a constant, fixed L^* of 6.0, using activity-dependent magnetic field models such as Tsyganenko 2004 storm - this in effect removes the drift shell splitting effect from the data in order to highlight pitch angle changes due to other processes such as wave-particle interactions. We will then use this re-assembled dataset to investigate the pitch angle dependence at $L^*=6.0$ during dropout periods. We show that rapid dropout periods during moderately disturbed times coincide with observations of plumes by the LANL MPA instrument on the same spacecraft, and that the energy-dependence of the the dropout observations as a function of pitch angle are consistent with simple pitch angle diffusion modeling using realistic pitch angle diffusion coefficients that represent EMIC and whistler chorus interactions.

Rory Gamble
University of Otago, Dunedin, New Zealand

Radiation belt electron precipitation due to manmade VLF transmissions: satellite observations

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Previous studies have reported enhancements in drift-loss cone electron fluxes, and associated them with the operation of powerful VLF transmitters. Here we examine the significance of the VLF transmitter NWC on the inner radiation belt by combining DEMETER satellite observations

with ground-based determined NWC on/off times. We find that enhancements in the ~100-300 keV drift-loss cone electron fluxes are directly linked to NWC operation and ionospheric absorption. Daytime ionospheric absorption of the transmitter waves means that no drift-loss cone electron flux enhancements are observed at these times. In contrast, ~95% of nighttime measurements made "down-stream" of the operational transmitter show such enhancements. No enhancements were observed during periods when NWC was not transmitting. This provides conclusive evidence linking drift-loss cone electron flux enhancements and VLF transmitter operation. We find that ~400 times more 300 keV electrons are driven into the drift-loss cone during NWC transmission periods than during non-transmission periods.

Richard Horne (3 abstracts)
British Antarctic Survey, Cambridge, UK

1. Electron acceleration in the Van Allen radiation belts by fast magnetosonic waves

Richard B. Horne, Richard M. Thorne, Sarah A. Glauert, Nigel P. Meredith, Dimitry Pokhotelov, and Ondrej Santolik

Local acceleration is required to explain electron flux increases in the outer Van Allen radiation belt during magnetic storms. Here we show that fast magnetosonic waves, detected by Cluster 3, can accelerate electrons between ~10 keV and a few MeV inside the outer radiation belt. Acceleration occurs via electron Landau resonance, and not Doppler shifted cyclotron resonance, due to wave propagation almost perpendicular to the ambient magnetic field. Using quasi-linear theory, pitch angle and energy diffusion rates are comparable to those for whistler mode chorus, suggesting that these waves are very important for local electron acceleration. Since pitch angle diffusion does not extend into the loss cone, these waves, on their own, are not important for loss to the atmosphere. We suggest that magnetosonic waves, which are generated by unstable proton ring distributions, are an important energy transfer process from the ring current to the Van Allen radiation belts.

2. Slot region electron loss timescales due to plasmaspheric hiss and lightning generated whistlers

Nigel P. Meredith, Richard B. Horne, Sarah A. Glauert, and Roger R. Anderson

Energetic electrons (E > 100 keV) in the Earth's radiation belts undergo Doppler-shifted cyclotron resonant interactions with a variety of whistler mode waves leading to pitch angle scattering and subsequent loss to the atmosphere. In this study we assess the relative importance of plasmaspheric hiss and lightning-generated whistlers in the slot region and beyond. Electron loss timescales are determined using the PADIE code with global models of the spectral distributions of the wave power based on CRRES observations. Our results show that plasmaspheric hiss propagating at small and intermediate wave normal angles is a significant scattering agent in the slot region and beyond. In contrast, plasmaspheric hiss propagating at large wave normal angles and lightning generated whistlers do not contribute significantly to radiation belt loss. The loss timescale of 2 MeV electrons due to plasmaspheric hiss propagating at small and intermediate wave normal angles in the centre of the slot region (L = 2.5) lies in the range 1-10 days, consistent with recent SAMPEX observations. Wave turbulence in space, which is responsible for the generation plasmaspheric hiss, thus leads to the formation of the slot region. During active periods losses due to plasmaspheric hiss may occur on a timescale of 1 day or less for a wide range of energies, 200 keV < E < 1 MeV, in the region 3.5 < L < 4.0. Plasmaspheric hiss may thus also be a significant loss process in the inner region of the outer radiation belt during magnetically disturbed periods.

3. Electron acceleration inside Jupiter's radiation belt and the origin of synchrotron radiation

Richard B. Horne, Richard M. Thorne, Sarah A. Glauert, J. Douglas Menietti, Yuri Y. Shprits, and Donald A. Gurnett

Jupiter has the most intense radiation belts of all the magnetised planets. While betatron and Fermi acceleration are well known for producing energetic electrons inside planetary and stellar magnetic fields, here we show that electromagnetic whistler mode waves with frequencies of a few kilohertz accelerate electrons up to relativistic energies (~10 MeV) via Doppler shifted cyclotron resonance. Wave acceleration traps electrons inside the magnetic field and is most effective outside the orbit of the moon Io where wave power intensifies and magnetic flux interchange drives wave instabilities. We propose that wave acceleration forms part of a multi-step process responsible for synchrotron radiation from relativistic electrons trapped in planetary and stellar magnetic fields.

Vania Jordanova
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Effects of EMIC Wave Scattering on Energetic Ions and Electrons

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We study the effect of electromagnetic ion cyclotron (EMIC) wave scattering on ring current ions and radiation belt electrons during several geomagnetic storms. We use our global physics-based model, which calculates the evolution of H^+, O^+, and He^+ ions and electrons due to time-dependent earthward transport and acceleration. All major loss processes are included in our kinetic model, namely, charge exchange, Coulomb collisions, wave-particle interactions, loss due to collisions with the dense atmosphere, and convective loss through the dayside magnetopause. The kinetic model is coupled with a time-dependent plasmasphere model through the employed electric and magnetic fields. The excitation of EMIC waves is calculated self-consistently with the evolving ring current ion populations as the storms progress. We find that the presence of both cold an energetic heavy ions affects significantly the generation and propagation characteristics of the EMIC waves. The regions of maximum EMIC wave growth are usually located near the plasmapause, however with quite variable magnetic local time dependence. Pitch angle scattering by these waves cause significant ion precipitation into the atmosphere and generation of detached subauroral proton arcs. Furthermore, EMIC waves cause pitch angle scattering and loss of radiation belt electrons at energies larger than 500 keV.

Craig Kletzing
University of Iowa, Iowa City, USA

Waves in the Earth's Radiation Belt: The Electric and Magnetic Field Instrument Suite with Integrated Science on the Radiation Belt Storm Probes

C. A. Kletzing, W. Kurth, M. Acuna, R. Torbert, R. Thorne, V. Jordanova, S. Bounds, C. Smith, O. Santolik, R. Pfaff, D. Rowland, G. Hospadarsky, W. Baumjohann, R. Nakamura, and P. Puhl-Quinn.

The physics of the creation and loss of radiation belt particles is intimately connected to the electric and magnetic fields which mediate these processes. A large range of field regimes are involved in this physics from ring current magnetic fields to microscopic kinetic interactions such as whistler-mode chorus waves with energetic electrons. To measure these key field interactions, NASA has selected the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) on the Radiation Belt Storm Probes (RBSP). EMFISIS is an integrated set of instruments consisting of a tri-axial fluxgate magnetometer (MAG) and a Waves instrument which includes a tri-axial search coil magnetometer and which measures AC electric and magnetic fields from 10 Hz to 400 kHz. The broad frequency range of the Waves instrument enables the identification of resonances and cutoffs from Waves to achieve high cadence, accurate plasma density measurements that are essential to RBSP theory and modeling efforts. Of particular interest to the multi-institution EMFISIS team are the interactions of radiation belt particles with various wave modes such as VLF hiss, magnetosonic equatorial noise, electromagnetic ion cyclotron waves, and chorus. Data examples of these key waves along with their importance to radiation belt science are discussed.

Louis Ozeke
University of Alberta

The Equatorial Pitch-Angle Dependence on the Energization and Radial Transport of Radiation Belt Electrons by Poloidal ULF Alfven Waves.

L. G. Ozeke and I. R. Mann

Recent studies have shown that wave-particle interactions with ULF waves have a major influence on the energization and radial transport of radiation belt electrons. However, these studies have focused on the interaction of equatorially mirroring particles with ULF waves. Here we present results showing the trajectories of radiation belts electrons with a range of equatorial pitch angles in a 3D dipole magnetic field including the effects of ULF wave-particle interactions. We show that the change in energy of radiation belt electrons via a drift-resonant interaction with poloidal ULF waves is only weakly dependent on the equatorial pitch-angle of the particles. However, the radial transport of a resonant radiation belt electron is strongly dependent on the particles' equatorial pitch-angle. Interesting, we show how maximum radial transport of the radiation belt electrons typically occurs for particles with an equatorial pitch-angle below 45 degrees. These pitch-angle dependent resonant transport results may be able to offer an alternative explanation for the observed butterfly pitch-angle distributions which have been observed by the Combined Release and Radiation Effects Satellite (CRRES) and have previously been attributed to VLF wave-particle local acceleration or drift shell splitting mechanisms.

Geoffrey D. Reeves
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Latest Results from the DREAM Model

The Dynamic Radiation Environment Assimilation Model (DREAM) applies multi-satellite measurements, simple basic physics models, and the techniques of data assimilation to understand radiation belt dynamics. One use of the model is to develop applications for space weather. These include real-time, global specification of the fluxes or dose, rapid anomaly analysis, and long-term retrospective models (reanalysis) that can be used for new radiation design standards (AE-9). Data assimilation doesn't just provide another way to put different data sets together though. DREAM enables new science investigations that are not possible using either data or models alone. For example, we have studied where (and when) multi-satellite phase space density measurements can not be made consistent with radial diffusion and high-L sources. We can use the assimilative model to determine the location, timing, and magnitude of local, wave-particle acceleration processes without necessarily pre-supposing which acceleration processes are active. Likewise we can distinguish losses from precipitation from those produced by magnetopause shadowing to better constrain the rates, L-shells, and energy dependence of each process. In this paper we will give an overview of the DREAM model and describe how it can be used for basic investigations and for space weather applications with an emphasis on recent results and opportunities for collaborative development.

Craig Rodger (2 abstracts)
University of Otago, Dunedin, New Zealand

1. Observation of radiation belt losses into the ionosphere

In order to understand the changing nature of the radiation belts, we must understand acceleration, loss and transport processes, both during geomagnetic storms and also for post-storm and "undisturbed" periods. A significant loss mechanism for energetic electrons in the inner magnetosphere is precipitation into the atmosphere. The arrival of these electrons lead to increases in the electron density profiles in the lower-ionosphere, which can be measured by instruments located on the ground. In this presentation I will review a number of our ground-based studies of energetic precipitation, using large-scale remote sensing through the AARDDVARK array of subionospheric receivers and widely distributed riometers. Given time, I will present evidence for ground-based observations of relativistic electron microbursts, EMIC-driven precipitation, and plasmaspheric hiss caused precipitation after a large geomagnetic storm.

2. Ground based transmitter signals observed from satellite: ducted or nonducted?

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The principal loss mechanism for electrons from the inner radiation belt ($1.2<L<2.0$) and slot region ($2.0<L<3.0$) is atmospheric precipitation driven by several processes, including coulomb collisions, plasmaspheric hiss, lightning-generated whistlers, and man-made transmissions. Several studies have shown that ducted and nonducted VLF waves can precipitate radiation belt energetic electrons into the upper atmosphere. Here we investigate the propagation of VLF communication

transmitter signals using plasma wave instruments onboard the CRRES and DEMETER satellites in order to determine if nonducted transmitter signals are significant in radiation belt loss processes. We investigate the regions where strong transmitter signals are observed in the ionosphere directly above the transmitter, in the magnetosphere near where the signals cross the geomagnetic equator, and in the ionospheric region geomagnetically conjugate to the transmitter. For very low L-shell transmitters (L<1.5) there is evidence that a significant proportion of the wave energy propagating into the plasmasphere is nonducted. However, at higher L-shells the waves become highly ducted in the plasmasphere. Strong evidence for this comes from the lack of significant wave power propagating above the electron half gyro-frequency limit for inter-hemispherically ducted waves. We conclude that man-made transmissions in the frequency range (18-25 kHz) will be restricted to driving electron precipitation primarily from the inner radiation belt (L=1.3-2.5). This will come about through a combination of propagation types, partly through nonducted wave propagation at very low L-shells (L=1.3-1.5), but predominantly through ducted wave propagation at higher L-shells (L=1.5-2.5), ultimately limited by the electron half-gyro frequency limit for ducted waves.

Richard Thorne
UCLA, Los Angeles, USA

Dynamic evolution of energetic outer zone electrons due to wave-particle interactions during storms.

Richard M. Thorne, Wen Li, and Y. Y. Shprits

Relativistic electrons in the outer radiation belt are subjected to pitch-angle and energy diffusion by chorus, electromagnetic ion cyclotron (EMIC) and whistler-mode hiss. Using quasi-linear diffusion coefficients for cyclotron resonance with field-aligned waves, we evaluate rates of pitch-angle scattering and local energy diffusion, based on models for the observed global distribution of waves. The diffusion rates are used in a 2D diffusion code to model the dynamical evolution of the radiation belts during storm conditions. Specifically, we examine the local acceleration and scattering loss of relativistic electrons during interaction with chorus. We also examine the effect of pitch-angle scattering by EMIC and whistler-mode hiss in plumes during the main and recovery phases of a storm. The numerical simulations show that wave-particle interactions with whistler-mode chorus waves with realistic wave spectral properties result in a net acceleration of relativistic electrons, while EMIC waves which provide very fast scattering near the edge of the loss cone, may be a dominant loss mechanism during the main phase of a storm. In addition, hiss in plumes are effective in scattering equatorially mirroring electrons and may be an important mechanism of transporting high pitch-angle electrons towards the loss cone. Observations of changes in the energetic electron energy spectrum and pitch-angle distribution during storms can be used to test the importance of these wave-particle scattering processes on the dynamical evolution of the radiation belts.

Mike Wiltberger
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Advances in Magnetospheric Modeling

M. Wiltberger, J. G. Lyon, W. Lotko, F. R. Toffoletto

An accurate understanding of the spatial and temporal evolution of the magnetic field in the inner magnetosphere is essential to modeling the behavior of energetic particles. Global scale numerical models using ideal MHD have proven effective in reproducing some of the observed characteristics of these events, but there a several problems that remain to be address. A key factor in the structure of the magnetic field during storms is the development of the ring current which is not well represented in global models like the Lyon-Fedder-Mobarry global MHD code. We will present recent work using the Rice Convection Model to add this physics to the simulation of the magnetosphere. Another key feature that effects the evolution of the system is the outflow of plasma from the ionosphere into the inner magnetosphere. We will also present work on the development of causally driven empirical model for ionospheric outflow. Ionospheric outflow includes a significant fraction of ionized oxygen which requires the implementation of multifluid version of the basic MHD solver to handle correctly its impacts on the system. I will conclude this presentation of how these modifications will effect coupling the energetic particle simulations driven by the electric and magnetic fields taken from the MHD solutions for the magnetosphere.