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Radiation belt dynamics: The importance of wave-particle interactions

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[1] The flux of energetic electrons in the Earth's outer radiation belt can vary by several orders of magnitude over time scales less than a day, in response to changes in properties of the solar wind instigated by solar activity. Variability in the radiation belts is due to an imbalance between the dominant source and loss processes, caused by a violation of one or more of the adiabatic invariants. For radiation belt electrons, non-adiabatic behavior is primarily associated with energy and momentum transfer during interactions with various magnetospheric waves. A review is presented here of recent advances in both our understanding and global modeling of such wave-particle interactions, which have led to a paradigm shift in our understanding of electron acceleration in the radiation belts; internal local acceleration, rather than radial diffusion now appears to be the dominant acceleration process during the recovery phase of magnetic storms. **Citation:** Thorne, R. M. (2010), Radiation belt dynamics: The importance of wave-particle interactions, *Geophys. Res. Lett.*, *37*, L22107, doi:10.1029/2010GL044990.

1. Introduction

[2] In the basically collision-less magnetosphere, changes in the energetic electron population are controlled by interactions with a variety of plasma waves, which lead to violation of one or more of the particle adiabatic invariants [*Schulz and Lanzerotti*, 1974]. Consequently, our ability to understand and model the dynamic variability of the radiation belts requires the development of global models of the power spectral intensity and polarization characteristics of all important magnetospheric waves, and their variability due to changes in either solar wind forcing or geomagnetic activity. This information is needed to evaluate bounce-averaged rates of pitch-angle scattering, energy diffusion, and radial diffusion. Simulation of the dynamical variability of the radiation belts can subsequently be obtained from multi-dimensional transport codes, which have recently been developed to incorporate these important physical processes [*Miyoshi et al.*, 2006; *Jordanova et al.*, 2007, 2010; *Fok et al.*, 2008; *Tao et al.*, 2008, 2009; *Varotsou et al.*, 2008; *Albert et al.*, 2009; *Shprits et al*, 2009b; *Subbotin and Shprits*, 2009; *Tu et al.*, 2009].

[3] During magnetically active periods, intense plasma waves are excited in the magnetosphere, which are able to violate all three electron adiabatic invariants. Low frequency hydromagnetic waves can violate the third adiabatic invariant and cause radial diffusion [*Perry et al.*, 2005]. Higher frequency kinetic waves, which are excited by the injection of plasma sheet particles into the outer radiation zone during enhanced convection (Figure 1), can violate the first and second adiabatic invariants, leading to energy diffusion (local stochastic acceleration) and pitch-angle scattering (with ultimate loss to the atmosphere) [*Horne and Thorne*, 1998; *Shprits*, 2009]. The rates of scattering associated with these non-adiabatic processes [e.g., *Summers et al.*, 2007; *Albert*, 2008] lead to a net source or loss at any given location in the radiation belts [*Selesnick*, 2006]. All important processes must therefore be carefully evaluated to understand the dynamic response of energetic particle fluxes to solar activity. Previous reviews of the dominant source and loss processes for the radiation belts were given by *Millan and Thorne* [2007] and *Shprits et al.* [2008a, 2008b]. With the upcoming launch of NASA's LWS Radiation Belt Storm Probe mission, this review provides a timely update of recent progress in our understanding of wave-particle interactions. A brief summary is given of the observational properties of important magnetospheric waves, their excitation process, and their potential ability to cause variability in the radiation belts.

2. ULF Waves and Radial Diffusion

[4] Ultra Low Frequency (mHz) waves are excited at the magnetopause boundary in response to velocity shear [*Claudepierre et al.*, 2008] or solar wind pressure fluctuations [*Ukhorskiy et al.*, 2006; *Claudepierre et al.*, 2009]. Hydromagnetic waves may also be excited internally by natural instability of the magnetospheric plasma. The global distribution and variability of low frequency Pc4 and Pc5 waves can be monitored by ground-based magnetometers and by satellites [*Liu et al.*, 2009], and the observed wave spectral characteristic have been used to evaluate radial diffusion coefficients [*Brautigam et al.*, 2005; *Perry et al.*, 2005; *Ukhorskiy et al.*, 2005; *Huang et al.*, 2010] and employed in dynamic modeling of the outer radiation belt [*Loto'aniu et al.*, 2006a; *Ukhorskiy et al.*, 2009; *Chu et al.*, 2010]. The properties of magnetospheric ULF waves, excited in response to solar wind variability, have also been obtained from global MHD simulations and used to study the dynamic variability of radiation belt electrons [*Fei et al.*, 2006; *Kress et al.*, 2007].

[5] Inward radial diffusion was originally thought to be the dominant mechanism for energizing particles in the radiation belts as they are transported inwards from a source region at higher L [*Schulz and Lanzerotti*, 1974]. However, recent analyses of energetic electron phase space density clearly indicate a peak in the radial profile near L~5 [*Chen et al.*, 2006, 2007; *Ni et al.*, 2009a, 2009b], which becomes more pronounced as the electron flux is enhanced in the recovery phase of a storm. The peak in phase space density is indicative of a local acceleration source operating in the heart of

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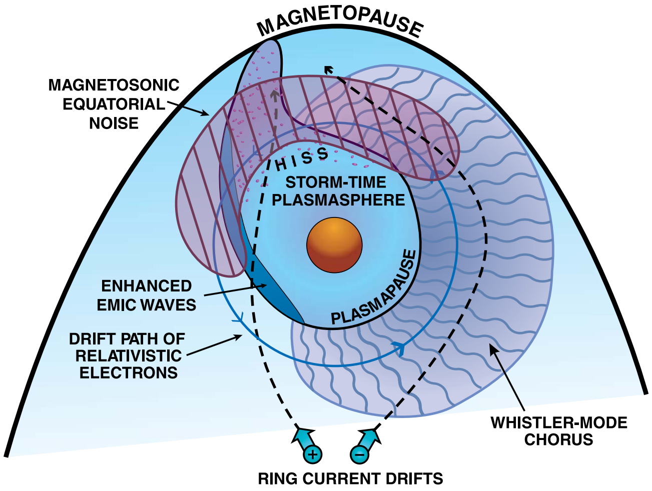

Figure 1. Schematic illustration of the spatial distribution of important waves in the inner magnetosphere, in relation to the plasmasphere and the drift-paths of ring-current (10–100 keV) electrons and ions and relativistic (≥0.3 MeV) electrons.

the outer radiation belt. The presence of this additional source in the storm recovery has also been inferred from the innovation vector of Kalman filter analyses [*Shprits et al.*, 2007]. Radial diffusion interior to the peak can still lead to electron acceleration [*Selesnick and Blake*, 1997; *Chu et al.*, 2010], but outward radial diffusion exterior to the peak leads to de-energization and ultimate loss to the magnetopause [*Shprits et al.*, 2006b].

3. Chorus Emissions

[6] Chorus emissions are discrete coherent whistler mode waves, which occur in two distinct bands above and below one-half the electron gyrofrequency f_{ce} [*Tsurutani and Smith*, 1974]. Chorus is important since it plays a dual role in both the loss and local acceleration of radiation belt electrons [*Bortnik and Thorne*, 2007] and is the dominant scattering process leading to diffuse auroral precipitation [*Ni et al.*, 2008; *Nishimura et al.*, 2010; *Thorne et al.*, 2010].

3.1. Properties of Chorus and Global Distribution

[7] A statistical analysis of the global distribution of chorus observed on the THEMIS spacecraft indicates that the spectral intensity is highly variable and responds to geomagnetic activity [*Li et al.*, 2009a]. Chorus is enhanced over a broad spatial region [*Hayosh et al.*, 2010] exterior to the plasmapause (Figure 1) associated with cyclotron resonant excitation during the convective injection of plasma sheet electrons into the magnetosphere [*Li et al.*, 2008, 2009b]. Nightside chorus is strongest inside L = 8, and is also confined to latitudes below 15^0, due to strong Landau damping of oblique waves during their propagation towards higher latitude from the equatorial source region [*Bortnik et al.*, 2007]. In contrast, dayside chorus is found over a broad range of latitudes, is most intense in the outer (L ~ 8) magnetosphere, and shows less dependence on geomagnetic activity [*Tsurutani and Smith*, 1977; *Li et al.*, 2009a]. The wave normal distribution of chorus is required to accurately evaluate resonant electron energies and quantify the associated rates of scattering [*Shprits and Ni*, 2009]. Unfortunately, recent satellite observations [*Chum et al.*, 2007; *Breneman et al.*, 2009; *Santolík et al.*, 2009; *Haque et al.*, 2010] indicate a wide range of values for this key property, which adds uncertainty to modeling studies.

3.2. Chorus Excitation Mechanisms

[8] Chorus is excited during cyclotron resonant interaction with plasma sheet electrons that are injected into the inner magnetosphere during enhanced convection [*Hwang et al.*, 2007]. Simulation of the linear phase of excitation of nightside chorus observed on CRRES and THEMIS, using measured injected electron distribution, yields a path-integrated gain well in excess of 100 db [*Li et al.*, 2008, 2009b], which is sufficient to drive the wave amplitudes to non-linear levels. The non-linear growth and saturation of parallel propagating chorus has been simulated by *Katoh and Omura* [2007] and *Omura et al.* [2008]. Simulation of the convective injection of anisotropic plasma sheet electrons into the inner magnetosphere during a magnetic storm with the coupled RCM and RAM codes has been used to evaluate the global distribution of excited chorus emissions [*Jordanova et al.*, 2010]. The results of this modeling agree well with the statistical distribution obtained from satellite observations on the nightside [*Li et al.*, 2009a]. However, understanding dayside chorus excitation remains problematic [*Tsurutani et al.*, 2009; *Santolík et al.*, 2010; *Spasojevic and Inan*, 2010], since the waves often occur under relatively quiet geomagnetic conditions, when the resonant electron flux is low [*Li et al.*, 2010].

3.3. Role of Chorus in Scattering Loss of Radiation Belt Electrons

[9] Pitch-angle scattering during cyclotron and Landau resonance with chorus emissions provides a major mechanism for diffusive transport towards the loss cone and ultimate loss by collisions in the atmosphere for a broad range of electron energies [*Lam et al.*, 2010; *Hikishima et al.*, 2009, 2010; *Orlova and Shprits*, 2010]. Corresponding electron lifetimes, which are primarily controlled by scattering rates near the edge of the loss cone [*Shprits et al.*, 2006c, 2006d], range from values near the minimum lifetime associated with strong diffusion (~an hour) at energies below 10 keV [*Ni et al.*, 2008] to values comparable to a day at MeV energies [*Thorne et al.*, 2005].

3.4. Role of Chorus in Local Stochastic Acceleration

[10] Chorus emissions also provide an efficient mechanism for energy transfer between the injected low-energy (few keV) electron population, which generates the waves, and the trapped high energy radiation belt electrons by the process of energy diffusion [*Horne and Thorne*, 2003]. Calculations of quasi-linear energy diffusion rates demonstrate that outer zone electrons can be accelerated to relativistic energies on timescale comparable to a day [*Albert*, 2005; *Horne et al.*, 2005a]. Simulations of specific storm events has demonstrated that energy diffusion by chorus can account for electron flux enhancement in the outer radiation belt in association with sustained geomagnetic activity [*Tsurutani et al.*, 2006] during the storm recovery [*Horne et al.*, 2005b; *Shprits et al.*, 2006a] and for the refilling of the electron slot between the inner and outer radiation belts during a storm [*Thorne et al.*, 2007]. Furthermore, despite

the rapid scattering loss, a 2D simulation of energy and pitch-angle diffusion [*Li et al.*, 2007], with a global chorus distribution modeled on statistical wave observations, demonstrates that chorus leads to a net MeV electron flux enhancement over a period of a few days in the recovery phase of a magnetic storm consistent with observations [*Kasahara et al.*, 2009]. The importance of local stochastic acceleration by chorus, relative to acceleration associated with inward radial diffusion, has recently been demonstrated by modeling with 3D diffusion codes [*Albert et al.*, 2009; *Varotsou et al.*, 2008; *Shprits et al.*, 2009b].

3.5. Non-linear Interactions

[11] Extremely intense chorus emissions are occasionally observed [*Cattell et al.*, 2008; *Tsurutani et al.*, 2009] with amplitudes (>100 mV/m) far in excess of those where quasi-linear scattering is valid. A statistical analysis of intense chorus waves observed on THEMIS, with amplitudes 10 times larger than the mean, indicates a relatively high frequency (~2.5%) of occurrence [*Cully et al.*, 2008]. Non-linear test particle scattering of resonant electrons in such large amplitude waves [*Roth et al.*, 1999; *Bortnik et al.*, 2008a] shows that resonant electrons tend to exhibit advective transport towards the loss cone rather than the stochastic diffusive behavior. Such advective scattering could dramatically increase the average rate of resonant electron loss, and may thus be related to the observed electron dropouts [*Onsager et al.*, 2007; *Morley et al.*, 2010] during the main phase of magnetic storms. Non-linear phase trapping of electrons in large amplitude chorus can also lead to non-diffusive acceleration at relativistic energies [*Albert*, 2002; *Furuya et al.*, 2008; *Summers and Omura*, 2007].

4. Plamaspheric Hiss

[12] Hiss is an incoherent whistler-mode emission mostly confined within the dense plasmasphere and within dayside plasmaspheric plumes. Over the years there has been controversy over the origin of this important emission [*Green et al.*, 2006; *Meredith et al.*, 2006a; *Thorne et al.*, 2006], which is mainly responsible for the formation of the quiet time electron slot between the inner and outer radiation belt [*Lyons and Thorne*, 1973; *Abel and Thorne*, 1998]. Recent ray trace modeling has finally resolved the issue and shown that hiss originates from a subset of chorus emissions that avoid Landau damping during propagation from the equatorial source region to higher latitude. Such waves also propagate to lower L where they enter and are trapped within the plasmasphere, where the discrete chorus emission merge together to form incoherent hiss [*Bortnik et al.*, 2008b, 2009a]. The unexpected association between hiss and chorus has been confirmed by simultaneous observations on two THEMIS spacecraft [*Bortnik et al*, 2009b] and differences in the statistical MLT distribution of the two emissions has been explained by 3D ray tracing [*Chen et al.*, 2009b].

[13] Observed characteristics of hiss have been used to evaluate electrons lifetimes within the plasmasphere and account for the slow decay of the outer radiation belts following storm time enhancements [*Meredith et al.*, 2006b, 2007, 2009a; *Baker et al.*, 2007]. Hiss is also observed in plasmaspheric plumes during a storm, and such waves are sufficiently intense ($B_W \sim 100$ pT) to contribute significantly to the scattering loss of outer zone electrons [*Summers et al.*, 2008].

5. Equatorial Magnetosonic (MS) Waves

[14] Equatorial magnetosonic waves are highly oblique whistler-mode emissions excited within a few degrees of the equatorial plane at frequencies between the proton gyrofrequency and the lower hybrid [e.g., *Santolík et al.*, 2004]. The waves are observed both inside and outside the plasmapause and are excited by a cyclotron resonant instability with a ring distribution of injected ring current ions [*Horne et al.*, 2000]. CRRES data has been used to confirm the association between MS waves and the presence of ion rings [*Meredith et al.*, 2008]. Kinetic modeling of ring current ion evolution with the RAM code has been employed to simulate the development of ion rings and the global distribution and spectral properties of MS wave growth [*Chen et al.*, 2010b]. MS waves also undergo a Landau resonance with radiation belt (100 keV – few MeV) electrons, and the spectral properties of intense MS waves observed on Cluster have been used to demonstrate that timescale for energy diffusion (~day) can be comparable to that due to chorus scattering [*Horne et al.*, 2007]. Test particle scattering of electrons in a finite amplitude MS wave have confirmed the rate of Landau resonant scattering [*Bortnik and Thorne*, 2010] and demonstrated additional non-resonant “transit time” scattering due to the equatorial confinement of MS wave power.

6. Electromagnetic Ion Cyclotron Waves

6.1. EMIC Wave Properties and Excitation

[15] EMIC waves are discrete electromagnetic emission, which occur in distinct frequency bands separated by the multiple ion gyrofrequencies. The EMIC source region is typically confined within ~10 degrees of the geomagnetic equatorial plane, and the Poynting flux at higher latitude is always directed away from the equator, dispelling the long-standing bouncing wave packet model [*Loto’aniu et al.*, 2005]. The wave group velocity is closely aligned with the magnetic field direction, allowing the waves to propagate to the Earth where they are observed in the Pc1 and Pc2 bands [*Engebretson et al.*, 2008]. EMIC waves are enhanced during magnetic storms [*Fraser et al.*, 2010], as anisotropic energetic ring current ions are injected into the inner magnetosphere [*Jordanova et al.*, 2008]. Favored regions for EMIC excitation include the overlap between the ring current and the plasmasphere [*Pickett et al.*, 2010], dayside drainage plumes [*Morley et al.*, 2009], and the outer dayside magnetosphere in association with solar wind pressure fluctuations [*Arnoldy et al*, 2005; *Usanova et al.*, 2008; *McCollough et al.*, 2009]. Theoretical global modeling of EMIC wave excitation has confirmed the plasmapause and plume as favored regions of cyclotron resonant instability [*Jordanova et al.*, 2007; *Chen et al.*, 2010a] and demonstrated that the wave excitation can also be enhanced by density fluctuations within a plume [*Chen et al.*, 2009a]. Hybrid codes have recently been used to evaluate the spectral properties and ultimate saturation amplitudes of EMIC waves [*Hu and Denton*, 2009; *Omidi et al.*, 2010]. Such information is important for an accurate assessment of the role of EMIC waves on the global rates of resonant ion and electron precipitation.

6.2. Resonant Scattering Loss of Ring Current Ions and Relativistic Electrons

[16] Resonant pitch-angle scattering and ultimate precipitation of ring current protons by EMIC waves in dayside plasmaspheric plumes has been directly associated with observations of detached sub-auroral proton arcs [*Jordanova et al.*, 2007; *Spasojevic and Fusilier*, 2009; *Yuan et al.*, 2010]. EMIC waves can also cause the resonant scattering of relativistic electrons leading potentially to rapid loss during the main phase of a storm [*Thorne and Kennel*, 1971; *Bortnik et al.*, 2006]. However, such scattering only occurs at geophysically interesting energies (~MeV) when EMIC waves are excited in regions of high plasma density and have significant power at frequencies just below the He^+ gyrofrequency [*Li et al.*, 2007; *Shprits et al.*, 2009a]. Observed properties of EMIC waves have been used to evaluate rates of quasi-linear pitch-angle scattering [*Loto'aniu et al.*, 2006b; *Ukhorskiy et al.*, 2010], and test particle scattering has been performed for large amplitude EMIC waves [*Albert and Bortnik*, 2009; *Liu et al.*, 2010]. A global ring current code has also been used to model EMIC excitation and evaluate the rate of electron scattering loss [*Jordanova et al.*, 2008], and several independent observational studies have linked the precipitation of relativistic electrons with EMIC wave scattering [*Clilverd et al.*, 2007; *Millan et al.*, 2007; *Miyoshi et al.*, 2008; *Rodger et al.*, 2008].

7. Electrostatic Electron Cyclotron Harmonic Waves

[17] ECH waves are electrostatic emissions, which occur in harmonic bands between multiples of the electron gyrofrequency. These waves are excited by the loss cone instability of injected plasma sheet electrons [e.g., *Horne and Thorne*, 2000]. The global distribution of ECH emission intensity and its dependence on geomagnetic activity has been analyzed by *Meredith et al.* [2009b] and shown to be similar to that of chorus. However, although ECH emissions resonate with and cause the scattering loss of plasma sheet electrons below a few keV, their contribution to diffuse auroral precipitation is insignificant in comparison to scattering by chorus [*Thorne et al.*, 2010].

8. Summary and Conclusions

[18] Over the last 5 years major advances have been made in our understanding of the origin and spectral characteristics of several key magnetospheric waves and their influence on the dynamic variability of radiation belt electrons. Codes have been developed to accurately evaluate bounce and drift-averaged rates of quasi-linear pitch-angle and energy diffusion and thus evaluate temporal changes in the phase space density of radiation belt electrons due to processes that violate the first adiabatic invariant. Rates of radial diffusion have been parameterized, based on available information of the properties of ULF waves or by MHD simulations. A combination of theoretical modeling and observations of the radial profile of electron phase space density has lead to a paradigm shift in our understanding of electron acceleration in the radiation belts; internal local acceleration, rather than radial diffusion now appears to be the dominant acceleration process during the recovery phase of magnetic storms. It has also been shown that non-linear scattering can at times lead to very different rates of transport compared to the expectations of quasi-linear theory, and these effects need to be included in future global modeling. 3D diffusion-advection codes and 4D transport codes are being developed, which will ultimately be capable of incorporating all important non-adiabatic processes. However, the ability of such modeling to simulate or potentially predict changes in the radiation belts in response to solar variability will ultimately be dependent on the accuracy of the global wave models. Nonetheless, the wave-particle community has made great strides to get ready for the launch of the LWS Radiation Belt Storm Probes, and we eagerly await the first comprehensive measurements of waves and particles from two identically instrumented spacecraft that this mission will bring to the field.

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