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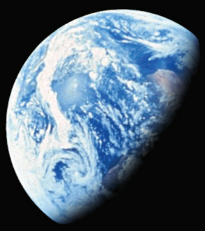
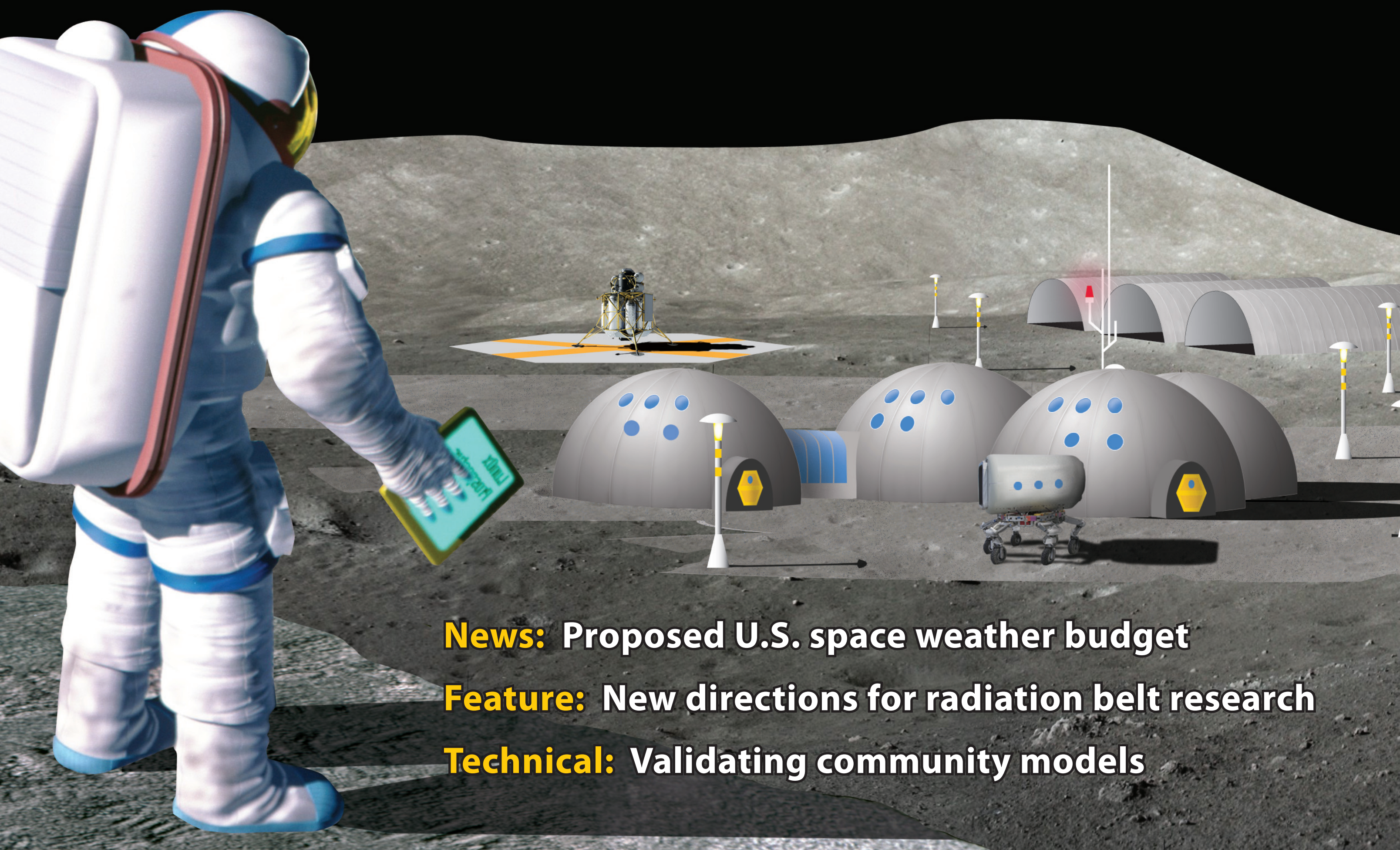


Protecting Lunar Colonies From Space Radiation



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New Directions for Radiation Belt Research

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The Earth's radiation belts have fascinated and puzzled scientists for more than 50 years. Scientists know that extremely energetic electrons and protons are trapped in the geomagnetic field, but how did they get so energetic? Measurements show that the radiation belts can change in intensity by many orders of magnitude, but what makes them change so dramatically? Solar activity and interplanetary disturbances affect the belts' structure and characteristics, but what are the processes that connect cause to effect? Researchers do not yet have answers to these fundamental questions. However, recent observational and theoretical work has led to a growing consensus on the new directions in radiation belt research that will be the key to answering these questions.

These questions are important not just to science—radiation belt dynamics also have important economic and societal consequences. Protons and electrons within the radiation belts have energies that can penetrate the bodies of spacecraft and space instruments, potentially affecting the materials, circuits, and detectors inside those structures. The penetrating radiation from these particles has a variety of adverse effects on spacecraft systems including total dose, material activation, displacement damage, internal charging/discharging, and single-event upsets/latch-up. These penetrating radiation effects are responsible for satellite malfunctions, degradation of on-orbit performance, and in extreme cases, expensive (and disruptive) satellite failures.

The effect on detectors in scientific and operational instruments can be even more complex because of secondary radiation, produced by the interaction of satellite materials with radiation belt electrons and protons. Secondary radiation products include electrons, neutrons, X rays, and gamma rays.

Understanding the processes that accelerate charged particles to extreme energies is critical for predicting and mitigating their space weather effects as well as for understanding the fundamental nature of energetic particle acceleration, which is also present in less accessible solar, planetary, and astrophysical systems.

Over the past decade, the rate of publication of new observations, theories, and models of the Earth's radiation belts has increased dramatically. During times of such fast paced change, it is useful to reflect on how new developments interrelate and where areas of consensus and controversy are beginning to crystallize. Such an opportunity was offered recently at an international workshop on radiation belt physics held on Rarotonga, in the Cook Islands. This workshop was the latest in a series of meetings dating back to 1994 that have brought scientists together to hold informal yet in-depth discussions of radiation belt physics and related magnetospheric and heliospheric processes.

Scientific discussions often highlight differences in opinion or evidence for a particular hypothesis, producing creative friction that leads to further investigations (see *Shprits et al.* [2008a, 2008b] for recent overviews of radiation belt topics). Less common are discussions that reveal new common understandings. Yet such intervals of consensus are also important—they refocus scientific activity on major open questions. The Rarotonga radiation belt workshop resulted in remarkable agreement on several key topics in radiation belt studies: the importance of local acceleration in electron radiation belt dynamics, the role of electromagnetic "chorus" waves (a specific class of electromagnetic waves) as the source of that acceleration, the competing role that chorus waves play in depleting the radiation belts, other candidate processes for acceleration and losses, and the new theoretical tools and numerical models that can be used to quantitatively test understanding.

Particle Acceleration in the Radiation Belts

According to the traditional explanation for acceleration of particles in radiation belts, fluctuations in the large-scale geomagnetic field allow particles to radially diffuse and gain energy as they travel. In this theory (letting L represent the distance in Earth radii at which a magnetic field line crosses the equator) the source of electrons is the plasma sheet at $L \gtrsim 7$ and the sink is the Earth's atmosphere at $L \approx 1$. The observed presence of an "inner belt" and "outer belt" is attributed to a "slot region" that forms near $L = 3$, where electron loss lifetimes become shorter than diffusion timescales [*Schulz and Lanzerotti,* 1974].

Numerous studies demonstrate that radial diffusion is real and affects radiation belt structure and dynamics in profound ways. However, a growing body of observational evidence indicates that radial diffusion alone cannot explain the full range of radiation belt dynamics. For example, simultaneous multisatellite observations of the electron belt at the outer edge ($L \gtrsim 7$), in the center, and at the inner edge ($L \lesssim 4$) recently showed that increases in intensity started in the middle of the belts, not at the edges, as would be required by diffusion acting alone [*Chen et al.,* 2007]. Observations such as these have led to the search for an alternative (or, more likely, complementary) mechanism that can accelerate electrons locally, at the most intense parts of the belts.

These results are supported by global magnetohydrodynamic (MHD) models, which provide both the global configuration of electric and magnetic fields and the fluctuations in those fields, enabling direct calculation of the amount and location of energization [*Fei et al.,* 2006]. MHD models can also be used to drive test particle simulations that track the motion, trapping, and acceleration of radiation belt electrons. These tests reveal that some enhancements require local particle acceleration [*Elkington et al.,* 2004]. Similarly, data assimilation techniques that estimate the strength and location of acceleration suggest that significant local acceleration is required in most cases.

The convergence of results from a variety of techniques leads to the emerging consensus that in addition to radial diffusion, some other mechanism accelerates electrons locally, at the most intense parts of the belts.

The Role of Chorus Waves

Acceleration by chorus waves is a leading candidate process for local radiation belt electron acceleration because (1) theories show they are capable of accelerating relativistic electrons and (2) they have been observed at appropriate times and places.

As an electron moves along and gyrates around a magnetic field line, it may encounter an electromagnetic wave with frequency, polarization, and wave vector such that the electron experiences a constantly directed electric field in its own rest frame. This electron can extract energy from the wave, causing the particle to accelerate. Such processes (including gyroresonance and Landau resonance) are collectively referred to as local wave-particle acceleration because they do not rely on radial transport across field lines.

But what kinds of waves accelerate electrons? Observations show that electrons with megaelectron volt (MeV) energies resonate with waves in the ultralow frequency (ULF) to very low frequency (VLF; <1 to tens of kilohertz) ranges. Commonly observed in the magnetosphere, VLF chorus waves (classified as electromagnetic whistler mode waves) are thought to be generated by unstable electron distributions produced when hot plasma sheet electrons are convected, or injected, into the inner magnetosphere. Most radiation belt acceleration events occur during geomagnetic storms when near-Earth convection and substorm particle injections are enhanced [*Reeves,* 1998]. Because the electron source is above the Earth near midnight local time, and the electrons drift eastward in the geomagnetic field, chorus waves are typically observed in the dawnside hemisphere.

VLF chorus waves were the primary (but not the only) mechanism for accelerating electrons discussed at the Rarotonga workshop. Observations and theory point to several important characteristics of chorus waves: They form near the magnetic equator, propagate away from the equator in both hemispheres, and are damped before they can be reflected back toward the equator (Figure 1). As a result, MeV electrons resonate with the waves in the same manner during each half of their bounce motion for net energy gain. Several recent studies have presented indirect but compelling evidence of this mechanism. For example, *Horne et al.* [2007] documented satellite observations of VLF chorus waves in strong electron acceleration events, such as those seen during storm recovery. These acceleration events occur deep in the radiation belts, where radial diffusion is expected to be slow.

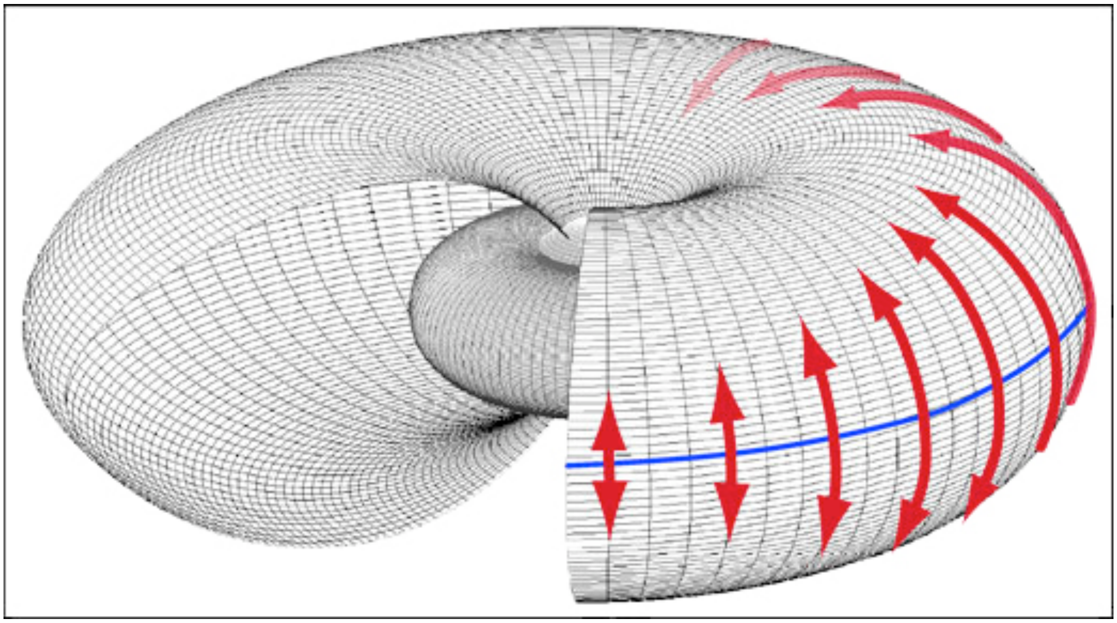

Figure 1. Chorus waves propagate from the equator following a specific pattern. Electrons that are injected on the nightside drift eastward toward noon. Near midnight, chorus waves are strongly damped and stay near the equator. As the electrons drift, their distributions change, allowing chorus waves to propagate to higher latitudes, where they may also further intensify before they eventually lose their energy [see *Bortnik et al.,* 2007].

As the plasma sheet electrons drift eastward from midnight to noon, the characteristics for generating chorus waves, and perhaps more important, the conditions for damping these waves, change. Theory and observations suggest that in predawn local times, chorus waves are damped before they can propagate very far from the magnetic equator. At postdawn local times, chorus waves propagate to higher latitudes and possibly grow in amplitude. Radiation belt electrons spend different amounts of time at different latitudes depending on the angle between the local magnetic field and the particle velocity vector (pitch angle). Thus, the effect of chorus waves varies with local time.

Effects of Wave-Particle Resonance

A characteristic feature of local wave-particle interactions is that resonances change an electron's pitch angle as well as its energy—a process known as pitch angle scattering or pitch angle diffusion—which can deplete the radiation belts by scattering particles into the atmosphere. Such diffusion is different from but coupled to "energy diffusion," which can increase the intensity of the radiation belts.

Recently, much effort has been devoted to developing new theoretical and numerical schemes for calculating energy, pitch angle, and cross-diffusion coefficients, which are needed to quantify electron energization rates and pitch angle scattering. Schemes that treat the full range of wave normal angles and frequencies require expensive, time-consuming calculations. Scientists have used simplifying approximations such as assuming only parallel-propagating waves, but those approximations do not represent the full physics.

The Rarotonga workshop introduced new techniques that preselect a finite number of resonances over a range of frequencies and wave vectors. These new techniques promise a "sweet spot" between physical accuracy and computational resources [*Albert,* 2007]. Numerically solving the diffusion equation with the full set of diffusion coefficients is another challenge, met by diagonalizing the diffusion matrix through a change of variables [*Albert and Young,* 2005]. An alternative approach avoids the numerical pitfalls of finite difference schemes by using stochastic differential equations (SDEs) to advance particle distribution [*Tao et al.,* 2008].

Figure 2 illustrates how energy and pitch angle diffusion affect particle distributions. The figure plots velocities parallel and perpendicular to the magnetic field. The red arcs represent contours of constant energy as a function of equatorial pitch angle (α). The blue curves represent a diffusion surface along which particles will "move" in energy and pitch angle as they interact with chorus waves. The particular conditions of wave power spectral density and plasma conditions will determine the range of pitch angles and energies over which resonance occurs, represented by the shaded green areas. Within the resonance region, diffusion will move particles from regions of higher to those of lower phase space density (flux over momentum squared). Phase space density decreases with increasing energy and for pitch angles nearly parallel to the magnetic field. Therefore, in this simplistic picture, chorus waves that resonate with large pitch angles will energize electrons with large pitch angles and scatter them toward the geomagnetic equator while waves that interact with electrons that have small equatorial pitch angles (and mirror at high latitudes) will tend to scatter them along the field, toward the atmosphere.

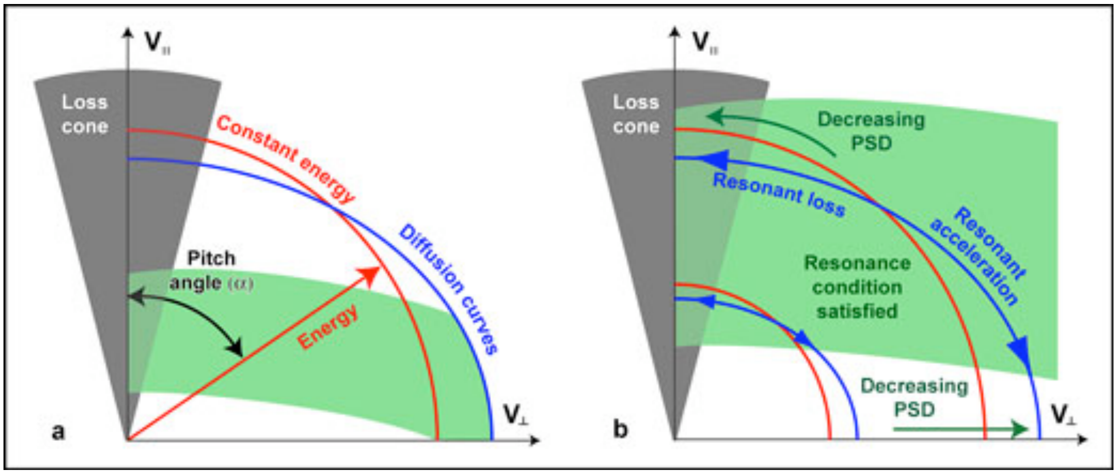

Figure 2. A schematic of energy and pitch angle diffusion from resonant chorus wave interactions. Constant energy curves are represented in red. The resonance conditions are satisfied for pitch angles and energies represented by green areas. The axes represent velocity parallel and perpendicular to the magnetic field; higher velocities (and thus higher energies) have lower phase space density (PSD). (a) Resonantly interacting electrons will move along the diffusion curves (blue), changing both energy and pitch angle. (b) An expanded detail showing the resonance interaction region and effects. Lower PSDs are found in the loss cone and at higher energies. Within the resonance region, these gradients can cause energy and pitch angle diffusion that scatter electrons into the loss cone or cause them to accelerate and move toward 90° pitch angles. The resonances that control energization and pitch angle scattering are thought to play a critical role in radiation belt dynamics.

What If It Isn't Chorus Waves?

Observations of radiation belt dynamics show the key role played by local wave-particle interactions. Observations, however, are not yet sufficiently detailed to say for certain whether chorus waves or some other electromagnetic wave is responsible. Electromagnetic waves called magnetosonic waves are another candidate [*Horne et al.,* 2007]. Magnetosonic waves, generated by plasma distributions that have energy peaks in the 10- to 30-kiloelectron volt (keV) range, are known as "proton ring distributions." Like chorus waves, magnetosonic waves can efficiently accelerate electrons in the 30-keV to several megaelectron volt energy range.

Current observations cannot distinguish between the effects of chorus and magnetosonic waves—or even other resonant wave modes. Additionally, nonlinear interactions (for both energy and pitch angle scattering) are also thought to be important when wave amplitudes are large, but the expected macroscopic effects are still poorly understood.

Understanding Radiation Belt Depletions

While flux enhancements have a more direct effect on satellite systems, flux depletion events are equally important in radiation belt dynamics. In the case of depletions, though, several processes are known to operate, and the outstanding questions concern which are most important and under what circumstances. Loss to the magnetopause determines the outer boundary of the outer radiation belt [*Ukhorskiy et al.,* 2006], and loss to the atmosphere by scattering due to plasmaspheric hiss controls the inner edge of the outer belt [*Li et al.,* 2001]. Within the outer belt, periods of rapidly decreasing relativistic electron fluxes are produced either by enhanced transport toward the inner or outer sink regions or by scattering of electrons into the atmospheric loss cone.

Of the candidate processes for enhanced electron precipitation into the atmosphere, electromagnetic ion cyclotron (EMIC) waves are the most frequently discussed. EMIC waves are produced by temperature anisotropies when the low-energy storm-time ring current (which determines the strength of geomagnetic storms) or plasma sheet ions are injected into the radiation belt regions. EMIC waves can produce strong pitch angle scattering, which can rapidly fill the loss cone with electrons. The lower-energy limit of that interaction is controlled by plasma density and composition, so the conditions that produce EMIC waves inside the high-density plasmasphere (or its plumes) are important to the precipitation of MeV electrons. However, much remains unknown about the generation, propagation, statistical occurrence, and effects of EMIC waves [*Fraser et al.,* 2006].

In addition to satellite measurements, it is hoped that ground-based [*Clilverd et al.,* 2007; *Rodger et al.,* 2007] and balloon [*Millan et al.,* 2007] observations will provide critical insights to help determine the relative importance of various electron loss mechanisms.

A Critical Turning Point

As recently as 2 years ago, sessions at conferences asked whether local wave-particle interactions were even important for radiation belt dynamics. Now scientists are recognizing an emerging consensus: New observations and analyses provide definitive evidence that local wave-particle interactions play a fundamental role in accelerating radiation belt electrons. This has refocused research, shifting questions from whether local acceleration is important to questions such as, How does local acceleration work? Which waves? When do they act? How do those processes combine with others?

Answering these questions and understanding and modeling the complex interactions between radiation belt electrons and various waves in the magnetosphere were recurring themes at the Rarotonga workshop. Similarly, understanding the effects of local wave-particle interactions in relationship to radial diffusion (as a function of energy, location, and storm phase) is a primary objective of NASA's Radiation Belt Storm Probes (RBSP) mission [*Reeves,* 2007], the Canadian Space Agency's Outer Radiation Belt Injection, Transport, Acceleration and Loss Satellite (ORBITALS) [*Mann et al.,* 2006], and the Japanese Energization and Radiation in Geospace (ERG) satellite [*Shiokawa et al.,* 2006].

While a new consensus on important processes has developed, current thought on radiation belt dynamics continues to evolve as new theories and observations fundamentally shift paradigms. Such a shift requires new observations and models to test theories and guide current and future radiation belt research.

For a description of the Rarotonga workshop and copies of presentations, see http://www.physics.otago.ac.nz/space/REPW2007_Home_Page.htm.

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