Earth's Radiation Belts:
The Hazards to Satellites and What Can Be Done to Mitigate the Risks?

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ABSTRACT

This talk covers several space weather impacts of the Earth's Van Allen radiation belts. Radiation belt particles are of particular interest to space weather and space situational awareness because they have energies sufficient to penetrate spacecraft shielding and cause internal damage to satellites. Radiation belt protons can cause single event effects (such as single event upsets, SEU) and radiation damage. Both protons and electrons contribute to satellite dose effects which often determine a satellite's operational lifetime. Radiation belt electrons can cause internal charging and discharging when the fluxes of electrons are sufficient to build up charges in insulators and semiconductors. The resulting discharges can damage or disable electric systems. Radiation belt fluxes change on many time scales - from hours to decades - meaning fluxes can often exceed design thresholds. The recent US National Space Weather Strategy and Action Plan [1] calls for, among other recommendations, the establishment of benchmark for the 1-in-100 year extremes of radiation belt intensities. Radiation belt fluxes that exceed even those intense levels can be produced by high altitude nuclear explosions (HANE). Fortunately, new programs are underway to systematically model, evaluate, and experimentally verify the effectiveness of potential radiation belt remediation systems (RBR).

1. THE EARTH'S RADIATION BELTS

The Earth's radiation belts are populations of extremely high energy charged particles (primarily protons and electrons) that are trapped in the Earth's magnetic field. Radiation belt particles have high enough energy that they can penetrate spacecraft shielding and cause damage or destruction of sensitive internal components.

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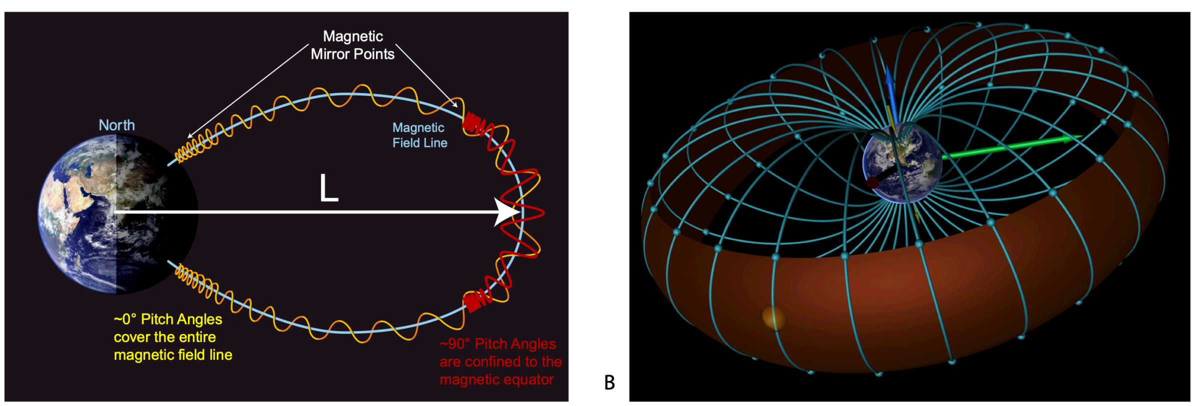


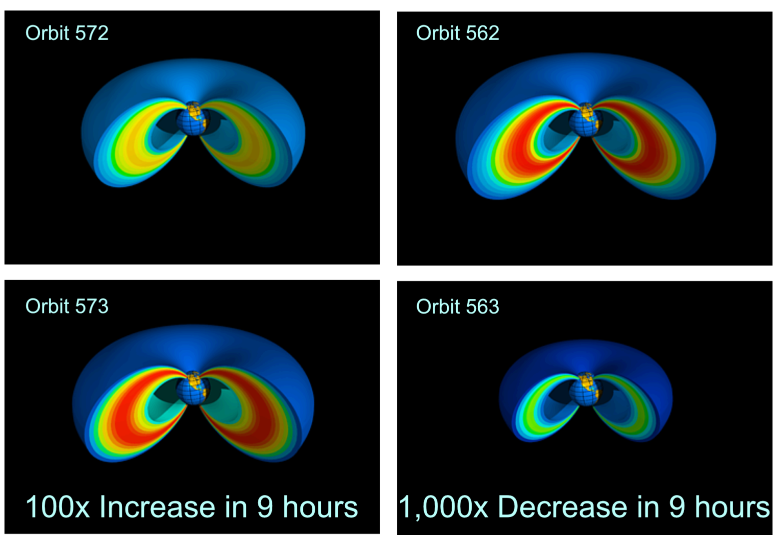
Fig. 1.The structure and dynamics of the Earth's radiation belts is defined by three types charged particle motion: gyration around the geomagnetic field, 'bounce' motion along the magnetic field between magnetic mirror points, and azimuthal 'drift' around the Earth on a shell defined by the parameter "L" [2, 3].

Any discussion of the radiation belts benefits from a basic explanation of charged particle motion in the Earth's magnetic field which is illustrated schematically in Fig. 1. The structure and dynamics of the Earth's radiation belts is defined by three types charged of particle motion. The first is gyration around the magnetic field line. This is the fastest motion and has a characteristic time scale of milliseconds. The second is 'bounce' along the magnetic field lines. Because the magnetic field intensity increases toward the Earth's surface particles will mirror (reverse direction) at points defined by the particle's pitch angle (the angle of the velocity vector relative to the magnetic field). Particles with ~0° or 180° pitch angle move nearly parallel or antiparallel to the magnetic field and will actually hit the Earth's atmosphere where they will be absorbed (as we will discuss later). Particles with pitch angles closer to 90° will be magnetically 'trapped' as they bounce between mirror points. Charged particles will also 'drift' azimuthally around the Earth on a surface called a 'drift shell' or 'L-shell'. The term 'L-shell' comes from a covenant quantity that defines the shell which, in a dipole magnetic field, is the distance from the center of the Earth to the magnetic equator measured in units of Earth radii (1 R_E = 6370 km: geosynchronous orbit is at L ≈ 6.6 R_E.). The parameter, L, is more convenient than, say, altitude because it defines the same set of particles regardless of their position along the field line or around the Earth.

The proton and electron radiation belts are quite different in origin and dynamics. The proton radiation belts occupy a region of space relatively close to the Earth (L < 3) and are composed of protons with energies greater than about 10 MeV. Their primary source is from the decay of neutrons produced by cosmic rays that hit the atmosphere [4]. Therefore, they tend to change slowly with the 11 year solar cycle. Their primary space weather effects are total dose, material displacement damage, and single event upsets/latchups. The proton belts are of particular concern for the operation of low-Earth orbit (LEO) satellites.

The electron radiation belts consist of relativistic (greater than ~0.5 MeV) electrons and are the primary focus of this paper. Typically the electron radiation belts consist of a relatively stable inner belt (L < 2) and a highly dynamic outer belt (L > 3) separated by a 'slot' region where fluxes are much lower. More recently the Van Allen Probes mission has shown that the outer belt can split into multiple belts [5], that the inner and outer belts can merge into a single belt [6], and that the inner belt rarely contains electrons with energies >1 MeV suggesting previous measurements may have been highly contaminated by penetrating radiation from the proton belt.

The outer electron radiation belts have also been shown to be extremely dynamic [7] in response to driving from the solar wind and internal acceleration and loss processes. Electron intensities can either increase or decrease by factors of 100 or 1,000 in a matter of hours. Fig. 2 shows fluxes from NASA's Polar satellite projected onto three-dimensional drift shells. The lower panels show the changes that occurred in just one orbit (9 hours) relative to the



previous orbit (upper panels).

Fig. 2. Data from NASA's Polar satellite projected onto 3D drift shells. Fluxes can increase or decrease by factors of a thousand from one orbit to the next (hours) in response to solar wind driving and radiation belt acceleration and loss processes. [image courtesy M. Henderson, LANL]

On the other extreme, radiation belt fluxes can also change on time scales of decades. Fig. 3. shows ~2 MeV electron fluxes from Los Alamos National Laboratory (LANL) sensors at geosynchronous orbit for most of the past three solar cycles (22-24) along with the monthly and smoothed sunspot numbers. Conditions that might appear as 'normal' in one phase of the solar cycle are poor indicators of conditions at other phases of the solar cycle. Likewise the conditions seen in the last (or last several) solar cycles may be poor indicators of conditions expected in the next solar cycle.

One of the primary hazards to satellites from radiation belt electrons is internal charging. Electrons that are energetic enough to penetrate spacecraft shielding deposit their charge in internal components where the charge can build up and discharge creating effects ranging from false signals to permanent damage of critical components and entire satellite failure. The amount of charging is a function of the electron flux, the energy spectrum, and the materials inside the spacecraft. Relatively good conductors can shed charge even at high flux levels. Semi-conductors and insulators can accumulate large internal charges even at moderate flux levels. Therefore the dynamics of the electron radiation belts are directly related to the level space weather hazard.

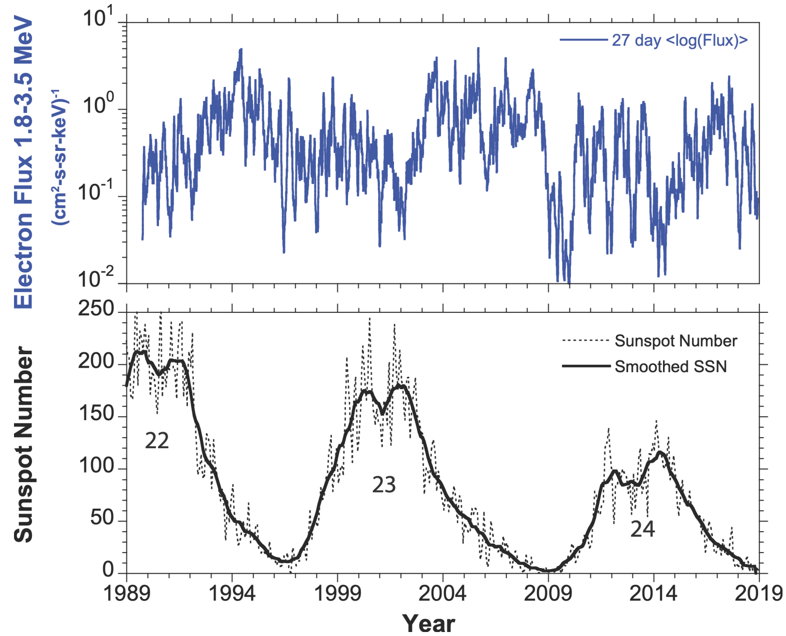


Fig. 3. Fluxes of 1.8-3.5 MeV (~2 MeV) electron fluxes from 1989-2019 (top) along with the sunspot number and smoothed sunspot number for most of solar cycles 22-24 (bottom). Radiation belt fluxes that are normal for one solar cycle or one phase of the solar cycle may not be good predictors of future conditions.

2. NEW UNDERSTANDING OF ELECTRON RADIATION BELT PROCESSES

The processes that control radiation belt dynamics can be broadly classified into acceleration processes and loss processes. Acceleration processes add energy to pre-existing, lower-energy electrons referred to as a ‘seed’ population. Electrons with energies too low to penetrate spacecraft shielding can become energized to MeV energies where they present much greater hazard. On the other hand loss processes typically do not work by de-energizing electrons. Rather, losses occur because MeV electrons are removed from the radiation belts either by exiting the magnetosphere into the solar wind and interplanetary space or by precipitating into the atmosphere where they are absorbed and therefore removed from the radiation belts.

NASA’s Van Allen Probes mission [8] which operated from 2012-2019 has dramatically increased our understanding of the Earth’s radiation belts and the processes that control them. So far the results from the Van Allen Probes (previously called the Radiation Belt Storm Probes, or RBSP) have produced over 700 papers representing a vast body of new physical understanding. Perhaps the most important paradigm shift concerns the coupling of the radiation belts to low-energy and medium-energy plasmas through the intermediary of electromagnetic waves.

Unstable distributions of low- and medium-energy plasmas are a source of free energy in the system that spontaneously converts to electromagnetic wave energy through linear and/or non-linear plasma instabilities. A variety of electromagnetic plasma waves with different properties can be produced under different conditions including waves known as ultra-low frequency (ULF), Alfvén, hiss, chorus, electromagnetic ion cyclotron, magnetosonic, and others. Each of these types of waves can interact with radiation belt electrons when the wave frequency and velocity is in resonance with the gyro-, bounce, or drift motion of the electrons.

Wave-particle interactions are now known to be the dominant processes that control both acceleration [9, 10] and loss [11] of radiation belt electrons. Knowing how wave particle interactions accelerate radiation belt electrons makes it much more likely that we will be able to develop physics-based, predictive space weather models of radiation belt enhancement events. An equally important (but not yet realized) application is to determine the conditions that could produce extreme radiation belt events (analogous to the well-known 1859 Carrington event) and whether there is a theoretical upper limit on how intense the radiation belts could become. Likewise, understanding the processes that lead to rapid loss of electrons from the radiation belts opens up the possibility of actively mitigating radiation belt hazards by intentionally injecting electromagnetic waves into the system. Both applications are discussed further in the following sections.

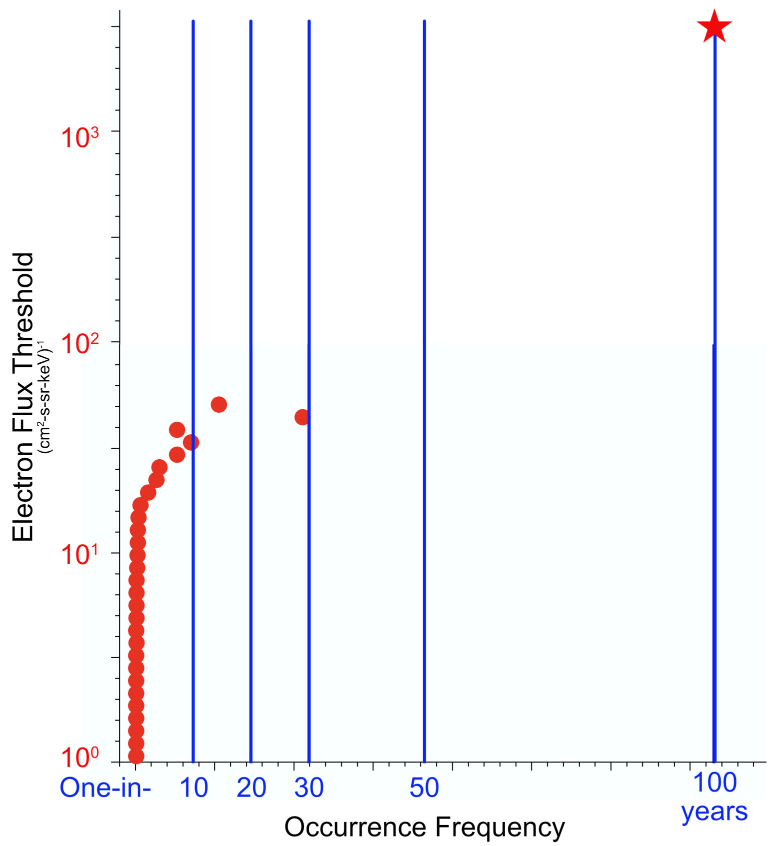


Fig. 4. The flux threshold that corresponds to the 1-in-10 through 1-in100 event occurrence frequency for ~2 MeV electrons at geosynchronous orbit. Red points are derived from daily-averaged fluxes 1989-2019 [based on 12]. The red star represents the 1-in-100 year baseline value of 1.5 x 10^3 from the Phase 1 Benchmark report [1] which is approximately 30 times higher than the maximum daily flux observed from 1989-2019.

3. EXTREME RADIATION BELT EVENTS

The recently-published US National *Space Weather Strategy and Action Plan* (SWAP) draws new attention to extreme space weather conditions, their effects on critical infrastructure, and the need for preparedness and mitigation plans [xxx 2019]. The current Space Weather Strategy and Action Plan has evolved from earlier studies and activities starting with the 1995 National Space Weather Program Strategic Plan.

Preceding the 2019 SWAP, in June of 2018, the Space Weather Operations, Research, and Mitigation (SWORM) Subcommittee of the National Science and Technology Council (NSTC) released the *Space Weather Phase 1 Benchmarks* report which attempts to specify the 1-in-100 year extremes for 5 categories of space weather hazards:
(1) Induced geo-electric fields (including ground induced currents, GIC)
(2) Ionizing radiation (including radiation belts, solar energetic particles, and galactic cosmic rays)
(3) Ionospheric disturbances (including conditions that disrupt communications and navigation)
(4) Solar radio bursts (including conditions that affect radars and communications)
(5) Upper atmospheric expansion (which produces satellite drag effects)

Highlighting the importance of benchmarks for critical infrastructure preparedness and disaster mitigation, the Space Weather Strategy and Action Plan called for a program to periodically evaluate and improve the Phase 1 benchmarks. The first such assessment was *Next Step Space Weather Benchmarks* report [13]. The Next Step Benchmark report makes numerous recommendations for improving both the quality and utility of the space weather benchmarks and for the types of near- and longer-term research that could accomplish that objective. However, the Next Step Benchmark report also acknowledges the current benchmark values are generally quite good and of sufficient confidence to start using immediately for critical infrastructure security. While the benchmark values may improve in the future, waiting for those improvements is decidedly not a recommended course of action.

Fig. 4. Uses ~2 MeV daily-averaged electron fluxes from geosynchronous orbit to illustrate benchmark values relative to past data. The figure plots the threshold that corresponds occurrence frequencies up to the 1-in100 year. Red points are derived from daily-averaged fluxes 1989-2019 [based on 12]. Fully 99% of the observations fall below the 1-in-10 year levels while the 1-in-20 and 1-in-30 year events are based on only a few days of data. Nevertheless, it is possible to use extreme value analysis [14, 15] to extrapolate the data we have to the 1-in-100 year flux to use as a baseline value. The value given in Phase 1 Benchmark report is 1.5×10^3 $(cm^2\text{-s-sr-keV})^{-1}$ [1] and is plotted with a red star in Fig. 4. It is interesting to note that 1-in-100 year benchmark value is approximately 30 times higher than the maximum daily flux observed from 1989-2019 which implies effects on satellite systems that are far worse than anything we have observed in the modern space era.

It's important to note that extreme conditions for one phenomenon may not produce extreme conditions for another. For example, while the 1859 Carrington event produced extreme ground induced currents (and likely produced strong ionospheric disturbances and atmospheric expansion) it is likely that it compressed the magnetosphere so much that geosynchronous orbit was out in the solar wind and experienced severely ***reduced*** flux levels.

4. RADIATION BELTS FROM HIGH ALTITUDE NUCLEAR EXPLOSIONS (HANE)

One extreme event, not caused by natural space weather, is anthropogenic radiation belts produced by high altitude nuclear explosions/detonations (HANE or sometimes called HAND with D for detonation). Recently significant advances have been made in our ability to predict the intensity and characteristics of HANE-produced radiation belts and potential risks to space-based critical infrastructure. The most well-documented HANE radiation belt was produced Starfish Prime nuclear test which took place on July 9, 1962 at an altitude of ~400 km over Johnston Island which crippled approximately ⅓ of all satellites operating at that time.

HANE belts are produced by a series of processes. A byproduct of nuclear explosions is production of copious positively-charged radioactive debris fragments. For explosions above the atmosphere these debris fragments will travel up and down the magnetic field lines like any other ion but, unlike other ions, the radioactive fragments produce MeV electrons by 'beta decay'. Those electrons are also trapped on the magnetic field lines. While HANE-produced radiation belts are sometimes referred to as 'artificial belts' there is nothing artificial about them. The HANE electrons undergo the same motion as natural radiation belt electrons quickly filling an entire shell spanning both hemispheres and encircling the Earth (Fig. 5). Therefore, while effects such as electromagnetic pulses (EMP) are fairly localized, the HANE belts present a global hazard.

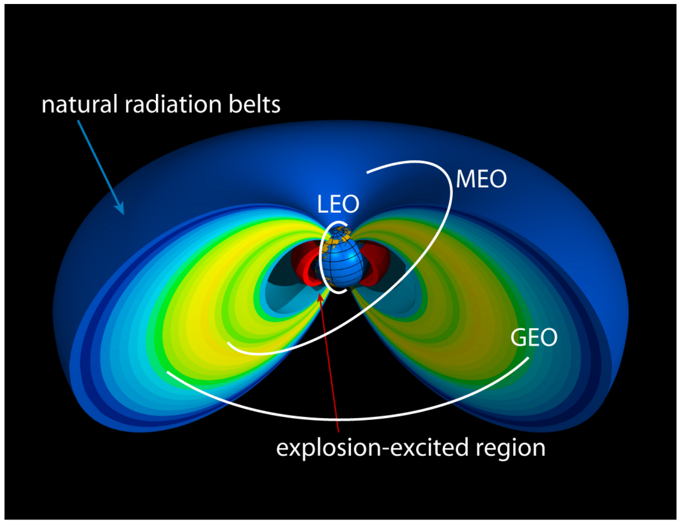


Fig. 5. The expected intensity and location of a HANE-produced radiation belt relative to natural radiation belts measured by Polar. Geosynchronous (GEO), medium Earth orbit (MEO), and low Earth orbit (LEO) are also shown to scale.

HANE radiation belts are primarily a hazard for low Earth orbit (LEO) satellites. There are several reasons for this. One is that most likely areas of conflict (other than the northern parts of Russia and North America) are at latitudes that connect to field lines with $L \lesssim 3$. For context, the Global Positioning Satellites (GPS) are in medium Earth orbit (MEO) and connect to field lines with $L > 4.2$. Geosynchronous orbit (GEO) is at $L \approx 6.6$. A second reason is that the lifetime of electrons in MEO and GEO orbits are measured in days-to-weeks while the lifetimes at LEO are measured in years. A typical LEO satellite will traverse the explosion-excited region four times per orbit in the Northern and Southern hemispheres on both the Northbound and Southbound legs.

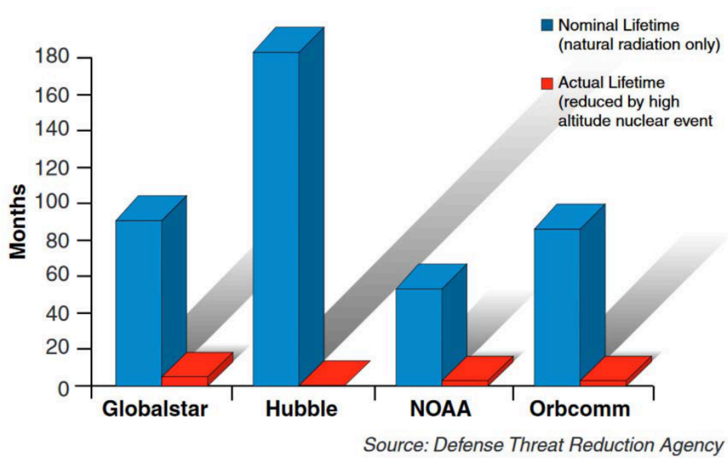


Fig. 6. 2001 Rumsfeld Commission Report [16] summary of the effects of a 10 kT HANE-produced radiation belt on the lifetimes of four LEO satellites.

Even relatively modest nuclear yields can produce satellite-killing conditions for years. While the intensity of an expected HANE belt scales with nuclear yield, even modest yields have serious, long-term consequences. Fig. 6. shows the expected lifetime (in months) for 4 different LEO satellites given the natural radiation belt environment (blue) and with a HANE belt produced by at 10 kT explosion (red). Besides the crippling effect on existing satellite infrastructure the long duration of the belts relative to the rapid loss of satellites makes replacement unfeasible without some means of mitigating the environment.

5. ARE RADIATION BELT REMEDIATION (RBR) SYSTEMS POSSIBLE?

The renewed emphasis on extreme radiation belt environments (from either natural or nuclear sources) has led to renewed interest in techniques to for radiation belt remediation (RBR). As discussed in sections 1 and 2, the primary loss mechanism for radiation belt electrons is wave-particle interactions that remove them from the belts. For regions at and inside MEO orbits the electrons are primarily lost by precipitating into the atmosphere [17]. Electron precipitation occurs when waves 'scatter' the electrons by changing their pitch angle. Waves with the right frequency to resonantly scatter radiation belt electron are in the Very Low Frequency (VLF) band (10's kHz).

The electron scattering and loss process is illustrated in Fig. 7. As electrons travel down the magnetic field lines (B) they encounter stronger magnetic fields. The pitch angle of the electron (the angle between the magnetic field and the electron's velocity vector) determines where the electron 'mirrors' (reverses direction). Electrons with mirror points above the atmosphere are 'trapped' and undergo the motion described in Fig. 1. Electromagnetic waves can change (scatter) the electron's pitch angle. Electrons that get a slight kick along the field will have mirror points at lower altitudes. If the mirror point is below the top of the atmosphere ($\lesssim$ 100 km) the electron is absorbed by the atmosphere and lost from the radiation belts. Since only small changes in the electron's direction of motion are required, the energy required to precipitate radiation belt electrons is much less than the energy of the electrons themselves. The process is identical for HANE belts and for natural radiation belts. However, the wave-particle scattering is more effective at higher L-shells and for lower-energy electrons [18]. Radiation belt remediation systems could take advantage of this now well-established natural process by enhancing the rate of wave-particle scattering by introducing intense, man-made waves.

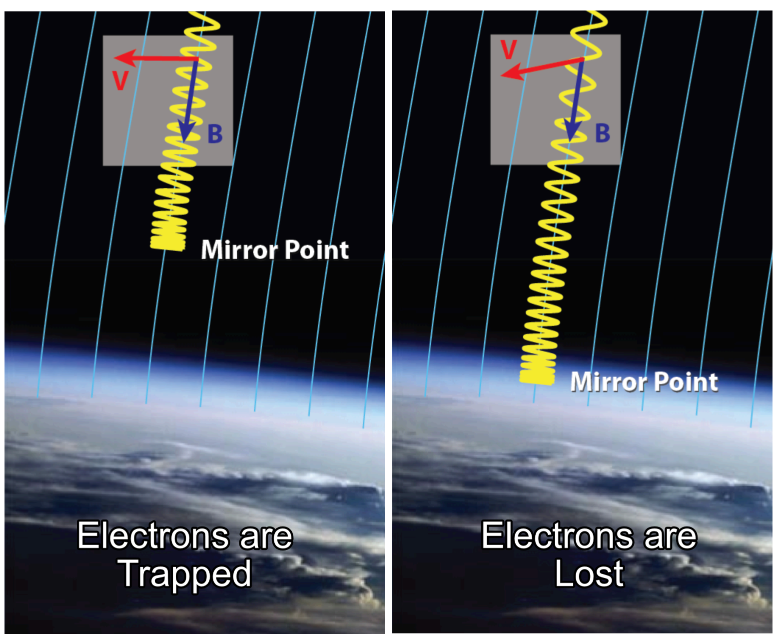


Fig. 7. Electrons that have a magnetic mirror point above the atmosphere are trapped on the magnetic field line. Electrons with mirror points below the top of the atmosphere are absorbed and lost from the radiation belts.

The goal of radiation belt remediation is to reduce the dose (and/or dose rate) on a set of LEO satellites. The steps to achieving that goal are illustrated schematically in Fig. 8.

(1) High power VLF waves are injected into the system from the ground or from satellites (labeled "VLF Transmitter in Fig. 8.). The VLF waves must have the right properties (including frequency, polarization and wave normal angle) to resonantly pitch angle scatter radiation belt electrons.
(2) The the waves must propagate from the source (transmitter) to the HANE belt region where they can scatter HANE electrons (as indicated by the green path in Fig. 8.). As they propagate the waves can also change characteristics due to interaction with the background plasma.
(3) At various points along the wave path the injected waves can resonantly pitch angle scatter HANE electrons. The wave-particle interactions that scatter electrons can happen at any point along the magnetic field line and still have the effect of precipitating electrons and removing them from the system.
(4) No matter where the wave particle interactions occur, scattering will move the mirror point of some of the electrons down into the atmosphere where they will be lost from the belts. Trapped electrons are naturally bouncing between mirror points so only a small amount of scattering is needed to ensure that some electrons are lost.
(5) The result of many such scattering interactions is to move toward a uniform distribution of electrons along the field. But, the electrons mirroring close to the atmosphere are continuously being removed so, eventually, the scattering reduces the fluxes of electrons throughout the explosion-enhanced belts.
(6) Ultimately, an evaluation of the effectiveness of the RBR system must determine the dose rates and operational lifetimes of specific satellites in specific orbits with and without RBR as shown in Fig. 6.

Important questions remain regarding each of the 6 steps listed above. Uncertainties associated with each of those steps results in an even greater uncertainty in the potential effectiveness of an overall RBR system. Currently those uncertainties are so large that an RBR cost/benefit analysis isn't realistic. It is not possible, however, to dramatically reduce those uncertainties through a series of current and upcoming space experiments combined with development of a computational framework to simulate end-to-end system performance.

Los Alamos National Laboratory (LANL) has embarked on a large-scale, 3-year project (FY2020-2022) to produce end-to-end models of proposed RBR systems and to assess their effectiveness at protecting critical satellite infrastructure [19]. The project is called Radiation Belt Remediation - A Complex Engineered System (RBR-ACES). The RBR-ACES project aims to develop models of each component of an RBR system, couple the models into a single computational framework, and apply the model to a variety of HANE scenarios to determine the ability of each system to mitigate the dose from HANE to different satellites in different orbits. Each component of the model will be validated against data from space and laboratory experiments in order to drive down uncertainty to the point where systems engineering studies for an RBR system are feasible and realistic.

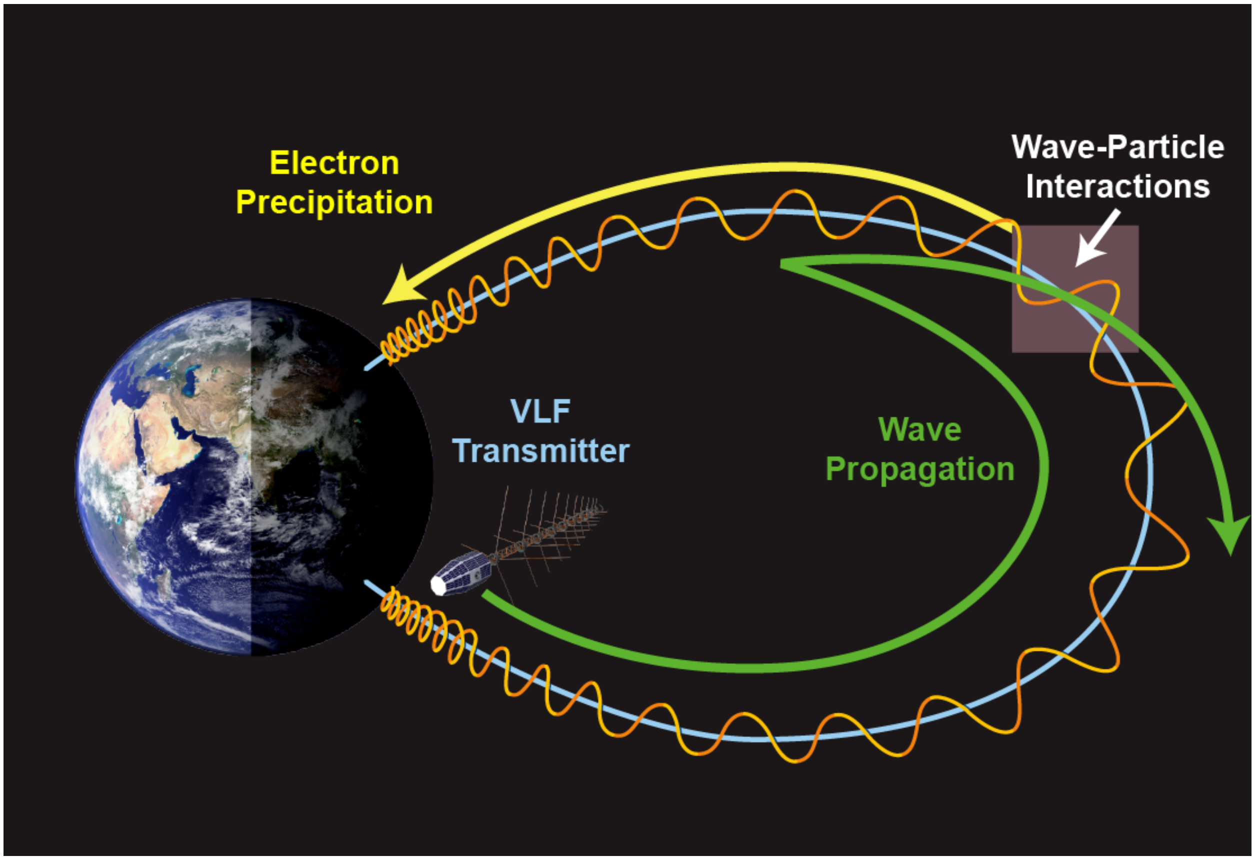


Fig. 8. A schematic representation of how radiation belt remediation works. The 6 key components of the system are discussed in the text.

6. RBR COMPONENTS, OUTSTANDING QUESTIONS, AND PATHS TO CLOSURE

As noted above, there are important, outstanding questions that need to be answered through a combination of experiments, insights gained from studying the natural radiation belt system, and advanced computer simulations.

The first component of an RBR system (step 1 in the preceding section) is a means of injecting high-power VLF waves into the space environment. At least four methods have been proposed for introducing man-made waves into the HANE-belt environment:

(1) injecting waves into space from VLF transmitters on the ground
(2) releasing chemicals in space which leads to a chain of processes that also produce VLF waves
(3) directly producing waves in space with a physical antenna
(4) directly producing waves in space with a pulsed electron beam

We briefly discuss each of these proposed mechanisms below.

Waves from ground-based transmitters lose power as they propagate through the ionosphere. While, in practice, large amounts of power are available on the ground, the main limitation is that high-power, ground-based systems could not easily be deployed to locations where the waves would reach the HANE belt.

Chemical releases have the advantage of tapping the large amount of kinetic energy contained in an orbiting mass. Investigations are ongoing to determine the efficiency of converting that kinetic energy into electromagnetic wave energy. In particular, a rocket experiment led by the US Naval Resaerch Laboratory, called Space Measurement of A Rocket-Released Turbulence (SMART) [20], is designed to understand the evolution of plasma turbulence and the nonlocal consequences of electrostatic-electromagnetic turbulence that may be critical to converting that kinetic energy into the types of VLF wave modes that can efficiently scatter radiation belt electrons.

Physical antennas (i.e. dipole or loop antennas) seem like an obvious choice but their ability to efficiently create waves in space at VLF frequencies is actually rather poorly understood at this point. Antennas used for communications, navigation, etc. operate at much higher frequencies where the space plasma environment can essentially be treated as a vacuum. VLF frequencies are low enough that they couple strongly to the plasma surrounding the antennas. Furthermore, the plasma medium has a complex, three-dimensional index of refraction that supports a wide variety of different wave modes some of which are more effective at scattering radiation belt electrons than others. The US Air Force Research Laboratory recently launched a satellite mission called the Demonstrations and Science Experiment (DSX) [21] whose primary mission is to determine the efficiency of injecting VLF wave power into the magnetosphere from a large, in-situ dipole antenna [22].

Electromagnetic radiation can be produced by any time-varying currents so an interesting alternative to physical antennas is to use a modulated electron beam to create VLF waves in space. Several experiments in the 1980s demonstrated the utility of using electron beams to generate VLF waves including two highly-successful Space Shuttle experiments [23, 24]. Since that time there have been many advances in both accelerator technology for electron beams and in receiver technology for detecting and characterizing the resulting waves. Another rocket experiment from Los Alamos and Goddard Space Flight Center will apply these new technological advances to study the how efficiently electron beams can generate VLF waves in space. The experiment is called the Beam Plasma Interactions Experiment (Beam PIE) [25] and is scheduled to launch in late 2021. Simulations suggest that the coupling efficiency (beam power to wave power) can be very high, making this a promising option for creating VLF waves in space.

The RBR-ACES modeling program is currently concentrating on modeling the coupling efficiency for physical antennas and electron beams with the intent to validate the models using data from DSX and Beam PIE.

Injecting high-power VLF waves into space is only the first component of a complete RBR system. Step 2 is getting the waves to the right region of space, specifically the HANE belt itself. Unlike high frequency waves used for communication and navigation, VLF waves interact with and are strongly modified by the space plasma medium. One consequence is that VLF waves cannot propagate freely in any arbitrary direction. Fig. 9. shows an example of ray-tracing the propagation of VLF ‘whistler’ waves injected from near geosynchronous orbit (L = 6). Waves with slightly different initial propagation directions end up in very parts of the radiation belts. The waves are also modified as they propagate through the background plasma medium.

The waves do not just refract, they also interact with the background plasma through both linear and nonlinear processes. The most common example is so-called Landau damping where the waves loose energy due to interaction with suprathermal (10’s eV) electrons in the background plasma. Landau damping is the primary process responsible for the eventual reduction of the wave power to zero. Other, less well-understood processes can actually amplify the waves as has been seen in the natural environment and in wave injection experiments from ground-based transmitters. One component of the RBR-ACES project is development of ray-tracing codes that will self-consistently account for both linear and non-linear interactions with the background plasma. The simulations can also inject the waves from different locations in the system to determine which injection locations produce the maximum wave power in the region of interest.

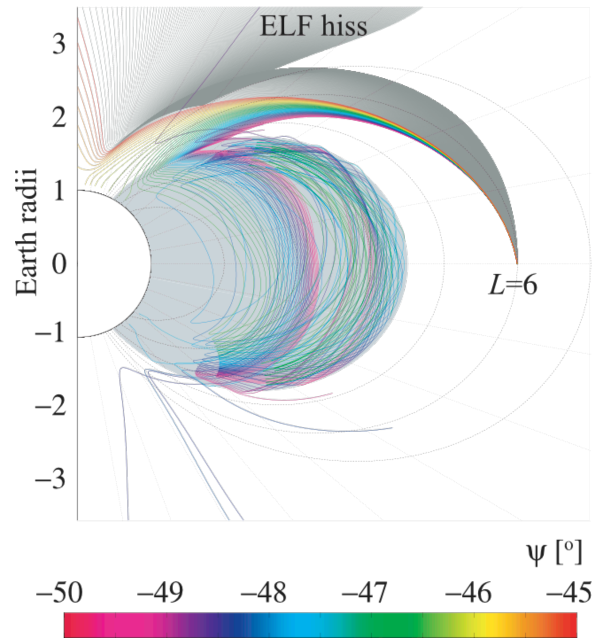


Fig. 9. An example of ray-tracing the propagation of VLF whistler waves injected from near geosynchronous orbit (L = 6). Waves with slightly different initial propagation directions end up in very parts of the radiation belts. The waves are also modified as they propagate through the background plasma medium. [26].

Once the wave generation and wave propagation have been modeled the next step (#3) is to understand the interaction of those waves with the electrons in the HANE belt. Great progress has been made in understanding of wave-particle interactions thanks to observations from the Van Allen Probes mission and others. Numerical models have been highly successful at reproducing acceleration and loss processes that occur in the outer radiation belts [27, 28]. However, several challenges remain. Currently, wave particle interactions are primarily modeled using a quasi-linear diffusion approximation which is a good approximation for modeling the natural environment. Two important assumptions in the quasi-linear diffusion approximation are (a) that the power in the waves is fairly broadly distributed in frequency (and with a Gaussian distribution) and (b) that all of the wave-particle interactions produce small-angle scattering. For artificially injected waves neither of these assumptions is always true. Therefore new methods of modeling scattering by wave-particle interactions are needed and are being developed.

Scattering by wave-particle interactions are determined by the resonance conditions which, in turn, are determined by the background plasma conditions - plasma density and magnetic field strength. Modern magnetic field models are quite accurate even for geomagnetic storms but global plasma density models lag far behind. Density models are particularly important because, for a HANE belt, the region of interest is at low L-shells where the densities are much higher than in the outer electron belt, yet all of the modeling to date has been applied to outer electron belt dynamics. Fortunately, development of new 3D, time-dependent density models are possible thanks to the Van Allen Probes data and, importantly, are a topic of interest in the community.

Step 4 of evaluating an RBR system is understanding the cumulative effect of many wave particle interactions throughout the HANE belt - along the field line and around the drift shell. Essentially this boils down to understanding how the pitch angle distribution evolves with time. This is a particularly interesting problem for a HANE belt because the initial pitch angle distribution looks nothing like the pitch angle distribution in the natural belts. HANE electrons are generated in a limited spatial region and the resulting pitch angle distributions can be highly peaked, often with the peak very close to the atmospheric loss region. Similarly the waves from the RBR transmitter system are not uniformly distributed requiring standard Fokker-Planck model calculations to be generalized to include azimuthal dependence.

Step 5 takes all of the preceding model results to drive a global model of the time-dependent, 3D distribution of HANE electrons and the overall loss rates throughout the belt. For the natural belts this is typically done using a Fokker-Planck formalism using energy, pitch angle, and radial diffusion coefficients. The RBR-ACES project starts with a previously-developed Fokker-Planck model known as the Dynamic Radiation Environment Assimilation Model (DREAM) [2, 29]. The DREAM framework, however, is not currently general enough for the RBR problem. There are, however, techniques being tested to generalize the formalism to include the global effects from nonlinear wave particle interactions and from highly spatially and temporally-varying wave fields.

The final product of the RBR-ACES framework is an assessment of the accumulated dose and satellite lifetimes with and without remediation. This is the basic test of whether a remediation system is effective or not. DREAM already has a 'satellite fly-through' module that can calculate accumulated dose for arbitrary satellite orbits and shielding levels. The challenge of step 6 is that a thorough assessment requires running a large number of simulations. We want to asses the effects on a range of satellites in different orbits. We also need to model a variety of HANE conditions produced by explosions at different locations (latitude, longitude, altitude) and yields. In addition to evaluating the most efficient types of VLF transmitters, we also need to model different transmitter locations. Antenna or electron beam systems would be deployed on a satellite which means that the transmitter location is also a function of time. A large number of model runs will be needed to determine an optimal orbit to address a range of possible RBR scenarios.

With current numerical and computational resources, end-to-end computational modeling frameworks of the type just described are actually feasible - yet they remain challenging and complex. Fundamentally, it is a multi-scale problem ranging from the microphysics of wave-particle interactions to the global dynamics of radiation belt pitch angle distributions and intensities. Problems such as the self-consistent interactions of waves with ambient plasmas span both local and global scales. Coupling the subsystems into a seamless whole has been demonstrated in other space weather applications [30] but each new, coupled framework presents its own challenges.

Likewise experimentally validating each subsystem and the coupled framework as a whole are both required. The experimental validation portion of the RBR-ACES program relies heavily on the results from the DSX and Beam PIE experiments as well as laboratory experiments being conducted at the Large Area Plasma Device (LAPD) at the University of California, Los Angeles. Observations of the natural environment are also invaluable. We are, for example, analyzing satellite conjunctions (e.g. Van Allen Probes and Arase) to test wave propagation models and global radiation belt dropout events to test systems-wide understanding.

7. CONCLUSIONS

We have discussed several current aspects of radiation belt research, focusing on those that are most relevant to space weather applications - where 'space weather' is used generally to include natural and anthropogenic conditions. Specifically we discussed:

- The structure, dynamics, and hazards to satellites posed by the Earth's radiation belts,
- A new paradigm developed from observations by recent missions such as the Van Allen Probes satellites that emphasizes the importance of electromagnetic waves in coupling low-, medium-, and high-energy plasma populations in the magnetosphere,
- The ongoing US effort (that has parallels in other countries) to specify 1-in-100 year extreme space weather conditions and establish benchmarks that can be used for plans to protect critical technological infrastructure,
- The extreme anthropogenic space weather conditions that would be produced by a potential nuclear explosion in space and the resulting HANE radiation belt,
- The components of an engineered radiation belt remediation system that could be used to mitigate the hazards from an extreme radiation belt environment, and
- Current limitations on our understanding of those components and efforts that are being taken to reduce uncertainties in the net efficiency proposed RBR systems and their utility for protecting the vast and growing array of satellite systems on which our technological society increasingly depends.

It is important to note, also, that while the latter sections of the paper focused on HANE-produced belts, HANE is not the only potential source of intense, hazardous, and long-lasting radiation belts. The best-documented example is a large interplanetary shock event that produced an extremely intense belt of MeV electrons at L-shells where a HANE belt might be expected (L = 2.0-2.5). The event was observed by the USAF/NASA Combined Release and Radiation Effects (CRRES) satellite in March 1991 and was still very strong when the mission ended the following October.

8. ACKNOWLEDGEMENTS

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