Van Allen Probes Mission Overview and Discoveries to Date

Elena Y. Adams, Kristin A. Fretz, Aleksandr Y. Ukhorskiy, and Nicola J. Fox

ABSTRACT

The morning of 30 August 2012 saw an Atlas V rocket launch NASA's second Living With a Star spacecraft mission, the twin Radiation Belt Storm Probes (RBSP), into orbit for an epic mission to understand Earth's space radiation environment. Renamed the Van Allen Probes soon after launch, the Probes are designed to determine how populations of high-energy charged particles within Earth's radiation belts, dangerous to astronauts and satellites, are created, respond to solar variations, and evolve in space environments. Operating in nearly identical geocentric 1.1 × 5.8 R_E (10° inclination) orbits, the two Probes have advanced the goals of NASA's Science Plan *(2014) by radically revising our understanding of Earth's radiation belts and inner magnetosphere. As a key new member of the Heliophysics System Observatory, the mission has led to the discovery of several new and unanticipated structures, the verification and quantification of previously suggested energization processes, and the discovery of new energization processes. It has revealed the critical importance of dynamic injections into the innermost magnetosphere and has coordinated with the high-altitude Antarctic balloon mission Balloon Array for RBSP Relativistic Electron Losses (BARREL) to determine the nature of particle precipitation. The uniquely capable instruments have revealed inner radiation belt features that were all but invisible to previous sensors, and the mission has profoundly advanced our understanding of the measurements critical for predictive modeling of space weather. This article describes the science objectives of the Van Allen Probes mission, highlights the discoveries made so far, and explains the objectives and observation plan for the extended mission.*

INTRODUCTION

The NASA Van Allen Probes mission (previously known as Radiation Belt Storm Probes, or RBSP) addresses how populations of high-energy charged particles are created, vary, and evolve in space environments, and specifically within Earth's magnetically trapped radiation belts. The Probes were launched 30 August 2012 and entered into their 2-year prime mission science phase on 1 November 2012. The mission achieved all of its level-1 requirements by the end of the prime mission on 31 October 2014. Because the mission was out of synchronization with NASA's Senior Review process, NASA granted a "bridge phase" that allowed the mission to continue operating for an additional 11 months through September 2015. The mission was proposed and has been accepted for several more years of operation, specifically through the expected lifetime of the Probes, ~1 January 2019, limited by the fuel needed to maintain Sun-aligned positive power orientation.

Table 1. Van Allen Probes level-1 observations

Observations	Purposes
Determine spatial/temporal variations of medium- and high-energy electron and proton angle and energy distributions, faster than drift times, interior and exterior to acceleration events.	Determine time history of energization, loss, and transport for hazardous particles. Understand/quantify sources of these particles and source paths. Enable improved particle models.
Derive electron and proton radial phase space density (PSD) profiles for medium- and high-energy electrons and protons on short timescales compared to storm times.	Distinguish between candidate processes of acceleration, transport, and loss and statistically characterize these processes versus solar input conditions.
Determine spatial/temporal variations of charged particle partial pressures and their gradients within the inner magnetosphere with fidelity to calculate pressure-driven currents.	Understand how large-scale magnetic and electric fields in the inner magnetosphere are generated and evolve, their role in the dynamics of radiation belt particles, and their role in the creation and evolution of the plasma environments for other processes.
Determine spatial/temporal variations of low- to medium-energy electron and ion energy, composition, and angle distributions on short timescales compared to drift periods.	Understand/quantify the conditions that control the production and propagation of waves (e.g., electromagnetic ion cyclotron, whistler-mode chorus and hiss) and determine the wave propagation medium.
Determine the local steady and impulsive electric and magnetic fields with fidelity to determine the amplitude, vector direction, and time history of variations on a short timescale compared to times required for particle measurements.	Determine convective and impulsive flows causing particle transport and energization, determine propagation properties of shock-generated propagation fronts, and infer total plasma densities.
Determine spatial/temporal variations of electrostatic and electromagnetic field amplitudes, frequencies, intensities, directions, and temporal evolutions with fidelity to calculate wave energy, polarization, saturation, coherence, wave angle, and phase velocity for (A) very low-frequency and extremely low-frequency waves and (B) random, ultralow-frequency (ULF), and quasi-periodic fluctuations.	Determine the types/characteristics of plasma waves causing particle energization and loss, including wave growth rates; energization and loss mechanisms; diffusion coefficients and loss rates; plasma densities; ULF waves' versus irregular fluctuations' effects on radial transport; and statistical maps of wave fields versus position and conditions.
Provide concurrent, multipoint measurements sufficient to constrain global convective electric field and storm-time electric and magnetic field models.	Covert particle measurements to invariant coordinate systems; infer loss cone sizes; and model effects of global electric and magnetic field variations on particle distributions.
Track/characterize transient structures propagating through the inner magnetosphere with fidelity to determine amplitude, arrival times, and propagation directions.	Determine which shock-related pressure pulses produce significant acceleration and estimate their significance relative to other energization mechanisms.

Table 2. Van Allen particle measurement parameter requirements as specified in the Van Allen program-level requirements document

Requirement	Measurement	Cadence (distribution/min)	Energy Range (MeV)	Angular Resolution (deg)	Energy Resolution
4.1.1.1	High-energy electrons	1	1–10	30	30% at 3 MeV
4.1.1.2	Medium-energy electrons	1	0.05–1	20	30% at 0.3 MeV
4.1.1.3	High-energy protons	1	20–75	30	40% at 30 MeV
4.1.1.4	Medium-energy protons	1	0.1–1	20	40% at 0.3 MeV
4.1.1.5	Medium-energy ion composition	1	0.02–0.3	30	40% at 0.05 MeV
4.1.1.6	Low-energy ion/electron composition	1	50 eV–0.05 MeV	30	40% at 0.01 MeV

Measurement requirements are derived from the observation needs summarized in Table 1. All required on two platforms.

The Probes comprise two spacecraft taking *in situ* measurements in nearly the same highly elliptical, low-inclination orbits (1.1 × 5.8 R_E, 10°). For the prime mission, the orbits are slightly different so that one spacecraft laps the other spacecraft about every 67 days, allowing separation of spatial from temporal effects over spatial scales ranging from ~0.1 to 5 R_E. By adjusting the orbital phase of one spacecraft slightly with respect to the other during lapping events, the spacecraft can be roughly aligned along the same magnetic field line and thus sample field-aligned evolution of particles and wave fields. A comprehensive suite of instruments, identical on the two spacecraft, measures all of the particles (electrons, ions, ion composition), fields (E and B), and wave distributions (dE and dB) that are needed to resolve the most critical science questions. Detailed descriptions of all aspects of the mission are available in a 2013 volume of *Space Science Reviews* (volume 179).

SCIENCE OBJECTIVES

The fundamental science objective of the Probes mission is to promote understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in the radiation belts form or change in response to variable inputs of energy from the Sun.

This broad objective was parsed into three overarching science questions:

1. Which physical processes produce radiation belt enhancements, oftentimes with excess acceleration?

Table 3. Van Allen field and wave measurement parameter requirements as specified in the Van Allen program-level requirements document

Requirement	Measurement	Cadence	Frequency Range	Frequency Resolution
4.1.1.7	3-D magnetic field	20 vectors/s	DC–10 Hz	n/a
4.1.1.8	3-D wave magnetic field	6 s	10 Hz–10 kHz	20 channels per decade
4.1.1.9	3-D wave electric field	6 s	10 Hz–10 kHz	20 channels per decade
4.1.1.10	3-D electric field	20 vectors/s	DC–10 Hz	n/a
4.1.1.11	Plasma density	10 s	n/a	n/a

Measurement requirements are derived from the observation needs summarized in Table 1. All required on two platforms.

Table 4. Van Allen Probes investigations

Instrument/Suites	Principal Investigator	Key Partners	Science Investigation
Energetic Particle, Composition, and Thermal Plasma Suite (ECT)	Harlan Spence, University of New Hampshire	Los Alamos National Laboratory, Southwest Research Institute, Aerospace Corp., Laboratory for Atmospheric and Space Physics (LASP)	Measure near-Earth space radiation belt particles to determine the physical processes that produce enhancements and loss
Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS)	Craig Kletzing, University of Iowa	NASA Goddard Space Flight Center, University of New Hampshire	Understand plasma waves that energize charged particles to very high energies; measure distortions to Earth's magnetic field that control the structure of the radiation belts
Electric Field and Waves Instrument (EFW)	John Wygant, University of Minnesota	University of California, Berkeley; LASP	Study electric fields and waves that energize charged particles and modify the inner magnetosphere
Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE)	Louis Lanzerotti, New Jersey Institute of Technology	Johns Hopkins University Applied Physics Laboratory (APL), Fundamental Technologies	Understand the creation of the "storm time ring current" and the role of the ring current in the creation of radiation belt populations
Proton Spectrometer Belt Research (PSBR)	David Byers, National Reconnaissance Office	Aerospace Corp., MIT Lincoln Lab	Create specification models of the high-energy particles in the inner radiation belt
Relativistic Proton Spectrometer (RPS)	Joseph Mazur, Aerospace Corp.		
Balloon Array for RBSP Relativistic Electron Losses (BARREL)	Robyn Millan, Dartmouth College		Measure, study, and understand electron loss processes from Earth's outer electron belt

2. What are the dominant mechanisms for relativistic electron loss?

3. How do ring current and other geomagnetic processes affect radiation belt behavior?

These questions were answered through a series of observations, listed in Table 1. These observations were used to derive level-1 requirements for the mission. Tables 2 and 3 show the measurement requirements derived from the level-1 observations. The instruments and instrument suites are summarized in Table 4. Figures 1 and 2 show the overlap between various investigation measurements.

Particle energization mechanisms have been a key focus of the Van Allen Probes mission. The Probes have provided the first definitive evidence that peaks in the radial profiles of electron PSD result from local acceleration (Fig. 5; Ref. 6). Simultaneous determinations of PSD by the two spacecraft, one traveling Earthward and one traveling outward, were critical. In addition, sophisticated modeling using detailed measurements of plasma parameters and whistler-wave mode intensity spectra demonstrated that quasilinear whistler wave diffusive scattering suffices to locally accelerate the electrons over the ~12-h period of observed acceleration (Fig. 6; Ref. 2).

SCIENCE HIGHLIGHTS

As mentioned earlier, all of the level-1 objectives have been achieved. The mission has contributed immensely to knowledge of the radiation belts and resulted in numerous discoveries. This section highlights findings to date.

The Probes enabled discovery of several new and unanticipated structures within the radiation belts. The first is the so-called third belt or electron storage ring (Fig. 3; Ref. 1), lasting for months for electron energies greater than or equal to about 2 MeV. In retrospect, the belt is a predictable consequence of the weak whistler-wave scattering losses that occur for those portions of the outer belt that overlap the dense plasmasphere.[2,3] The surprising cause of a second new structure, the so-called zebra stripes within the inner electron belt, is drift resonance with the electric field induced by Earth's rotation (Fig. 4; Ref. 4). The third unanticipated, and as-yet unexplained, structure is the unusually sharp inner boundary for ultrarelativistic electrons at L ~ 2.8 R_E.[5]

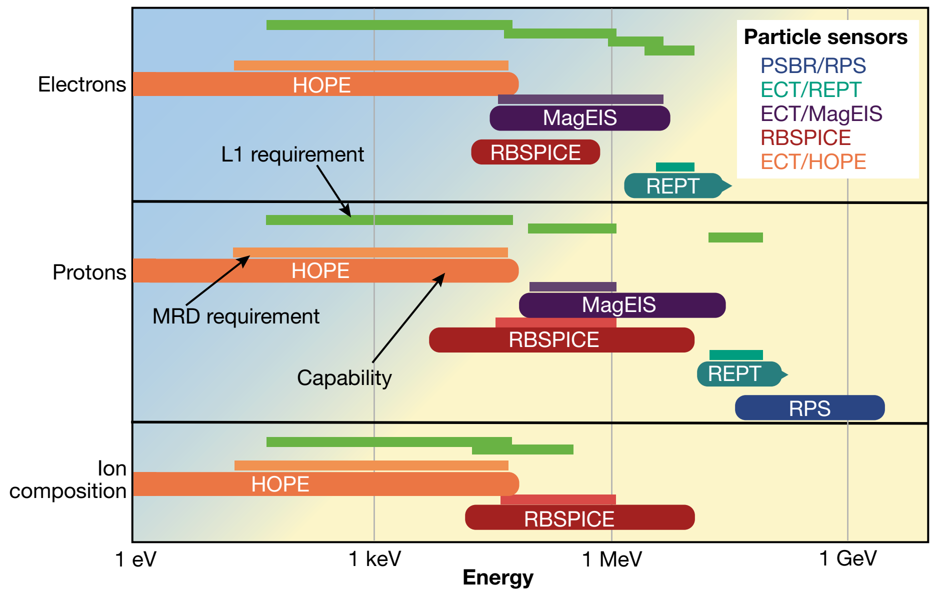

Figure 1. Comparison of the energetic particle observations from the science investigations. The observations overlap each other to ensure calibration across the board.

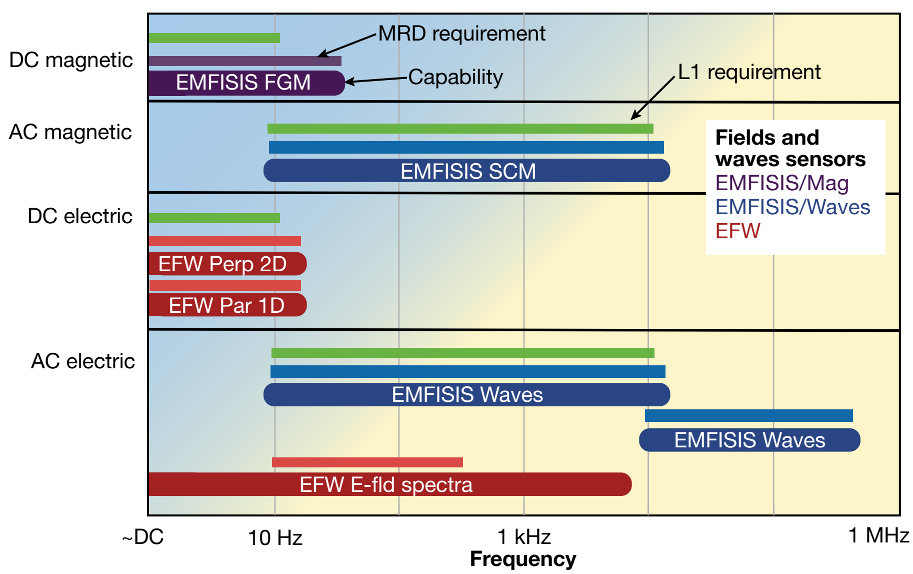

Figure 2. Comparison of the fields and waves observations across the frequency spectra.

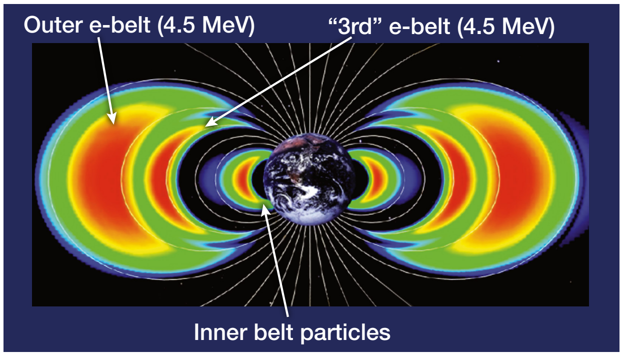

Figure 3. Van Allen Probes Relativistic Electron Proton Telescope (REPT) measurements demonstrated the existence of a third radiation belt.[7] Here, measurements from a single radial cut through the belts and an assumption of adiabatic transport were used to distribute intensities around Earth and along the field lines.

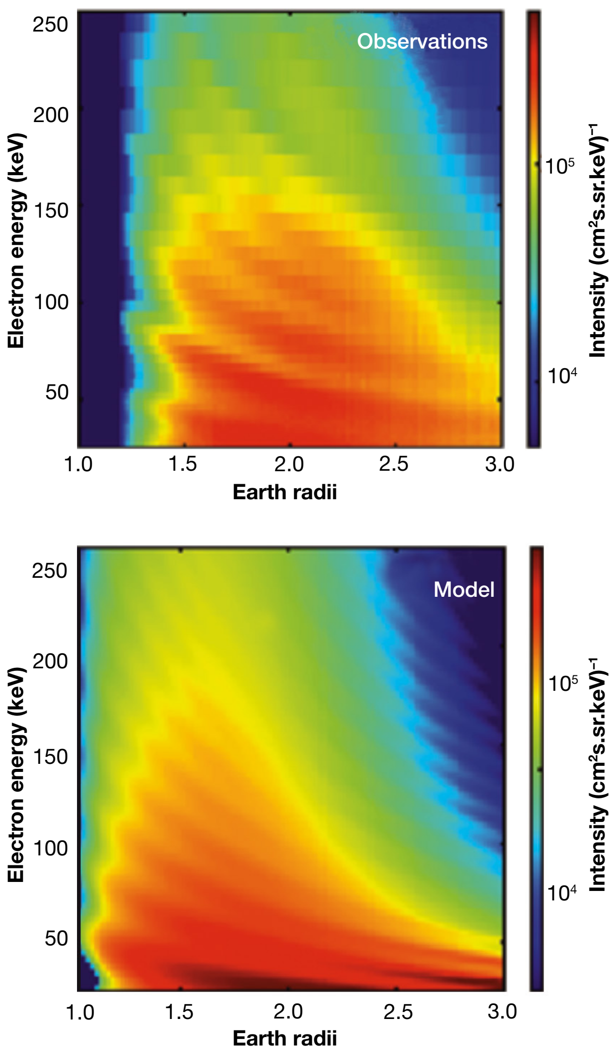

Figure 4. Top, Van Allen Probes RBSPICE measurements of inner belt electrons showing surprising "zebra stripes." Bottom, A model invoking quasi-resonant interactions between drifting electrons and the electric field induced by Earth's rotation explains the observations. (Adapted from Ref. 4.)

However, the Probes have also observed very coherent and possibly nonlinear electron-whistler mode interactions.[8] It is a key theme of the extended mission to sort out the relative importance of quasilinear and nonlinear interactions for a variety of external conditions.

Another theme for the extended mission will be to determine the relative importance of local and often more global transport-related acceleration. A critical process associated with transport-related acceleration is drift resonance between ULF waves and azimuthally drifting electrons. The Probes have directly observed such drift resonant interactions for the first time (Fig. 7; Ref. 9), enabling the team to establish which of several possible mechanisms generate some ULF waves.[10] These waves also play a key role in particle energization when interplanetary shocks strike the Earth's magnetosphere, as shown by the unique two-spacecraft measurements of the magnetospheric response to such shocks (Fig. 8; Ref. 11). A critical task of the extended mission is to distinguish between and quantify the energization associated with shock-generated wave fronts and ULF waves.

The discovery of double-layer-like electric field spikes within the heart of the radiation belts was completely unexpected.[12] Such structures, now thought to be a highly nonlinear evolution of strong whistler mode waves,[13] may locally accelerate very low-energy electrons up to the kiloelectronvolt range along field lines, thereby providing a seed population for subsequent acceleration to the megaelectronvolt range of energies. The importance of this seed population relative to that provided by injections and the inward radial transport of low-energy magnetotail populations (see, e.g., Ref. 14) remains unresolved and will be addressed during the extended mission.

Particle injections appear to be much more common in the inner (<5 R_E) region than previously recognized, and they play an unanticipated prominent role in creating ring current populations (Fig. 9; Refs. 15 and 16). These injections generate an array of different wave

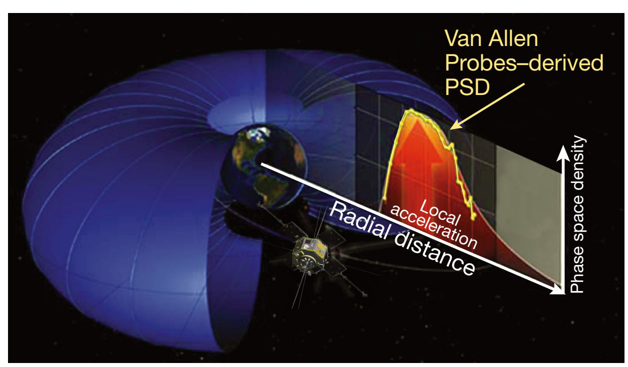

Figure 5. ECT measurements of a relativistic electron PSD radial profile as compared to expectations for local acceleration of the electrons.[6] Adiabatic radial transport would show a very different profile without a peak.

modes that may play a significant role in particle acceleration and loss. Injections generate an unusual low-frequency hiss mode within the plasmasphere,[17] coherent whistler modes,[8] double layers,[13] and kinetic scale field-line Alfvén resonances.[18] The relative importance of all of these wave structures will be established during the extended mission.

Particle scattering losses have been the particular focus of joint measurements between the Van Allen Probes and the associated Mission of Opportunity BARREL,[19] which comprises multiple high-altitude balloons deployed within the Antarctic during two winter seasons. The balloons carry X-ray spectrometers to measure the bremsstrahlung emissions from precipitating relativistic electrons on radiation belt field lines that sometimes map to the positions of the Van Allen Probes spacecraft. Exceedingly close correlations between whistler mode hiss waves and electron precipitation modulations have been observed (Fig. 10; Ref. 21), verifying an important theoretical expectation. Surprisingly, the correlation is coherent over vast spatial scales, suggesting a global extent for the losses.

The Probes mission has significantly advanced our understanding of Earth's inner radiation belt ($R < 2.5\ R_E$). East–west gradient measurements of inner belt energetic protons enabled by high-quality Probes instrumentation revealed the details of proton–atmosphere interactions.[22] Pitch angle distributions of this population clarified the role of interplanetary solar proton events as the source of the outer shoulder of the inner proton belt.[23] The first truly clean measurements demonstrated that the energies of inner radiation belt electrons never exceeded 900 keV during the Probes' prime mission.[24,25]

Finally, the Van Allen Probes mission has enabled substantial improvement to the modeling of radiation belt processes, and it repeatedly provided the measurements needed to constrain these models; these advancements are critical for space weather applications (see, e.g., Refs. 26 and 27).

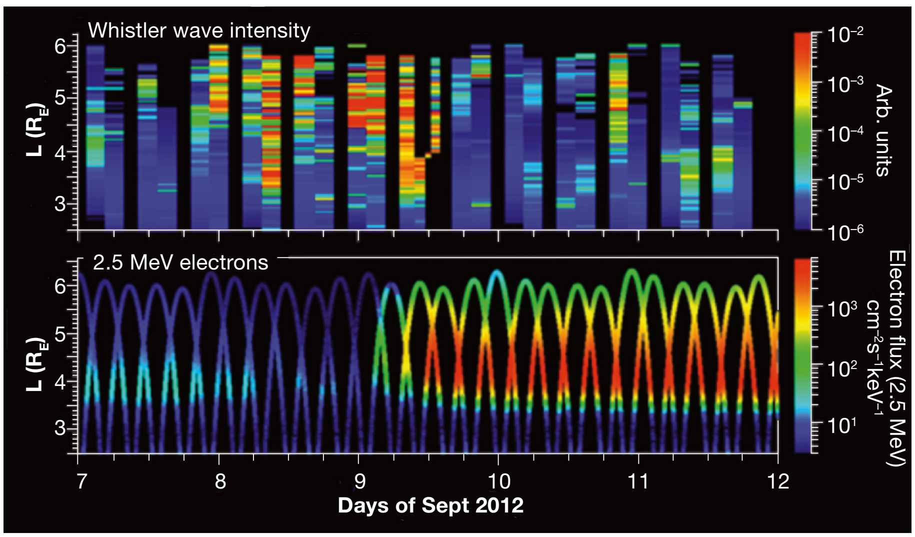

Figure 6. Five days of REPT relativistic electron intensity measurements revealed a 12-h interval of strong electron acceleration on 9 Sept 2012. Modeling revealed that the simultaneous whistler waves observed by EMFISIS and EFW performed the acceleration.[20]

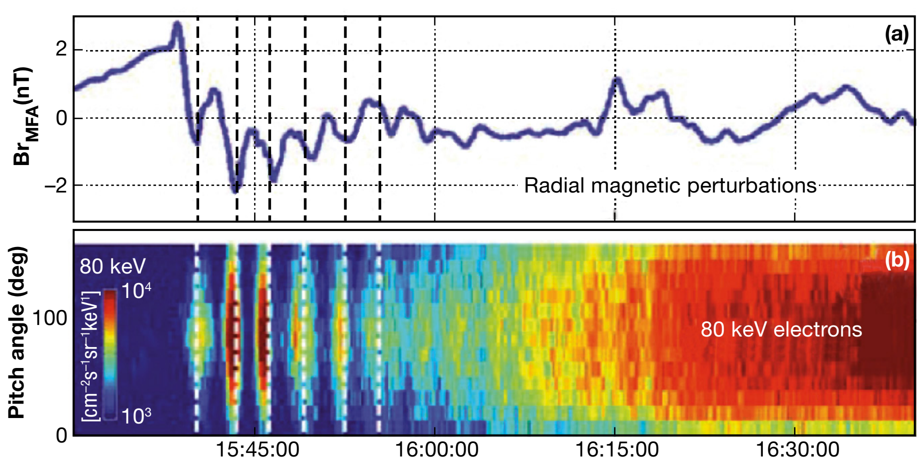

Figure 7. Magnetic Electron Ion Spectrometer (MagEIS) and EMFISIS made the first direct measurement of a drift-resonant energy exchange between ULF waves (a) and energetic electrons (b). The energy dependence of phasing (not shown) is critical to the interpretation.[9]

PLANS FOR EXTENDED MISSION

The great successes of the Van Allen Probes mission during its prime phase and the subsequent bridge phases introduced new science questions that need to be addressed before we can fully attain predictive understanding of radiation belt generation and dynamics. On 1 November 2015, the Van Allen Probes began the mission that will bring us much closer to meeting that objective.

The overarching objective of the Van Allen Probes extended mission is to quantify the processes governing the Earth's radiation belt and ring current environment as the solar cycle transitions from solar maximum through the declining phase. The sunspot number reached a peak in April 2014, and this number will likely become the official maximum of the current solar cycle (cycle 24). Based on historical measurements, the radiation belt activity is expected to continue to intensify with the decline of the solar cycle: the biggest radiation belt storms of two previous solar cycles occurred in their declining phase when the high-speed solar wind streams prevailed over coronal mass ejections. Not surprisingly, the two biggest solar storms of this decade occurred within the last several months on 17 March and 24 June 2015. Radiation belts comprise particles trapped by the Earth's geomagnetic field and held in closed drift trajectories around Earth. Particle intensities are controlled by the shifting balance among multiple acceleration and loss mechanisms that interact with particles at different parts of their drift trajectories. The lines of apsides of the Van Allen Probes orbits drift westward and complete a full circle around Earth over ~2 years (Fig. 11). By the end of the extended mission, the Van Allen Probes will be the first inner magnetospheric mission to circle around Earth four times, allowing the team to quantify how the relative role of various acceleration and loss mechanisms changes with the decline of the solar cycle.

Particle acceleration mechanisms have been a key focus of the Van Allen

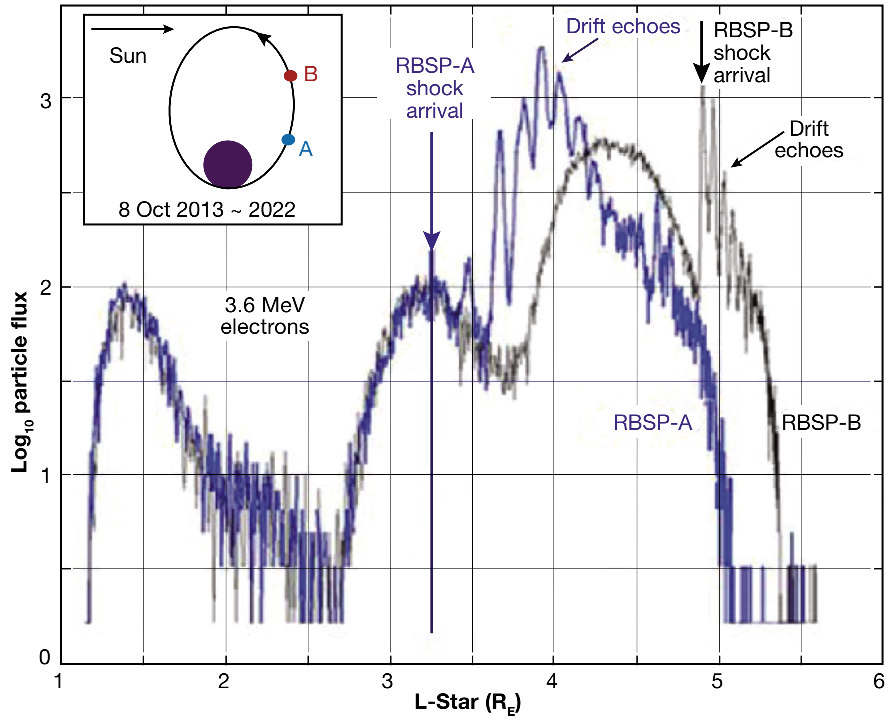

Figure 8. REPT measurements of relativistic electrons accelerated by interplanetary shock perturbations transmitted into the radiation belts. The shock-generated wave arrived almost simultaneously at both spacecraft while they were outbound from Earth at different positions (top left).[11]

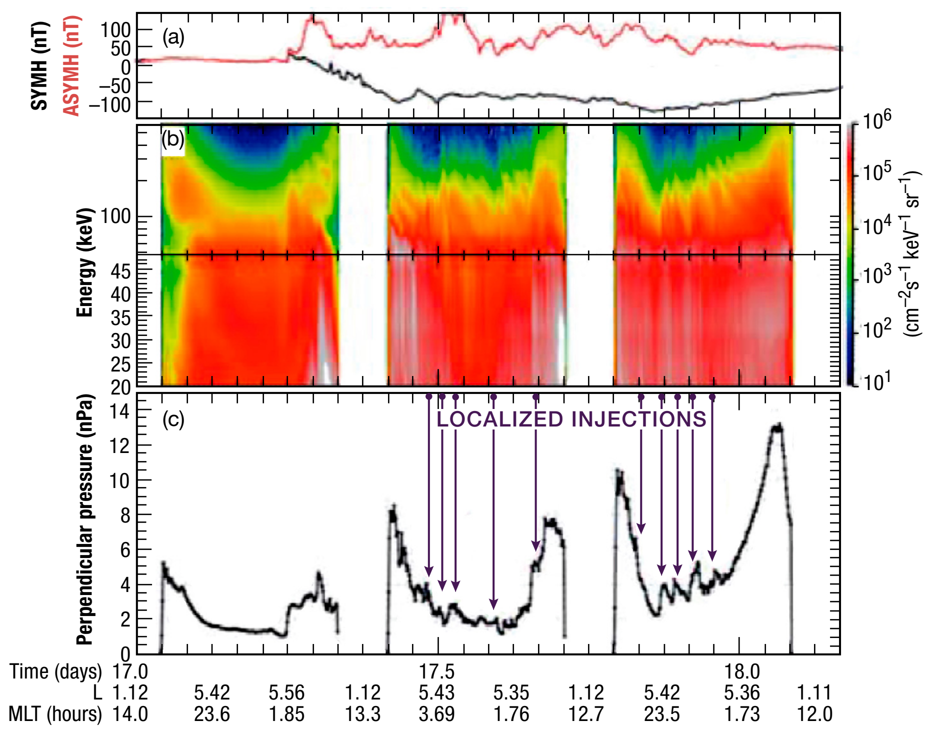

Figure 9. Three orbits of RBSPICE energetic ion data before and during a magnetospheric storm show that localized injections are far more common within the heat of the ring current populations than previously recognized. The color spectrogram shows angle-averaged proton intensities, and panel c shows integrated particle pressure.[15] (Adapted from Ref. 16.)

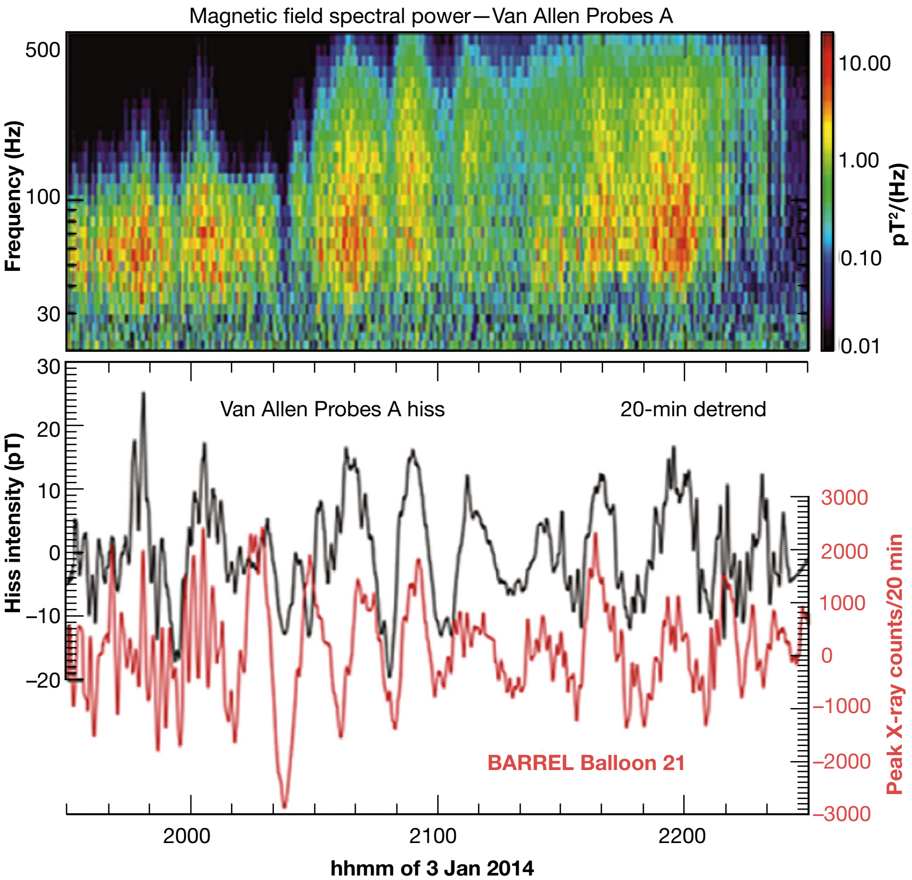

Figure 10. The close correlation of EFW measurements of whistler wave hiss emissions (top panel and bottom black curve) and the intensity of magnetically conjugate electron precipitation into the atmosphere as diagnosed from bremsstrahlung X-rays measured with one of the Antarctic BARREL balloons led Breneman et al.[21] to conclude that the hiss causes the precipitation over very broad regions. (Adapted from Ref. 21.)

Probes mission. The Probes have provided the first definitive evidence of local peaks in the radial profiles of electron PSD,[7] and these peaks were attributed to local quasilinear acceleration by whistler waves.[2] The Probes have also discovered highly unexpected nonlinear wave structures in the heart of the radiation belt.[28] Such structures can rapidly energize very low-energy electrons up to the kiloelectronvolt range, thereby providing a seed population for subsequent acceleration to radiation belt energies. The Probes have also observed large-amplitude whistler mode waves (~100–500 mV/m) (see, e.g., Refs. 29 and 30) that are likely to rapidly accelerate kiloelectronvolt particles to megaelectronvolt energies in the process on nonlinear wave–particle interactions along magnetic field lines. A key theme of the extended mission is to sort out the relative importance of quasilinear and nonlinear interactions for the buildup of radiation belt intensities.

To determine the relative importance of nonlinear interactions, the evolution of the wave fields and particle distributions along field lines needs to be measured. The extended mission will provide two unique opportunities for taking such measurements. The first opportunity arises because the spacecraft orbits were adjusted by increasing the separation of their apogees (i.e., the apogee of spacecraft A was raised by 75 km, and the apogee of spacecraft B was lowered by 75 km). This adjustment increased the cadence of lapping events from 67 to 35 days, doubling the opportunities for two-point sampling of wave–particle interactions along field lines. The second opportunity to sample wave interactions simultaneously at different magnetic latitudes will arise via coordinating with the Japanese Exploration of energization and Radiation in Geospace (ERG) spacecraft, planned for launch in the summer of 2016. ERG, by design, will sample at higher magnetic latitudes than the Probes. Using three-point measurements will provide a more global view of wave–particle interactions at different magnetic latitudes, important for quantifying nonlinear effects.

Particle loss mechanisms are another phenomenon that must be studied in pursuit of understanding dynamic variability of radiation belt intensities. Particle scattering losses into the atmosphere have been the particular focus of joint measurements of the Van Allen Probes and BARREL.[19] Exceedingly close correlations between whistler mode hiss waves and electron precipitation modulations have been observed,[21] suggesting a global extent for the losses capable of depleting radiation belt intensities on timescales as short as 1–20 min. Another process that can rapidly deplete radiation belt intensities during storms is particle streaming through the magnetopause boundary, causing particles to escape into the interplanetary environment. A goal of the Van Allen Probes extended mission is to enable understanding of the relative importance of precipitation and magnetopause losses. The launch of NASA Magnetospheric Multiscale (MMS) mission in March 2015 offers an ideal opportunity to observe directly these escaping electrons at the magnetopause while the Van Allen Probes measure inner magnetospheric losses and the processes that drive these losses.

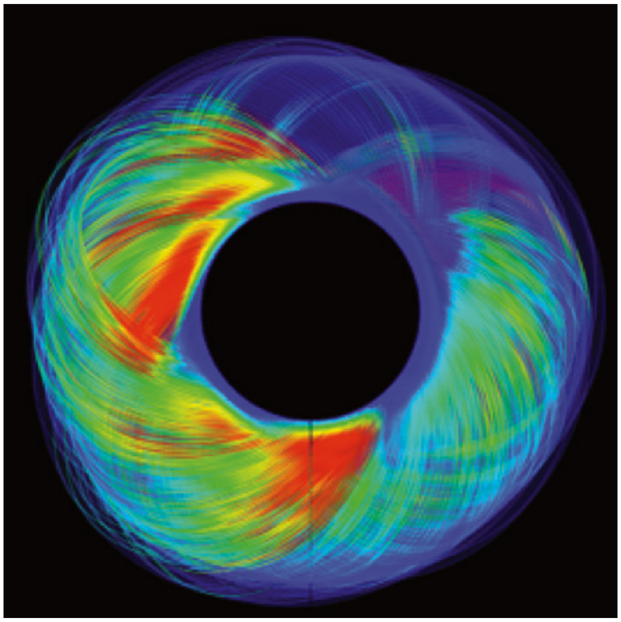

Figure 11. As the spacecraft orbits precess around Earth, the Probes sample different acceleration and loss mechanisms that sculpt global distributions of radiation belts and ring current populations.

During major loss events, the MMS spacecraft will skim the dayside magnetopause region for extended intervals. With huge energetic electron sensor geometric factors totaling more than G = 2 cm^2-sr for the cluster,[31] MMS will directly measure escaping radiation belt electrons.

The buildup of energetic (kiloelectronvolt) ion population during storms creates a source of hot plasma pressure in the inner magnetosphere that drives the global ring current system. Ring current controls the distribution of the magnetic field that governs the motion of radiation belt particles. Energetic ions also provide the energy source for an array of different wave modes that play a significant role in radiation belt acceleration and loss. A surprising discovery of the Van Allen Probes prime mission was that a substantial fraction of hot plasma pressure is transported in mesoscale (~1–2 R_E) dynamic ion injections that were previously considered infrequent in the inner magnetosphere. The structure and occurrence rates of the injections remain unknown, and the amount of hot plasma transported remains poorly quantified. It is our goal for the extended mission to understand the relative roles of global-scale transport processes and mesoscale injections in the buildup of hot plasma pressure during storms. This investigation will be greatly enabled by the recent adjustment of the spacecraft orbit, which doubled the cadence of simultaneous two-point measurements at the separation of 1–2 R_E, necessary to quantify the properties of dynamic injections.

CONCLUSION

Over last 3 years, the Van Allen Probes mission has radically changed our understanding of Earth's inner magnetosphere and radiation belts. As of March 2016, the Van Allen Probes bibliography contains over 225 publications, including a number of articles in prestigious journals such as *Nature* and *Science*. (See http://rbspgway.jhuapl.edu/biblio?s=year&o=desc&f[keyword]=10 for bibliographies.) With all instruments returning quality data, both spacecraft being healthy, and the remaining propellant sufficient to support spacecraft operations well into 2019, many more publications and science discoveries are expected during the extended mission. Stay tuned!

REFERENCES

[1]Baker, D. N., Kanekal, S. G., Hoxie, V. C., Batiste, S., Bolton, M., et al., "The Relativistic Electron-Proton Telescope (REPT) Instrument on Board the Radiation Belt Storm Probes (RBSP) Spacecraft: Characterization of Earth's Radiation Belt High-Energy Particle Populations," *Space Sci. Rev.* **179**(1), 337–381 (2013).

[2]Thorne, R. M., Li, W., Ni, B., Ma, Q., Bortniket, J., et al., "Rapid Local Acceleration of Relativistic Radiation-Belt Electrons by Magnetospheric Chorus," *Nature* **504**(7480), 411–414 (2013).

[3]Shprits, Y. Y., Subbotin, D., Drozdov, A., Usanova, M. E., Kellerman, A., et al., "Unusual Stable Trapping of the Ultrarelativistic Electrons in the Van Allen Radiation Belts," *Nat. Phys.* **9**(11), 699–703 (2013).

[4]Ukhorskiy, A. Y., Sitnov, M. I., Mitchell, D. G., Takahashi, K., Lanzerotti, L. J., and Mauk, B. H., "Rotationally Driven 'Zebra Stripes' in Earth's Inner Radiation Belt," *Nature* **507**(7492), 338–340 (2014).

[5]Baker, D. N., Jaynes, A. N., Hoxie, V. C., Thorne, R. M., Foster, J. C., et al., "An Impenetrable Barrier to Ultrarelativistic Electrons in the Van Allen Radiation Belts," *Nature* **515**(7528), 531–534 (2014).

[6]Baker, D. N., Kanekal, S. G., Hoxie, V. C., Henderson, M. G., Li, X., et al., "A Long-Lived Relativistic Electron Storage Ring Embedded in Earth's Outer Van Allen Belt," *Science* **340**(6129),186–190 (2013).

[7]Reeves, G. D., Spence, H. E., Henderson, M. G., Morley, S. K., Friedel, R. H. W., et al., "Electron Acceleration in the Heart of the Van Allen Radiation Belts," *Science* **341**(6149), 991–994 (2013).

[8]Fennell, J. F., Roeder, J. L., Kurth, W. S., Henderson, M. G., Larsen, B. A., et al., "Van Allen Probes Observations of Direct Wave-Particle Interactions," *Geophys. Res. Lett.* **41**(6), 1869–1875 (2014).

[9]Thorne, R. M., Li, W., Ma, Q., Ni, B., and Bortnik, J., "Radiation Belt Electron Acceleration by Chorus Waves During the 17 March 2013 Storm," in *Proc. XXXIth URSI General Assembly and Scientific Symp.*, Beijing, p. 1 (2014).

[10]Claudepierre, S. G., Mann, I. R., Takahashi, K., Fennell, J. F., Hudson, M. K., et al., "Van Allen Probes Observation of Localized Drift-Resonance Between Poloidal Mode Ultra-Low Frequency Waves and 60 keV Electrons," *Geophys Res. Lett.* **40**(17), 4491–4497 (2013).

[11]Dai, L., Takahashi, K., Wygant, J. R., Chen, L., Bonnell, J. W., et al., "Excitation of Poloidal Standing Alfven Waves Through the Drift Resonance Wave-Particle Interaction," *Geophys Res. Lett.* **40**(16), 4127–4132 (2013).

[12]Foster, J. C., Wygant, J. R., Hudson, M. K., Boyd, A. J., Baker, D. N., et al., "Shock-Induced Prompt Relativistic Electron Acceleration in the Inner Magnetosphere," *J. Geophys. Res. Space Phys.* **120**(3), 1661–1674 (2015).

[13]Mozer, F., Bale, S.., Bonnell, J. W., Chaston, C., Roth, I., et al, "Megavolt Parallel Potentials Arising from Double-Layer Streams in the Earth's Outer Radiation Belt," *Phys. Rev. Lett.* **111**(23), 235002 (2013).

[14]Mozer, F. S., Agapitov, O., Krasnoselskikh, V., Lejosne, S., Reeves, G. D., and Roth, I., "Direct Observation of Radiation-Belt Electron Acceleration from Electron-Volt Energies to Megavolts by Nonlinear Whistlers," *Phys. Rev. Lett.* **113**(3), 035001-1–035001-5 (2014).

[15]Boyd, A. J., Spence, H. E., Claudepierre, S. G., Fennell, J. F., Blake, J. B., et al., "Quantifying the Radiation Belt Seed Population in the 17 March 2013 Electron Acceleration Event," *Geophys. Res. Lett.* **41**(7), 2275–2281 (2014).

[16]Gkioulidou, M., Ukhorskiy A., Mitchell, D. G., Sotirelis, T., Mauk B., et al., "The Role of Small-Scale Ion Injections in the Buildup of Earth's Ring Current Pressure: Van Allen Probes Observations of the March 17th, 2013 Storm," *J. Geophys. Res. Space Phys.* **119**(9), 7327–7342 (2014).

[17]Yu, Y., Jordanova, V., Welling, D., Larsen, B., Claudepierre, S. G., et al., "The Role of Ring Current Particle Injections: Global Simulations and Van Allen Probes Observations During 17 March 2013 Storm," *Geophys. Res. Lett.* **41**(4), 1126–1132 (2014).

[18]Li, W., Thorne, R. M., Bortnik, J., Reeves, G. D., Kletzing, C. A., et al., "An Unusual Enhancement of Low-Frequency Plasmaspheric Hiss in the Outer Plasmasphere Associated with Substorm-Injected Electrons," *Geophys. Res. Lett.* **40**(15), 3798–3803 (2013).

[19]Chaston, C. C., Bonnell, J. W., Wygant, J. R., Mozer, F., Bale, S. D., et al., "Observations of Kinetic Scale Field Line Resonances," *Geophys. Res. Lett.* **41**(2), 209–215 (2014).

[20]Millan, R. M., McCarthy, M. P., Sample, J. G., Smith, D. M., Thompson, L. D., et al., "The Balloon Array for RBSP Relativistic Electron Losses (BARREL)," *Space Sci. Rev.* **179**(1), 503–530 (2013).

[21]Breneman, A. W., Halford, A., Millan, R., McCarthy, M., Fennell, J., et al., "Global-Scale Coherence Modulation of Radiation-Belt Electron Loss from Plasmaspheric Hiss," *Nature* **523**(7559), 193–195 (2015).

[22]Mazur, J. E., O'Brien, T. P., Looper, M. D., and Blake, J. B., "Large Anisotropies of >60 MeV Protons throughout the Inner Belt Observed with the Van Allen Probes Mission," *Geophys. Res. Lett.* **41**(11), 3738–3743 (2014).

[23]Selesnick, R. S., Baker, D. N., Jaynes, A. N., Li, X., Kanekal, S. G., et al., "Observations of the Inner Radiation Belt: CRAND and Trapped Solar Protons," *J. Geophys. Res.* **119**(8), 6541–6552 (2014).

[24]Fennell J. F., Claudepierre, S. G., Blake, J. B., O'Brien, T. P., Clemmons, J. H., et al., "Van Allen Probes Show the Inner Radiation Zone Contains No MeV Electrons: ECT/MagEIS Data," *Geophys. Res. Lett.* **42**(5), 1283–1289 (2015).

[25]Li, X., Selesnick, R. S., Baker, D. N., Jaynes, A. N., Kanekal, S. G., et al., "Upper Limit on the Inner Radiation Belt MeV Electron Intensity," *J. Geophys. Res. Space Phys.* **120**(2), 1215–1228 (2015).

[26]Tu, W., Cunningham, G. S., Chen, Y., Morley, S. K., Reeves, G. D., et al., "Event-Specific Chorus Wave and Electron Seed Population Models in DREAM3D Using the Van Allen Probes," *Geophys. Res. Lett.* **41**(5), 1359–1366 (2014).

[27]Li, Z., Hudson, M., and Chen, Y., "Radial Diffusion Comparing a THEMIS Statistical Model with Geosynchronous Measurements as Input," *J. Geophys. Res. Space Phys.* **119**(3), 1863–1873 (2014).

[28]Mozer, F. S., Agapitov, O. V., Artemyev, A., Drake, J. F., Krasnoselskikh, V., et al., "Time Domain Structures: What and Where They Are, What They Do, and How They Are Made," *Geophys. Res. Lett.* **42**(10), 3627–3638 (2015).

[29]Santolík, O., Kletzing, C. A., Kurth, W. S., Hospodarsky, G. B., and Boundset, S. R., "Fine Structure of Large-Amplitude Chorus Wave Packets," *Geophys. Res. Lett.* **41**(2), 293–299 (2014).

[30]Wygant, J. R., Bonnell, J. W., Goetz, K., Ergun, R. E., Mozer, F. S., et al., "The Electric Field and Waves Instruments on the Radiation Belt Storm Probes Mission," *Space Sci. Rev.* **179**(1), 183–220 (2013).

[31]Mauk, B. H., Blake, J. B., Baker, D. N., Clemmons, J. H., Reeves, G. D., et al., "The Energetic Particle Detector (EPD) Investigation and the Energetic Ion Spectrometer (EIS) for the Magnetospheric Multiscale (MMS) Mission," *Space Sci. Rev.* **199**(1), 471–514 (2014).

THE AUTHORS

Elena Y. Adams is a systems engineer in APL's Space Exploration Sector. She was a payload systems engineer for the Van Allen Probes, responsible for the ECT suite: MagEIS, HOPE, and REPT. **Kristin A. Fretz** is a systems engineer in APL's Space Exploration Sector. She led the fault management team for the Van Allen Probes mission during the development, integration, and test phases of the project and is currently serving as the Mission Systems Engineer for the extended mission. **Aleksandr Y. Ukhorskiy** is a senior scientist in APL's Space Exploration Sector. He is currently serving as the Project Scientist for the Van Allen Probes mission. **Nicola ("Nicky") J. Fox** is the Chief Scientist for Space Weather in the Space Research Branch of APL's Space Exploration Sector. She is the Deputy Project Scientist for the Van Allen Probes mission. For further information on the work reported here, contact Elena Adams. Her e-mail address is elena.adams@jhuapl.edu.