The Van Allen Probes' Contribution to the Space Weather System

Lawrence J. Zanetti, Ramona L. Kessel, Barry H. Mauk, Aleksandr Y. Ukhorskiy, Nicola J. Fox, Robin J. Barnes, Michele Weiss, Thomas S. Sotirelis, and NourEddine Raouafi

ABSTRACT

The Van Allen Probes mission, formerly the Radiation Belt Storm Probes mission, was renamed soon after launch to honor the late James Van Allen, who discovered Earth's radiation belts at the beginning of the space age. While most of the science data are telemetered to the ground using a store-and-then-dump schedule, some of the space weather data are broadcast continuously when the Probes are not sending down the science data (approximately 90% of the time). This space weather data set is captured by contributed ground stations around the world (presently Korea Astronomy and Space Science Institute and the Institute of Atmospheric Physics, Czech Republic), automatically sent to the ground facility at the Johns Hopkins University Applied Physics Laboratory, converted to scientific units, and published online in the form of digital data and plots—all within less than 15 minutes from the time that the data are accumulated onboard the Probes. The real-time Van Allen Probes space weather information is publicly accessible via the Van Allen Probes Gateway web interface.

INTRODUCTION

The overarching goal of the study of space weather is to understand and address the issues caused by solar disturbances and the effects of those issues on humans and technological systems. The space weather field has evolved over the past few decades. It began as a collection of concerned agencies and researchers, and today, the study of space weather is a critical function of the National Weather Service of the National Oceanic and Atmospheric Administration (NOAA). The general effects of space weather have evolved from telegraph disruptions of the mid-1800s to modern-day disturbances of the electric power grid, communications and navigation, human spaceflight, and spacecraft systems. The last two items in this list, and specifically the effects of penetrating radiation, were the impetus for implementing a space weather broadcast capability on NASA's Van Allen Probes' twin pair of satellites, which were launched in August 2012 and are currently orbiting directly through Earth's severe radiation belts.

The primary objective of the dual-spacecraft mission is to advance the scientific understanding of the physics of the radiation belts, specifically their creation, loss, and overall dynamics. In addition, the transmission of the space weather parameters related to radiation can provide valuable near real-time information on the severity of the radiation environment surrounding Earth; the radiation environment can affect spacecraft systems and operations as well as human safety, e.g., astronauts operating spacewalk tasks at the International Space Station.[1,2]

The Van Allen Probes mission, formerly the Radiation Belt Storm Probes (RBSP; http://vanallenprobes.jhuapl.edu), was renamed soon after launch to honor the discoverer of Earth's radiation belts at the beginning of the space age, the late James Van Allen (the spacecraft themselves are still referred to as RBSP-A and RBSP-B). The Van Allen Probes (see Mauk et al.[3] and other Van Allen team contributions in the same special 2013 issue of *Space Science Reviews*) are one part of NASA's Living With a Star (LWS; http://lws.gsfc.nasa.gov) program formulated to advance the scientific understanding of the connection between solar disturbances, the resulting heliospheric conditions, and their effects on the geospace and Earth environment. The LWS charter is to contribute to the advancement of the scientific understanding necessary to address how solar variability affects life and society. In this article, we show an example of space weather events that involved the Van Allen Probes mission: space weather predictions and real-time monitoring were associated with the Juno spacecraft's[4] recent gravity-assist encounter with Earth.

The heritage of the continuous telemetry transmission of space weather data dates back to NASA's Advanced Composition Explorer (ACE)[5,6] mission at the L1 Lagrange point. The ACE mission assembles a small fraction of the science data stream and then continually transmits these data in real time. The real-time transmissions are received worldwide and relayed to NOAA's Space Weather Prediction Center (SWPC; http://www.swpc.noaa.gov/), where they are converted into products and alerts and fed into predictive models that are distributed to concerned users, customers, and operators. NASA's STEREO mission[7] provides a similar broadcast; these transmissions are relayed to NOAA/SWPC whenever possible (STEREO is not continuously tracked worldwide) and are used primarily in the characterization of erupting coronal mass ejections.

Prior to launch, Kessel et al.[8] provided the technical details of the space weather broadcast capability on the Van Allen Probes mission. Specifically, although the vast majority of the science data are telemetered to the ground using a store-and-then-dump schedule, a small fraction of the data, the space weather data, are broadcast continuously during the approximately 90% of the time that the Probes are not sending down the science data. This space weather data set is captured by contributed ground stations around the world, automatically sent to the ground facility at the Johns Hopkins University Applied Physics Laboratory (APL), converted to scientific units, and put online in the form of digital data and plots, all within less than 15 min from the time that the data are accumulated onboard the Probes. At this time, two ground stations capture the data (Korea Astronomy and Space Science Institute and the Institute of Atmospheric Physics, Czech Republic), but the program is working toward a minimum of five ground stations that can provide near real-time coverage approximately 70% of the time. The real-time Van Allen Probes space weather information is publicly accessible online via the Van Allen Probes Gateway (http://rbspgway.jhuapl.edu/).

Figure 1 was customized to include the trajectory of NASA's Juno spacecraft as it performed its 9 October 2013 gravity-assist maneuver as well as to show the Van Allen Probes spacecraft orbits. The figure views the RBSP-A and -B orbits from north zenith in GSE coordinates with the Sun toward the right. The Energetic Particle, Composition, and Thermal Plasma (ECT) Suite/Relativistic Electron-Proton Telescope (REPT) energetic particle data[9] received from RBSP-A are displayed in near real-time on the left in terms of L-shell intensity versus time. The following three electron intensity channels (from top to bottom in Fig. 1) were derived from approximately 1 month of data: 10 MeV electrons and >70 MeV protons; 5 MeV electrons and >50 MeV protons; and 2 MeV electrons and >20 MeV protons; these data are also "painted" on the orbit tracks. Also shown (bottom panel) is the geomagnetic parameter Dst, indicating geomagnetic activity. The middle electron intensity channel shown on the left is also used to paint the spacecraft orbit with that channel intensity. The first small storm, indicated by a dip in Dst, enhanced the outer radiation belt intensity as seen in the top three panels, whereas the second, quite similar, storm drastically diminished belt intensities. The 2.3-MeV spin-averaged electrons from the Level 2 stream are shown in the third panel from the top; note the reflection of the near real-time data of the second panel from the top. The bottom two panels provide the geomagnetic parameters Dst and Kp as indicators of geomagnetic activity. Users can easily customize the display by selecting channels from the various Van Allen Probes instrument products; customization instructions are available on the Gateway website.

As mentioned above, an important test of the usefulness of the Van Allen Probes space weather broadcast came during the encounter of NASA's Juno spacecraft with Earth. Juno, which will arrive at Jupiter for orbit insertion in mid-2016, executed a gravity-assist Earth encounter on 9 October 2013. During this encounter, many of Juno's instruments were operating for the purposes of calibration and the determination of sensitivity to radiation, and space weather conditions were monitored in near real-time by the Van Allen Probes' broadcast. The predictions from NOAA/SWPC were checked to see whether there might be any issue with the radiation belts being energized by solar activity. A coronal mass ejection arrived at Earth at approximately 0000 UTC on the day of the encounter.

As also shown in Fig. 1, the space weather broadcast from the Probes observed that Earth's radiation belts, recently pumped up by a substantial storm that occurred about a week before, were effectively swept away or diminished by the response to a storm caused by the coronal mass ejection. The real-time space weather data provided reassurance that just prior to the Juno closest approach, the electron radiation of Earth's outer radiation belt would not challenge the Juno instruments. Juno did, however, transit the stable inner proton belt. Juno scientists and engineers used the passage through the inner proton belt to characterize the efficiency of subsystem and instrument shielding within a very penetrating radiation environment. Specifically, Becker et al.[10] report possible radiation-produced interference results from Juno's Stellar Reference Unit (SRU) and Advanced Stellar Compass (ASC) navigation units as well as the JunoCam Education and Public Outreach camera, as these imaging results are correlated with high-energy proton measurements from both the Juno and Van Allen Probes particle investigations. Gladstone et al.[11] reported on proton penetrations of the shielding for the ultraviolet auroral imager on Juno. All of these examinations showed that Juno is prepared for the radiation environment that will be encountered at Jupiter.

Space weather scenarios such as those described above are at the heart of the LWS program—to better understand the Sun–Earth interaction and its consequences and to enable improved predictions and spacecraft design. The response of Earth's radiation belts

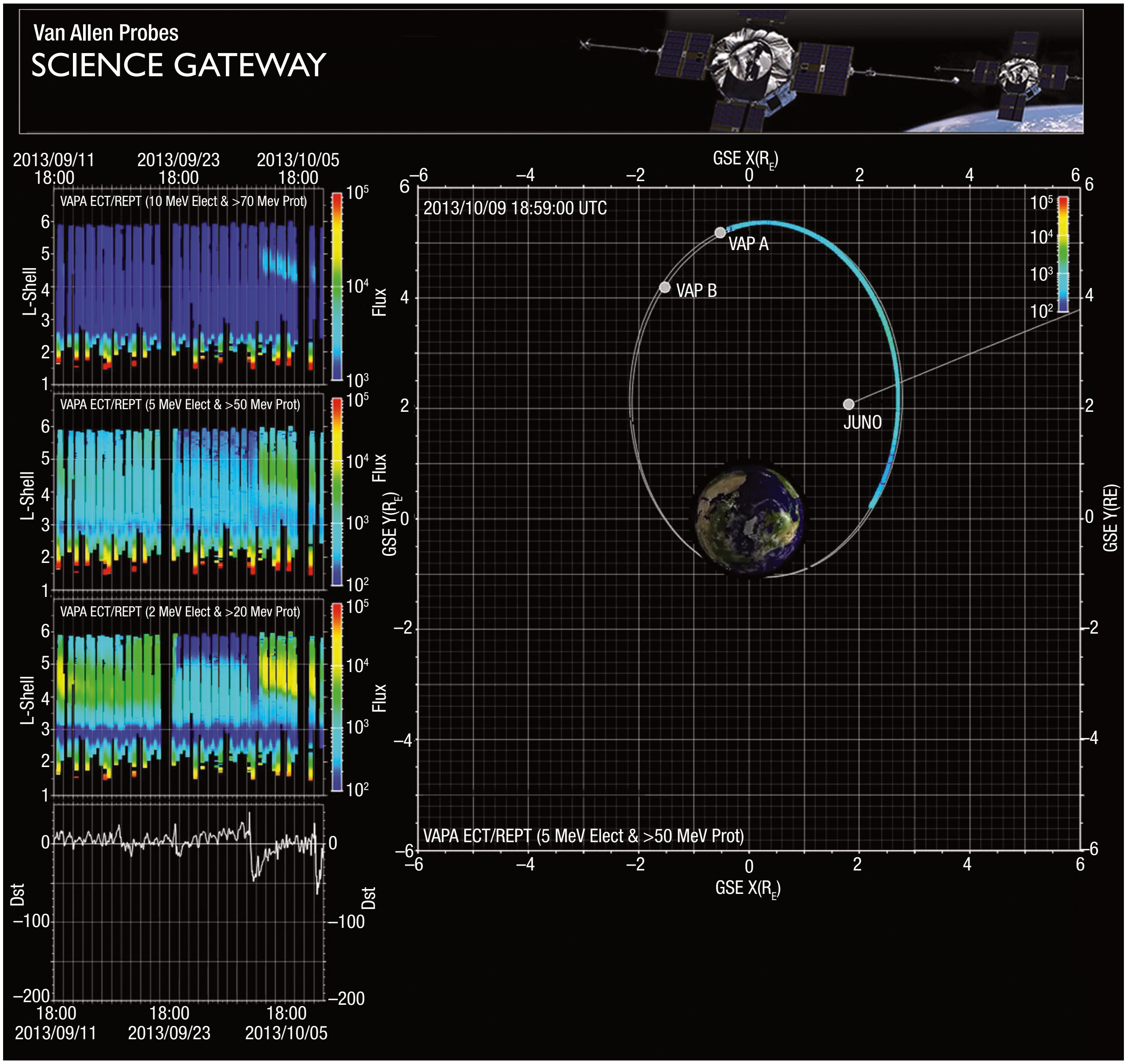

Figure 1. A Van Allen Probes space weather display especially configured to include the trajectory of NASA's Juno spacecraft.

to changing geomagnetic storm conditions is a primary scientific goal of the twin Van Allen Probes' mission; advanced models are being produced to assimilate the Probes' real-time data and then predict the radiation environment (e.g., Reeves et al.[12]). Often the radiation belts' response appears to be widely different to seemingly similar solar wind or geomagnetic forcings. Satellite operators require real-time information to determine whether system effects and anomalies are caused by the natural environment or other possible factors. The broadcast information from the Van Allen Probes is a critical addition to the LWS system and is a significant stride forward in understanding, now-casting, and eventually forecasting the radiation environment.

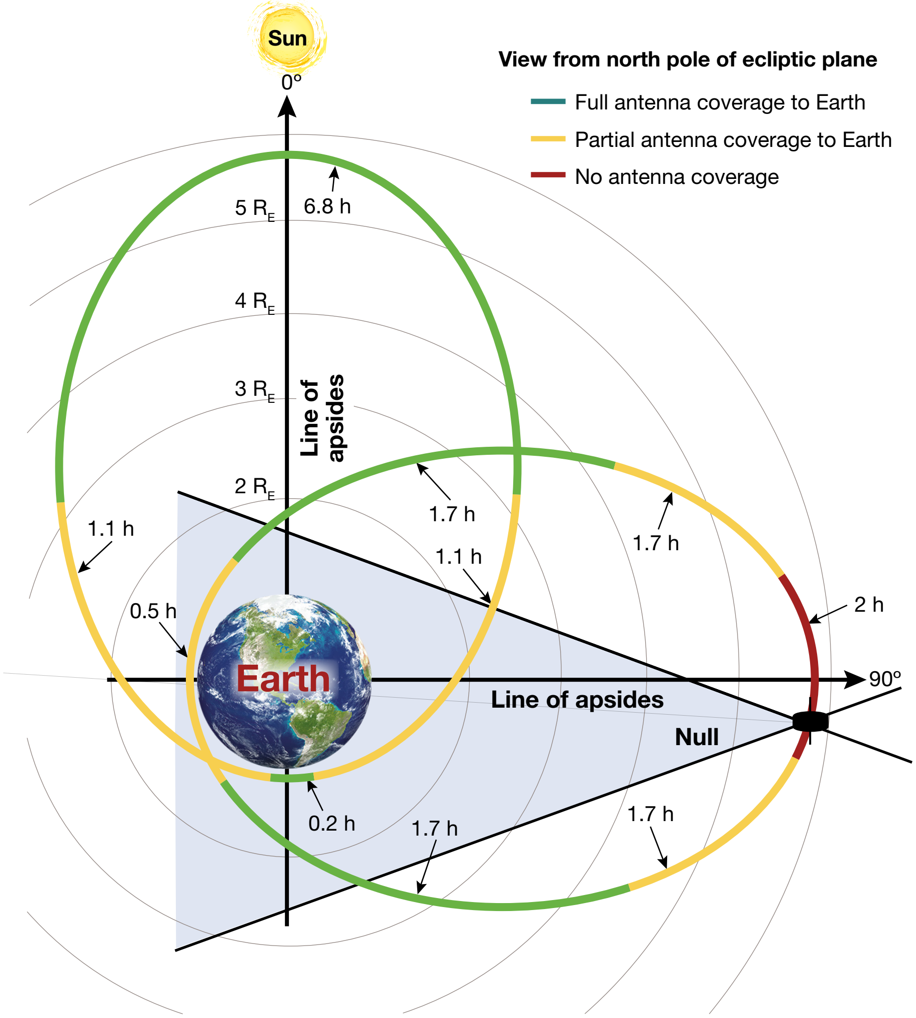

Figure 2. Regions of the Probes' orbits where communications downlinks are robust, variable, and impossible. The communications configuration changes over time because of the roughly 220° per year of clockwise (from the north) local time precession of the line of apogee.

DESCRIPTION OF THE PROBES

Each spacecraft broadcasts space weather data in real time through the primary spacecraft RF science downlink system whenever it is not engaged in science data downlink. Users who maintain and fund their own ground station antennas receive the data. This scenario is limited by the availability of space weather ground stations and antenna coverage. The real-time coverage is reduced by an average of 2.5 h for each spacecraft per day, or about 10% of the time, because of the other primary mission contacts. However, often when one of the spacecraft is broadcasting the primary science data, and therefore not broadcasting space weather data, the other spacecraft will still be broadcasting space weather data because many of the contacts with each spacecraft do not overlap in time.

Each of the Probes' payload instruments participates in the real-time space weather broadcast. The data include particle intensities at a variety of energies, as well as magnetic and electric field data. In addition to the real-time products, the project creates "quick-look" products to be produced by each of the individual instrument science operations centers. These products essentially fill in the gaps caused by times when the broadcast data cannot be received and also provide a more complete data set for use in diagnosing anomalies in low Earth orbit and mid Earth orbit.

The spacecraft pointing geometry, orbit, and spin stabilization determine communication system requirements. Earth's location, as viewed from the spacecraft, covers a very broad angle space (mast angle) as shown in the Probes' communications antenna angle coverage plot in Fig. 2. Contact geometry necessitates onboard antennas that have broad angular coverage and thus relatively low gain.

The coverage is maximized within practical limits by using two low-gain antennas. The two RF antennas' boresights are aligned with the spacecraft spin and anti-spin axes, providing coverage from each boresight to 70°. Despite maximizing the antenna coverage, there is still a 40° null band, depicted in Fig. 2 as the shaded area in the antenna angle coverage plot.

The possibility of users on Earth receiving the space weather broadcasts depends on an orbit geometry that varies with mission epoch as illustrated in Fig. 2—a view of the orbit changes as seen from a vantage pointing looking down on Earth from above the North Pole. Although antenna coverage is large, there are times when the antenna patterns are not aligned with Earth. The large eccentricity of the orbit causes longer periods of time when antennas are not in view during certain times of the year because the relative angle between the spacecraft and Earth changes slowly over long periods of time.

Spacecraft orbits are at a low inclination (10°), and the orbit harmonics cause the apogee and perigee to drift between the Northern and Southern hemispheres. Stations near the equator will have the best year-round coverage, while high-latitude stations have some limits in coverage over portions of the orbit for parts of the year. By using multiple stations at diverse longitudes, we can maximize potential spacecraft contact duration as a function of the number of ground stations.

Ideally, ground stations should be distributed around the globe at longitudinal separations of about 120° for an optimized three-station configuration. The telemetry link is subject to orbit geometry, the season, and the location of each ground station. It is estimated that with an ideal ground network, the link could be operational for about 65% of the time (assuming three longitudinally spaced stations). The normal spacecraft contacts reduce the available time for space weather by an average of 2.5 h per spacecraft per day. Discussions are underway with other possible international partners including Brazil, Japan, Argentina, Australia, South Africa, and India. APL regularly provides the participating ground stations with the spacecraft ephemerides and routinely retrieves the space weather data from those ground stations using either socket connections or FTP/SFTP protocols. The Van Allen Probes Space Weather Interface Control Document contains specific downlink and telemetry formats and is available to partners upon request.

MODELING

The Community Coordinated Modeling Center (CCMC) is a U.S. interagency activity, located at Goddard Space Flight Center, aimed at research in support of the generation of advanced space weather models (http://ccmc.gsfc.nasa.gov/). The first function of the CCMC is to provide a mechanism by which research models can be validated, tested, and improved for eventual use in space weather forecasting. Examples include NASA's Vision for Space Exploration Models. These models, which have completed their development and have passed metrics-based evaluations and science-based validations, are being prepared for space weather applications. In this function, the CCMC acts as an unbiased evaluator, bridging the gap between space science research and space weather applications.

As a second equally important function, the CCMC provides to space science researchers the use of space science models, even if those researchers are not model owners themselves. This service to the research community is implemented through the execution of model "runs-on-request" for specific events of interest to space science researchers at no cost to the requestor. Model output is made available to the science customer by means of tailored analysis tools and by means of data dissemination in standard formats. Through this activity and the concurrent development of advanced visualization tools, CCMC provides unprecedented access to a large number of state-of-the-art research models to the general science community. The continuously expanding model set includes models in all scientific domains from the solar corona to the Earth's upper atmosphere. Data received from the Van Allen Probes are available for scientific comparisons with model calculations and as inputs to model calculations performed following requests from the scientific community.

NOAA's SWPC is the U.S. government's official source for space weather forecasts. SWPC provides real-time monitoring and forecasting of solar and geophysical events that impact satellites, power grids, communications, navigation, and many other technological systems. It offers a range of online data products and services including alerts and forecasts, models, indices, and real-time or near real-time instrument measurements. Van Allen Probes data augment SWPC's current capabilities for understanding the space radiation environment. This provides a simple visual for the current level of charged particles in the radiation belts, and hence current internal charging conditions. A new service is under development within the National Geophysical Data Center that will combine near real-time and retrospective data for post-satellite-anomaly analysis. The center plans to develop a web page that will provide interactive plots of data and models for geostationary and low Earth orbits for determining whether an anomaly is likely related to surface charging, internal charging, single event effects, or total ionizing dose.

A particularly relevant model for analysis of space weather data from the Van Allen Probes mission is the Dynamic Radiation Environment Assimilation Model (DREAM). It was developed to provide accurate, global specification of Earth's radiation belts and to better understand the physical processes that control radiation belt structure and dynamics.[12] DREAM contributes to the Probes' science analysis in two major roles: (*i*) as a global context for understanding the local two-satellite measurements and (*ii*) as a test bed for real-time space

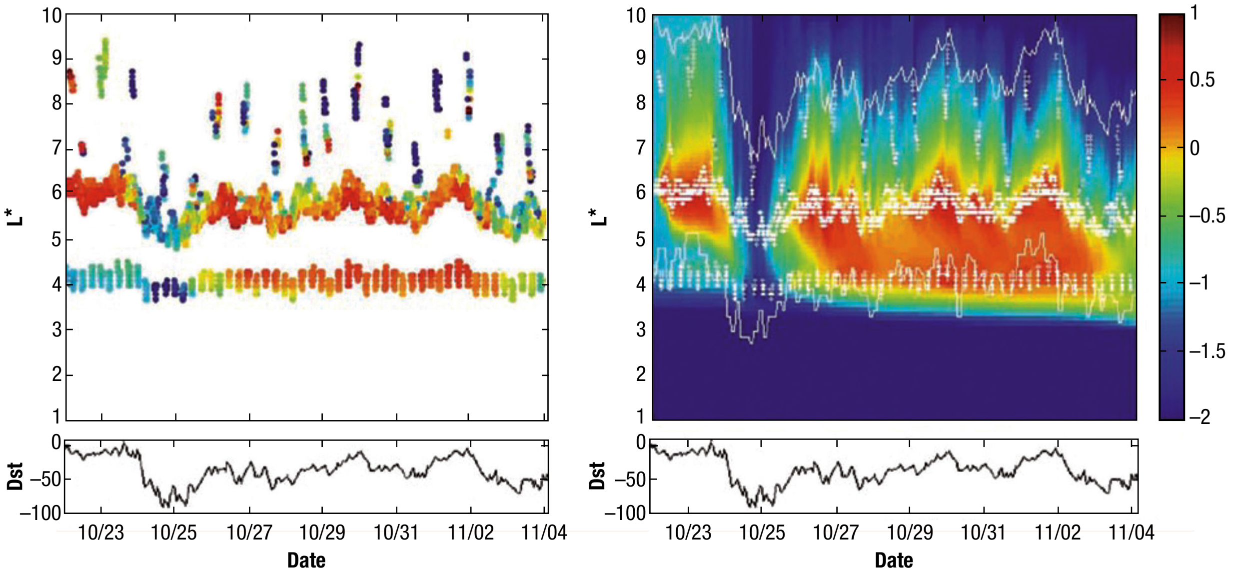

Figure 3. An example of the capability of the DREAM model[12] to assimilate sparse spacecraft measurements (left) together with empirical particle transport and energization algorithms to generate predictions of the overall state of Earth's electron radiation belt. The plots show the magnetospheric parameter L* (*y* axis) versus time (*x* axis) versus particle PSD (color scale), calculated from the particle intensity and the particle momentum. (Reproduced from Ref. 12.)

weather forecasting for the radiation belts. As the name implies, DREAM uses a powerful data-assimilation technique (specifically ensemble Kalman filtering) to calculate a global specification of the radiation belt environment that optimizes the match between the model and observations. Unlike traditional models that use "inputs" or "boundary conditions," data assimilation considers uncertainties in both the model and observations. The modeling uses core conditions (internal state) to extrapolate outside of the observation region; second "observations" should not be used.

DREAM uses a Fokker–Planck diffusion formulation (Reeves et al.[12]; see also Ukhorskiy and Sitnov[13]) as the physics engine that advances the forecast in time. At the time of this writing, data assimilation has only been implemented in the 1-D (radial diffusion) version, but a 3-D version with radial, energy, and pitch angle diffusion is undergoing testing. The radial diffusion calculation solves for phase space density (PSD) as a function of three magnetic invariants: μ, K, and L^* (invariants of gyration, bounce, and drift; again see Ukhorskiy and Sitnov[13]). DREAM first preprocesses data from intensity (as a function of energy, E, and pitch angle, α) to PSD as a function of μ, K, and L^*. (As part of the standard Probes data processing, μ, K, and L^* will be calculated along the satellite orbits using a variety of different magnetic field models and values and will be made available for analysis.) Data assimilation runs are done at each time step for each μ, K pair (typically 324 independent assimilations). In an asymmetric (and time varying) magnetic field, each point in space and time has a unique transformation from physical to magnetic coordinates. The same is true for the reverse transformation that takes the DREAM assimilation and converts back to intensity (versus E and α).

Figure 3 (from Reeves et al.[12]) shows an example of the incorporation of the PSD measurements shown on the left to create a prediction (on the right) for the PSDs throughout the radiation belt regions. The Van Allen Probes will give the predictions more fidelity by filling in many of the gaps between and inside of the present measurement positions.

The result is a model that gives the space weather forecast for the radiation belts—intensity, flux, and fluence, or dose—at any point in the radiation belts based on a very limited set of observations. For space weather forecasting, the model can be relatively simple with few (or no) free parameters—for example, 1-D radial diffusion with *DLL*(Kp), such as is now available with DREAM. For detailed scientific analysis, more complex models with 3-D diffusion and many free parameters will probably be needed with, for example, spatial and temporal distributions of wave power, frequency, and wave normal angle for a variety of wave modes. One of the goals of the Probes project is to evolve space weather products from the current state of now-casting with simple models to more sophisticated products that use more complex physics models (balancing accuracy and complexity) and provide forecasts days or more into the future.

SUMMARY

The two spacecraft that compose NASA's LWS Van Allen Probes mission continuously broadcast space weather data, except during prime science download and maneuvers. These data were selected to monitor the state of the radiation belts and to be incorporated into models such as DREAM that will lead to better space weather forecasts. The Van Allen Probes were designed to operate throughout the worst conditions expected in the hazardous radiation belt environment.[14,15] By design, the mission will make observations over the full range of particle energy levels and frequencies needed to decipher the mysteries described elsewhere.[3] The Probes are poised to significantly enhance our understanding of radiation belt dynamics with changing solar wind conditions and will enable the prediction of extreme and dynamic space conditions; they also provide the understanding needed to design satellites to survive in space for future missions.

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THE AUTHORS

Lawrence J. Zanetti is a Principal Professional Staff member in APL's Space Exploration Sector and a Program Scientist for NASA's Living With a Star (LWS) program. He has been on detail at NASA Headquarters as Program Scientist for Geospace missions and is presently on detail at NOAA as Space Weather Mission Scientist. He has considerable experience in conducting space physics research with spacecraft measurements, including experience with space weather warning monitors, the first of which was in concert with the electric power industry. He was the Principal Investigator for magnetic field instruments flown on space missions, including the Swedish Freja satellite, and Instrument Scientist and Lead for the NASA NEAR magnetometer. He participated on a number of review panels concerning the solar disturbances on geospace and the interaction of the Sun and planets as a system, developing new concepts to improve space weather understanding and prediction capability. **Ramona L. Kessel**, Program Scientist in the Heliophysics Division of NASA Headquarters, is a space scientist with wide-ranging interests in Earth and interplanetary space environments. She is presently the NASA Program Scientist on the Van Allen Probes mission, the Magnetospheric Multiscale mission, and the TWINS mission and Program Scientist for the Solar-Terrestrial Probes Program. She also serves as the Executive Secretary for the Heliophysics Subcommittee, an advisory group that reports to the NASA Advisory Council's Science Committee. Dr. Kessel was awarded the National Resource Award in February 2000 for seminal contributions enabling ISTP science. She has authored more than 100 publications that have been cited more than 1000 times. She was the focus of a front-page article in the *Greenbelt News Review* (13 March 2014) during Women's History Month for her outstanding contributions to the Van Allen Probes mission. **Barry H. Mauk** of the APL Space Exploration Sector is a space scientist specializing in planetary space environments. He is presently Lead Instrument Investigator for an instrument on NASA's Juno mission to a polar orbit of Jupiter and for a set of instruments on NASA's Magnetospheric Multiscale mission comprising four spacecraft orbiting Earth in close formation. He was Project Scientist for the prime mission of NASA's Van Allen Probes mission. He is also Co-Investigator on NASA's Voyager mission to the outer planets and beyond, and in the past he was member of NASA's Galileo mission to Jupiter, Project Scientist for the Phase B portions of both NASA' s TIMED mission and the Ballistic Missile Defense Organization's Nuclear Electric Space Test

Program. He has published more than 170 journal articles on space environments. **Aleksandr Y. Ukhorskiy** of the APL Space Exploration Sector is a space scientist specializing in Earth's space environments and the theoretical and numerical modeling of those environments. He is presently Project Scientist for NASA's Van Allen Probes mission. He has published more than 35 journal articles on Earth's space environment. **Nicola "Nicky" J. Fox** joined APL in 1998 as a research scientist studying various aspects of the geospace impact of coronal mass ejection events from the Sun. Since 2015, she has served as the Chief Scientist for Space Weather in the Space Research Branch. She has extensive project and program science leadership experience and is Project Scientist for the Solar Probe Plus mission as well as Deputy Project Scientist for the Van Allen Probes mission working with the NASA Center and NASA Headquarters on the full range of science issues for these high-profile missions. Before joining APL, Nicky was a USA National Research Council fellow at NASA Goddard Space Flight Center and a research scientist at Raytheon, with special responsibilities for the operations of the NASA Polar spacecraft and the International Solar Terrestrial Physics Program. **Robin J. Barnes** joined APL in 1997 as a software engineer in the space sector. He was the lead software engineer on the Super Dual Auroral Radar Network (SuperDARN) program that operates a network of high-frequency radars in the northern and southern polar caps. He developed operating systems, data analysis software, and the SuperDARN website at APL. He is the Lead Software Engineer on the AMPERE and SuperMAG programs and has worked on a number of other ground- and space-based missions. He is the Science Operation Center Coordinator for the Van Allen Probes mission and is also responsible for the development of the Van Allen Probes Science Gateway website. **Michele Weiss** joined APL in 1996 as a software engineer working on the TIMED GUVI science Payload Operations Center, VITMO and the RBSP Science Gateway. Since 2011, she was the Project Manager for the DMSP SSUSI and the GRACE Follow-On projects. She has extensive technical and program management experience. Prior to joining APL, Michele worked at Fairchild Defense, EER Systems, and Litton Amecom. **Thomas S. Sotirelis** of the APL Space Exploration Sector is a space scientist specializing in the physics of the Earth's space environment. He is Deputy Project Scientist for NASA's Van Allen Probes mission. He also develops reduced-size particle instrumentation for space weather applications. **NourEddine Raouafi** joined APL in December 2008 as a research scientist studying various aspects of the solar magnetic activity and coronal phenomena. Since 2009, he has been a member of the Solar Probe Plus project science team. Prior to joining APL, Nour worked at the National Solar Observatory from 2005 to 2008, and prior to that at the Max Planck Institute for Solar System Research (Göttingen, Germany). He has extensive experience in coronal physics and solar wind and has published more than 30 journal articles on coronal and cometary physics. For further information on the work reported here, contact Larry Zanetti. His e-mail address is larry.zanetti@jhuapl.edu.