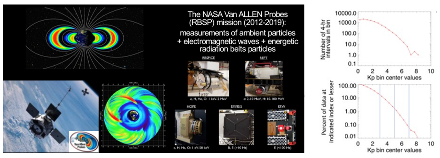
Active Physics of Energetic Particles, Waves, and their Interaction in the Near-Earth Space

J.-F. Ripoll[1,2], L. Cerfolli[1,2], T. Farges[1], O. Le Contel[3], A. Retino[3], P.-L. Blelly[4], A. Marchaudon[4] , S. A. Thaller[5,6], D. P. Hartley[7], D. Malaspina[8,9], V. Loridan[10], M. H. Denton[11], G. S. Cunningham[12], G. Reeves[12], A. Y. Drozdov[13], Y. Y. Shprits[14]

Introduction

Active experiments are man-made monitored disturbances of ionosphere or near Earth space, such as neutral release (barium or hydrazine burn for instance) or electron beam emission in the ionosphere. This is a way to understand electromagnetic wave propagation in near Earth's space. The motivation is to study wave-particle interactions occurring in the radiations belts. Inhere, we use observations of electromagnetic waves and cold electron plasma density measured by the NASA Van Allen Probes (RBSP). We explain how we generate formatted data & statistics usable for analyzing active experiments and radiation belt problems with accurate and validated simulations.



Geomagnetic activity during RBSP mission:
0<Kp<1 : 70% of times
1<Kp<3 : 18% of times
3<Kp<5 : 10% of times
5<Kp<8 : 2% of times

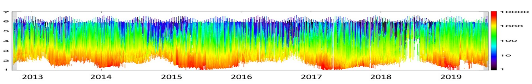
Fig 1. (left) The electron radiation belts, the NASA Van Allen Probes (RBSP) their precession and wave and particle instruments. (right) Activity during RBSP showing the dominance of quiet times and the rareness of storms.

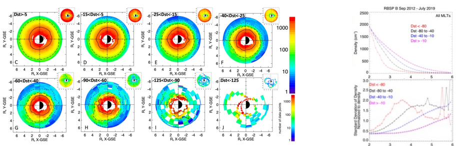
Reference: Ripoll, J.-F., Claudepierre, S. G., Ukhorskiy et al. (2020). Particle Dynamics in the Earth's Radiation Belts: Review of Current Research and Open Questions. Journal of Geophysical Research: Space Physics, 125, e2019JA026735.

The plasmasphere from RBSP

New electron density models

The Earth's plasmasphere is a region of cold plasma made of ions/electrons of a few eV, originating from upwelling air in the ionosphere and forming a rotating torus around the Earth. We analyze 7 years of RBSP data of the electron plasma density, which is a main parameter influencing WPI driving trapped particles in the inner magnetosphere.





Ripoll, J.-F., Thaller, S. A., Hartley, D. P., Cunningham, G. S., Pierrard, V., Kurth, W. S., et al. (2022). Statistics and empirical models of the plasmasphere boundaries from the Van Allen Probes for radiation belt physics. Geophysical Research Letters, 49, e2022GL101402.

Fig 2. (top) RBSP electron density. (left) Statistics of plasmaspheric density vs. geomagnetic activity (Dst index). (right) Empirial model of the mean and standard deviation of the electron density vs. Dst index.

New mean electron densities and their standard deviation are generated and fitted to be inputted in space weather codes. Complexity arises in very dense low-L regions, inside the plasmapause (150-10 #/cc), in plasma plumes and in detached plasma.

Wave-particle interactions

Whistler-mode waves and the plasmasphere

Whistler mode waves are electromagnetic, right-hand polarized whistler mode waves that are observed in the VLF range from tens of Hz to tens of kHz. Hiss waves are the main driver of the slot formation while chorus waves cause strong acceleration responsible of important flux enhancements during storms.

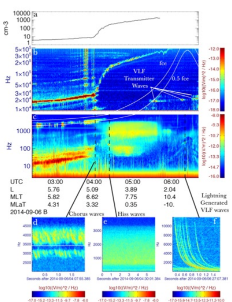
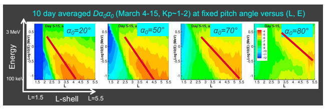


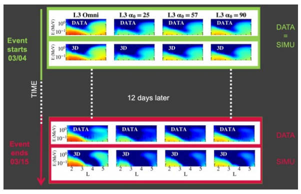
Fig 3. Whistler-mode waves power spectrum measured by RBSP during an inbound pass, from the plasma trough to the deep plasmasphere.

Wave-particle interactions cause the depletion of the slot and outer radiation belts

Hiss waves have tremendous effects (WPI) during extended plasmasphere times and sculpt the slot within the belts (L=2 to L=5.5). We compute and reproduction of the radiation belt energy structure for quiet times and moderate substorm activity.

Measured hiss wave properties are used in the computation of pitch angle diffusion coefficients (CEA CEVA code).





Properties of the radiation belts:

1. Higher flux in the inner belt at high pitch angles
2. Pitch angle dependence of the inner belt (agrees with QL theory)
3. Wider inner belt at high p.a.
4. Narrower slot at high p.a.
5. Relatively isotropic S-shaped structure of the outer belt

Fig 4. The 3D (L, E, a) dynamic radiation belt energy structure during quiet times: data vs. VERB3D simulations.

Ripoll, J.-F., Loridan, V., Denton, M. H., Cunningham, G., Reeves, G., Santolík, O., et al. (2019). Observations and Fokker-Planck simulations of the L-shell, energy, and pitch angle structure of Earth's electron radiation belts during quiet times. Journal of Geophysical Research: Space Physics, 124, 1125–1142.

ANR ASTRID PACTE-ESPACE

PACTE-ESPACE is a 3-year ANR project (2023-2025) with LPP, IRAP and Airbus DS Active physics of energetic particles, waves, and their interaction in the near-Earth space with 2 applications: 1- natural events, 2- active experiments. One objective is to develop new density/whistler property empirical models used for WPI simulations.

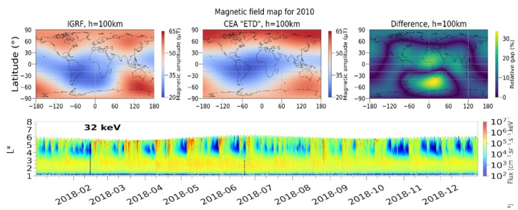
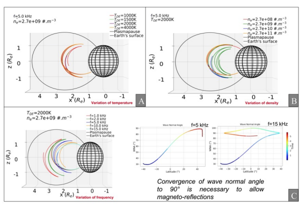


Fig 5. (top) The Earth's magnetic field computed with the IGRF model vs. a eccentric/tilted dipole. A good accuracy of the magnetic field is essential at low altitude/L-shell. (bottom) 32 keV electron flux in 2018 (RBSP-B) with daily injections populating both inner and outer belts and causing significant spacecraft charging (from M. Cosmides' PhD.).

Wave propagation by Ray Tracing

Ray Tracing is a numerical method of tracking wave fronts during propagation. We use the HOTRAY code (Horne, 1989) developed at BAS for simulating and understanding active experiments or natural events and for tracking wave power propagation and damping with application to wave-particle interactions with radiation belt electrons.



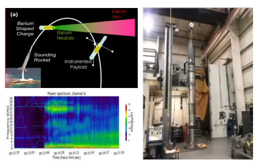
A: temperature does not change trajectory but shorten it by Landau damping
B: competition between magnetic field and density gradients. For low density, magnetic field gradients dominate and rays are guided by magnetic field line.
C: Lower frequency waves propagate with outward magneto-reflections. Higher frequency waves have inward propagation. (from L. Cerfolli's PhD.)

Fig 6. Influence of main parameters in Ray tracing simulations.

Future Work

Future work will be dedicated to study the radiation belt dynamic and both the REDA and SMART active experiments.

Fig 7. (top left) The NRL SMART active experiment principle. (bottom left) Power spectrum of whistler-mode waves measured by ePOP/RRI during the REDA active experiment. (right) SMART rocket.



1 CEA DAM DIF, Arpajon, France. 2 UPS, CEA, LMCE, Bruyeres-le-Chatel, France. 3 Laboratoire de Physique des Plasmas, École polytechnique, Palaiseau, France. 4 Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, CNES, Toulouse, France. 5 Orion Space Solutions, Louisville, CO, United States. 6 School of Physics and Astronomy, University of Minnesota, Minneapolis, MN, USA. 7 Department of Physics and Astronomy, University of Iowa, Iowa City, IA, USA. 8 Astrophysical and Planetary Sciences Department, University of Colorado Boulder, Boulder, CO, USA. 9 Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, CO, USA. 10 CEA, DAM, CESTA, Le Barp, France. 11 New Mexico Consortium, Los Alamos, NM, USA. 12 Los Alamos National Laboratory, Los Alamos, NM, USA. 13 Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, USA. 14 Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany.