Recent advances in our understanding of the Earth's Radiation Belts

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***Abstract*—The Earth's radiation belts were discovered by James van Allen more than fifty years ago and are a home to a plethora of fascinating processes ranging from low energy cold plasma to relativistic and ultra-relativistic particle populations. The traditional morphological picture of the radiation belts is that of an outer belt comprising mostly of electrons and an inner belt comprising mostly of protons with a so-called slot region separating the two. The inner belt is somewhat stable, while the outer radiation belt is very dynamical and shows variability in energetic electron populations over a wide range of energies, intensities, and time scales ranging from minutes, days and even years. This variability is due to dynamical processes of energization and loss with a variety of plasma waves playing an important and crucial role. The traditional picture has recently been challenged with new observations coming from the twin spacecraft mission, Van Allen Probes launched in the fall of 2012, which carries a comprehensive suite of instruments that measure particles and plasma waves. In more than 5 years of observations Van Allen Probes has advanced our understanding of fundamental questions regarding the acceleration and loss of outer Van Allen belt electron population. Van Allen Probes observations have also revealed new phenomena such as the "electron Storage ring", and the "impenetrable barrier".**

This article reviews electron dynamics in the Van Allen belts focusing on van Allen Probes observations and discuss exciting new ways of advancing radiation belt science with CubeSats and CubeSat constellations.

***Index Terms*—Radiation belts, relativistic electrons, energization, loss, CubeSat**

I. INTRODUCTION

The Earth is surrounded by regions of charged particles trapped by the geomagnetic field called radiation belts. They were discovered by James Van Allen [1], [2] more than five decades ago. However the quantitative understanding of the energization and loss processes of electrons from the outer radiation belts is not completely established. The outer Van Allen belt contains mainly energetic electrons and exhibits high variability; electron intensities increase and are lost on time scales ranging from minutes, days and even on solar cycles times. The processes that drive this variability are ultimately driven by solar phenomena [3], [4]. Currently it is qualitatively understood that the balance between energization and loss processes that increase or decrease the electron fluxes determine the net intensity of energetic electrons in the outer belt [5]. Although there have been earlier missions that studied the radiation belts NASA's flagship mission, the Radiation Belt Storm Probes (RBSP) is one of the most advance missions to probe radiation belt dynamics. The mission carryies a comprehensive suite of sensors on each of the two identically instrumented spacecraft. RBSP was named Van Allen Probes soon after launch on August 30, 2012 [6]. The science goal of the mission is to improve our "fundamental understanding of radiation belt dynamics in a quantitative and predictable manner". Van Allen Probes has made significant and important contributions to radiation belt physics including major discoveries [7] and first-time observations [8], [9]. This paper reviews some of the results from Van Allen Probes emphasizing energetic electron dynamics with most of the observational data obtained from the Relativistic Electron Proton Telescope (REPT) [10].

II. MISSION, INSTRUMENTATION AND DATA

While detailed descriptions of the Van Allen Probes mission [7] and the Relativistic Electron REPT [10] are readily available, we provide a brief description here to set the context and features relevant to this study. The twin Van Allen Probes spacecraft were launched into a near equatorial orbit (about 10°) inclination with an apogee of about 5.8 $\mathrm{R_E}$ and a perigee of 600 km with a nominal prime mission of 2 years (sufficient to cover all MLT). The spinning spacecraft enable particle instruments to provide a broad coverage of pitch angles. The mission is currently in the extended phase and is expected to end in summer/fall of 2020.

The REPT instrument measures electrons(protons) in 8(12) differential channels and 4(1) integral channels and covers energy range of ≈ 1.6 to > 19.0 MeV(≈ 1.6 to > 115 MeV) [10]. The differential channels have an energy resolution, $\Delta E/E \approx 30\%$. REPT is a solid state particle telescope with a total of 24mm of silicon stack made up by 1.5mm thick individual detectors surrounded by an W-Al shielding to minimize background from side penetrating particles and has a geometry factor of 0.2 cm^2-sr [10].

REPT covers pitch angles from $\approx 30^\circ \mathrm{to} 150\circ$ even under stretched geomagnetic field configuration. The REPT and Magnetic Electron Ion Spectrometer, MagEIS [11] together with the Helium, Oxygen, Proton, and Electron (HOPE) [31]

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mass spectrometer instrument comprise the ECT suite [12] on the Van Allen Probes.

III. RADIATION BELT ELECTRON DYNAMICS

As mentioned in I electrons in the outer belt are subject to energization, which enhances their fluxes, and losses, which deplete them. The energization processes are understood to be largely of two types, viz., radial transport and in-situ wave particle interactions (for reviews see [13]–[15]). Electrons are lost by pitch angle scattering [15] and magnetopause shadowing [16]. It is well known that the radiation belts comprise an inner belt and an outer belt separated by the so-called slot region (see for example [17]). Electrons can also be rapidly energized, in a matter of minutes by interplanetary (IP) shocks [18]–[20]. The acceleration mechanism is known to be a resonant ”surfing” by electrons on the electric impulse generated by the shock [21].

Thus there is a rich variety of physical processes that drive electrons in the outer radiation belt [22], [23] and much remains to be explored. In this paper we review some of the more recent significant ”discoveries” and findings that have been made by the Van Allen Probes mission.

A. *Electron Storage ring*

Soon after Van Allen Probes launch, electron measurements made by the REPT instrument showed a remarkable, hitherto unseen structure of the outer radiation belt; the outer belt had ”split” into two stable regions. This ”third belt” or storage ring lasted several weeks [24]. Fig. 1 shows 3.6, 4.5, and 5.6 MeV electron fluxes during September 2012 as a function of L* and time. The intensties are color coded according to color bar at right. A third belt or storage ring in clearly seen. It is now believed that longevity of the storage ring was a result of the plasmapause moving outward and staying at distances, L $\gtrapprox$ 4. This resulted in the storage ring decaying very slowly as the main scattering agent was plasmaspheric hiss [26].

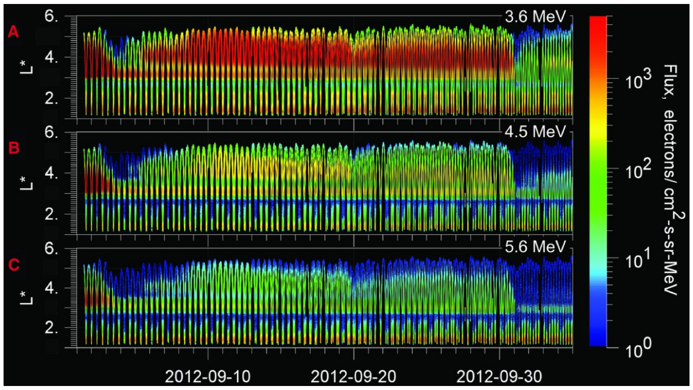

Fig. 1. REPT measurements of energetic electrons showing the electron storage ring (reproduced from [24]).

B. *Impenetrable barrier*

It is well known that electrons in the outer belt can radially diffuse inwards driven by geomagnetic field variations [26] and in principle can continue to drift inwards across all L shells. One of the more recent findings of Van Allen Probes has been the existence of a surprising ”barrier” or a limit beyond which highly energetic electrons do not diffuse [27]. This boundary is quite sharp and is not due to any morphological structure within the radiation belts. As Baker et al., point out [27] - ”exceptionally slow natural inward radial diffusion combined with weak, but persistent, wave-particle pitch angle scattering deep inside the Earths plasmasphere can combine to create an almost impenetrable barrier”. Fig. 2 from [27] shows 7.2 MeV electron fluxes as a function of L shell for extended periods of time during which these highly relativistic electrons are abruptly ”stopped” at about L=2.8

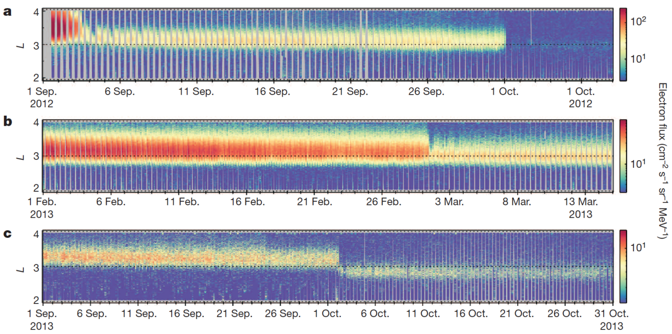

Fig. 2. REPT measurements of 7.2 MeV electrons during three distinct periods showing that the electrons do not penetrate deeper that L=2.8 (reproduced from [27]).

C. *Rapid Energization by IP shocks*

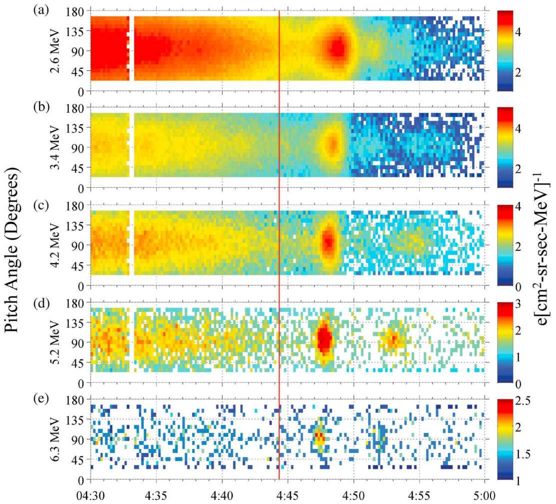

Fig. 3. REPT-A measurements of 2.6, 3.4, 4.2, and 6.3 MeV electrons on 17 March 2015 from 04:30:00 UT to 05:00:00 UT. Vertical red line shows IP shock arrival time. Enhancements in electron fluxes are clearly seen minutes after the shock arrival. (reproduced from [29]).

It is well known that IP shocks can energize electrons very rapidly on time scales of minutes [19]–[21]. The most dramatic case of such an event was the famous March 1991 event, which resulted in electrons being energized to almost 50

MeV and being transported to very low L-shells [20]. Clearly these events are not only of scientific interest but also from the space weather aspect [28], [29]. During March 2015, the magnetosphere was impacted by an IP shock and resulted in energization of electrons up to energies, $E > 6$ MeV. These electrons reached deep into the magnetosphere and were observed at L=3 by the REPT instrument on Probe-A [30]. The electric field impulse that energized electrons, however did not affect $\approx 250 - 900$ keV electrons. The availability of electric field measurements and interplanetary measurements enabled an accurate determination of the impact position of the shock, the time to energization, and the extent of spectral hardening [30].

IV. SUMMARY

In this paper, we have reviewed some of the ”discoveries” and findings by NASA’s Van Allen Probes mission. Our review focused on energetic electron dynamics as revealed by the REPT instrument. We note that this review does not cover many other important and significant contributions by the Van Allen Probes mission, e.g., plasma wave properties and their role in particle energization. Although limited in scope, our review clearly highlights some of the significant and substantial contributions made by NASA’s Van Allen Probes mission. The mission is now currently in its ”extended” phase and expected to last until summer-fall of 2020. We hope that there may yet be many crucial contributions by this mission, whose data may well be analyzed for years to come and reveal new insights into radiation belt dynamics.

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