Recent Advancements on the Sources of the Inner Radiation Belt Particles

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Van Allen Probes/REPT

3U CubeSat: Colorado Student Space Weather Experiment (CSSWE)/REPTile
- Involved over 65 students
- Launched: 9/13/12 (>2 yr op)
- Orbit: ~480 km x 790 km, inclination 65°

- Inner belt (L ≤ 2) consist of energetic protons and electrons
  - Protons: CRAND and Solar Energetic Particles
  - Electrons, >1MeV: Rarely seen, only during extreme SW conditions
  - Electrons, <1MeV: Commonly seen, from CRAND and Outer Belt

CRAND electrons → neutron density
Inner-Zone ($L \leq 2$) Proton Production Mechanisms

**Fast neutrons made by direct interaction of high-energy cosmic rays: knock-on neutrons**

- **proton + electron + neutrino**
  (production of $\geq 10$ MeV energetic protons ($L \sim 1.5$) that can be trapped). This mechanism is also referred to as CRAND: Cosmic Ray Albedo Neutron Decay
The trapped inner belt protons (>65 MeV) measured from Van Allen Probes/RPS and OV1-20 are dramatically similar across a 41 yr interval.

OV1-20 and RPS $J_{\text{perp}}$ Versus L

(Mazur et al., Fall AGU, 2014)

The situation is very different for lower energy protons at the outer edge of the inner belt.
Monthly averages of proton flux measured by REPT from 2013/10 – 2016/08 (extended from Selesnick et al., JGR, 2016)
Inner belt (L ≤ 2) consist of energetic protons and electrons

- **Protons**: CRAND and Solar Energetic Particles
- **Electrons, >1MeV**: Rarely seen, only during extreme SW conditions
- **Electrons, <1MeV**: Commonly seen, CRAND and transported inward from outer belt electrons
Li et al., JGR, 2015: **Upper limit on the inner radiation belt MeV electron intensity**

Fennell et al., GRL, 2015: *... the inner radiation zone contains no MeV electrons ...*
Color-coded ~2MeV electron flux

(Li et al., JGR, 2017)
Injections of multi-MeV electrons into the slot region and inner belt did happen when the sun was much more active.

(Baker et al., *Nature*, 2004)

Horne et al., *Nature*, 2005: Wave acceleration of electrons ...

Kim et al., *JGR*, 2016: Fast injection of the relativistic electrons (~1MeV) into the inner zone ... the Bastille Day storm in July 2000

(Li et al., *SW*, 2009)
Injections of multi-MeV electrons into the slot region and inner belt did happen when the sun was much more active (Li et al., 1993).
• Inner belt (L ≤ 2) consist of energetic protons and electrons
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CRAND electrons ➔ neutron density
CSSWE/REPTile E1 (~0.5 MeV) Measurement, Jan 4-14, 2013

B-field at s/c orbit South and North

binned in L=1.45-1.55, Jan 4-14, 2013
CSSWE/REPTile: 0.5 MeV Electrons for Jan 4-14, 2013

(Li et al., *Nature*, 2017)
Some possible explanations:
(1) Drift-shell splitting, stably trapped $\rightarrow$ quasi-trapped at lower $L$ ($\Delta L \sim 0.02$)
(2) $L$ calculation uncertainties due to convection electric field ($\Delta L \sim 0.01$)
(3) Inward radial transport

Drift-shell splitting effect assessment

(Li et al., Nature, 2017)
The only feasible explanation: Cosmic Ray Albedo Neutron Decay (CRAND) via evaporation process

CRAND electrons are mostly from the $\beta$-decay of thermal neutrons:

$$(m_n - m_p - m_e)c^2 \approx 782 \text{ keV}$$

(upper limit)
First direct detection of CRAND electrons in near-Earth space
CRAND: the only source for the quasi-trapped electrons (L<1.14), then neutron density can be determined from the measured electron flux:

\[ J(E) = \frac{nv}{4\pi} \frac{T_e}{T_n} \varphi(E) \]

For a 0.5 MeV electron at L=1.2, v: speed (2.6x10^{10}\,cm/s); \( T_e \): drift period (1.5 hr); \( T_n \): mean neutron lifetime (887 s), \( \varphi(E) \): energy spectrum of \( \beta \)-decay

\[ n = 4\pi J(E) \frac{T_n}{T_e} \left[ \varphi(E) \right]^{-1} v^{-1} \]

For the first time, we determined: \( n = \sim 2 \times 10^{-9} \, \text{cm}^{-3} \) in near-Earth space.

Attempts* were made to directly measure the thermal neutron density in space, but results were contaminated by locally generated neutrons from energetic particles striking on the spacecraft.

* Koga, K., Muraki, Y., Matsumoto, H. & Kawano, H. in Selected Papers from the 30th International Symposium on Space Technology and Science (under review)
CRAND: contributing to other regions as well, trapped and quasi-trapped. The quasi-trapped flux reaches about 25 at 0.5 MeV in less than ~1.5 hr. At this rate, in 30 days the intensity from CRAND would be about $10^3$, comparable to the trapped level observed at $L = 1.2$ during quiet times.

**IMPLICATION:** Source and Loss (pitch angle scattering) for the inner belt and slot region need to be re-visited.
Confirmation and extended study with other measurements

DEMETER: low polar orbit of 710 km altitude and an inclination of 98.3°

(Zhang et al., Fall AGU, 2017)
Solar Cycle Dependence of the Quasi-trapped Electrons

- **Neutron Monitor Counts**
- **Sunspot Number**
- **10-day Averaged Dst**

running average 509 keV quasi-trapped e L=1.13-1.14
Conclusions

Inner belt protons, higher energy (>65 MeV) at lower L(<1.5), CRAND sources, are stable (RPS)

Inner belt protons, lower energy (<60 MeV) at higher L (>1.6), SEP sources, are much more dynamic than previously thought (REPT)

Enhancements of >1 MeV electrons in the inner belt occur only when there are strong solar wind disturbances (CRRES, SAMPEX, REPT, MagEIS, REPTile)

Based on CSSWE/REPTile measurements, for the first time:

(1) direct detection of CRAND electrons in the inner belt
(2) experimental determination of the neutron density in near-Earth space

IMPLICATION: Source and Loss (pitch angle scattering) for the inner belt and slot region need to be re-visited.
(Li et al., *Nature*, 2017)