Van Allen Probes Observation of Prompt Energization of Electrons to Ultra-relativistic Energies During the 17 March 2015 IP shock

Shri Kanekal
Heliophysics Science Division, NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Dan Baker
Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA

†We acknowledge contributions to this work by J. B. Blake, S. Califf, S. Claudepierre, S. Elkington, J. F. Fennell, A. N. Jaynes, A. Jones, C. G. Kletzing, X. Li, G. D. Reeves, D. Turner, H. Spence, L. Wilson
The Van Allen Probes Mission

Mission Objective: To provide understanding ideally to the point of predictability of how populations of relativistic electrons and ions in space form or change response to variable inputs of energy from the Sun.

Two s/c with identical instruments
separation of temporal and spatial variations

Near Equatorial orbit
covers much of the equatorial pitch angle distribution

Comprehensive Instrumentation
low energy source population
energized relativistic population
fields and wave phenomena

Launched Aug 30 2012
Orbit: ~630 km x ~5.8 Re
Inclination ~10°
Sun pointing, spin stabilized
Prime mission duration 2 years
Currently in Extended Phase

Local time coverage
full coverage over mission lifetime
Van Allen Probes Spacecraft & Payload

**ECT Suite - HOPE, MagEIS, REPT**
(Energetic Particle, Composition, and Thermal Plasma)
- 20 eV-45 keV He+, O+, p+, e-
- 30 keV-20 MeV electrons
- 20 keV-100 MeV protons

**RBSPICE - ring current studies**
- 50 keV-10 MeV electrons
- 0-75 MeV Protons
- 20-1000 keV Ion

**EFW**
Spin Plane Booms
- all four at 50 m length
Axial Booms
- 12 m tip-to-tip (extendable to 14 m)

**EMFISIS**
Magnetometer Booms
- Extend 3 m from edge of spacecraft

**RPS** - inner belt protons
- 50 MeV-2 GeV protons
ECT consists of three coordinated sensor types:

• HOPE
• MagEIS
• REPT

ECT measures electrons (continuously) and ions (with composition up to 50 keV) from ~20 eV to ~10’s of MeV with energy resolution, and pitch angle coverage and resolution required for mission success.

PI Dr. Harlan Spence
REPT A & B measurements mission to date
Acceleration of electrons to ultra-relativistic energies: March 2015 CME

SOHO LASCO and CELIAS/PM
REPT(A) energetic electrons March 2015

- Energy dependent energization to relativistic energies

- Radial diffusion to lower Ls evident for > 5.0MeV electrons.

- Highest energy electrons (~8MeV) peak flux values appear about 5 days after shock passage.

Note: Probe B observations are nearly identical to probe A and are not shown.
REPT MagEIS spectra 16-26 March 2015

- **MagEIS spectra** show an abrupt hardening within a day after the shock passage
  - electrons from ~100s keV to ~1MeV
  - note fluxes at the lowest energies showed little change

- **REPT spectra** covering higher energies show a much more gradual hardening

- Enhanced chorus activity may be responsible for rapid energization at lower energies
Van Allen Probes and Themis observations of chorus waves

Intense wave activity can be seen early on 17 March 2015 after shock passage.
Intense chorus activity and rapid radial diffusion

Fast radial diffusion of ultra-relativistic electrons in the 7.2 MeV range, crossing 1.25 Lshell radial distance in \(~2\) days.

Compare to much slower diffusion seen in previous strong storm in Oct 2012 (inset).
Radial profile of 7.2 MeV electron flux at equally-spaced times throughout the 17-26 March time period at orbital passes with low MLAT.

Peak is seen to move in dramatically from 20 March to 23 March.
LFM simulation of March 1991 IP Shock

Elkington et al. 2002

Electron Trajectory: shock Injection
Prompt response: ultra relativistic electrons

Post injection velocity dispersion
REPT A observations continued

- Electrons energized to ultra-relativistic energies (>6 MeV)
- Clear velocity dispersion suggesting local injection
E and B Fields data from EFW and EMFISIS

Compression of the Magnetosphere and associated E field
Shock timing: THEMIS and ARTEMIS

- THEMIS impact times:
  - THD: 04:44:08 UT
  - THE: 04:44:19 UT
  - THA: 04:44:34 UT

- THEMIS in the sheath at the impact
- All s/c observed more intense sheath after impact and then were thrust into the solar wind as bow shock compressed
Drift Period Analysis from REPT A

Time_{injection} = 04:46:12 UT

Time_{shock} = 04:44:08 UT
Post shock pitch angle distributions Probe B

MagEIS

MagEIS & REPT
LFM simulation of March 1991 IP Shock

Elkington et al. 2002
Summary and conclusion

- Instruments onboard the twin Van Allen Probes spacecraft have provided a comprehensive view of the 17 March 2015 CME.
- Post shock passage butterfly-type pitch angle distributions were observed by REPT and MagEIS even at L shells as low as 3 deep within the magnetosphere.
- Intense chorus wave activity may have resulted in abrupt energization of ~100s keV to ~2 MeV electrons.
- The ultra-relativistic fluxes also peaked somewhat abruptly albeit in an energy dependent manner and days later than the shock passage. Electron spectra however, hardened more gradually. Rapid radial diffusion of ultra rel. electrons.
- Shock response of electrons show several interesting features:
  - prompt injection of ~1 to 6 MeV electrons
  - no discernible response of ~200 keV to ~1 MeV
- Ground level discontinuity 04:45 UT (shock passage):
  - Estimated time of injection 04:46:18 UT
  - Electrons energized to 6 MeV in < 2 minutes
- Drift echo times consistent with expectation [O’Brien et al.,2015]
REPT: Relativistic Electron Proton Telescope

- Solid state particle telescope with fast electronics and shielding.

- Differential energy channels using detector coincidence, anti-coincidence and $\Delta E$

- Differential channel Logic condition

$$E_{1.6-2.0} = (R1 \geq 0.4) \cdot (R2 \geq 0.4) \cdot (\Sigma R1R2 \leq 1.35) \cdot (R3 \ldots R9 \leq 0.4)$$

- Logic software configurable in FPGA

<table>
<thead>
<tr>
<th>Mass</th>
<th>13.4 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>10.7 W</td>
</tr>
<tr>
<td>Average Telemetry Rate</td>
<td>1.6 kbps</td>
</tr>
<tr>
<td>Energy Range</td>
<td>1.6-&gt;12 MeV (electrons) 17.-&gt;100 MeV (protons)</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>&lt;30% (electrons) &lt;30% (protons)</td>
</tr>
<tr>
<td>Geometric Factor</td>
<td>0.2 cm$^2$ sr</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>32°</td>
</tr>
</tbody>
</table>
REPT observations of Butterfly PAD

- Ultra relativistic energy electrons penetrate to low L

- Butterfly pitch angle distributions at the inner edge of the penetration can extend in energy > 5 MeV

- Note that the multi-MeV electrons do not diffuse past the “impenetrable barrier” [Baker et al., 2014]
Observations of Butterfly PAD

- Butterfly PADs extend over a substantial L range and observed by both probes
- Butterfly PADs persist over several days
Ultra-relativistic electrons: Latitudinal extent

electrons 7.7-9.7MeV
E and B Fields data from EFW and EMFISIS

Sam Califf
Drift velocity for electrons in a dipole field

\[ T = \frac{2\pi}{\langle \phi \rangle} = \frac{172.4}{E} \left( \frac{1 + E}{2 + E} \right) \left( \frac{m}{m_e} \right) \left( \frac{r_e}{r_0} \right) \left( \frac{G(\lambda)}{F(\lambda)} \right) \]

\[ \langle \dot{\phi} \rangle = \frac{2\pi}{T} = 2\pi \frac{E}{172.4} \left( \frac{2 + E}{1 + E} \right) \left( \frac{m_e}{m} \right) \left( \frac{r_0}{r_e} \right) \left( \frac{F(\lambda)}{G(\lambda)} \right) \]

where \( \langle \dot{\phi} \rangle \) is bounce averaged drift velocity, \( m \) is mass of the drifting particle, \( m_e \) is electron mass, \( r_0 \) the radial distance of drifting particle and \( r_e \) radius of Earth, \( \lambda \) is magnetic latitude, and \( F(\lambda), G(\lambda) \) are dimensionless functions of magnetic latitude [J.S. Lew, JGR, 1961].

For electron observations on the 17 March 2015 event, Probe A is at 5.9° magnetic latitude and L≈3.3 at UTC 04:45, so that

\[ \frac{r_0}{r_e} = 3.3 \]
\[ \frac{m_e}{m} = 1.0 \]
\[ \frac{F(\lambda)}{G(\lambda)} = 1.0 \]

so that

\[ \langle \dot{\phi} \rangle = 0.12E \left( \frac{2 + E}{1 + E} \right) \]
Ground magnetometer observations

Time of shock passage  04:45 UT

Joe Fennell, Bern Blake
## Peak flux times and drift speed

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>Vd (Rads/min)</th>
<th>Time (hr:min:sec)</th>
<th>T Mins. Of day</th>
<th>$\phi_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>1.572</td>
<td>4:47:28</td>
<td>287.47</td>
<td>0.461</td>
</tr>
<tr>
<td>5.2</td>
<td>1.337</td>
<td>4:47:43</td>
<td>287.65</td>
<td>0.464</td>
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<tr>
<td>4.2</td>
<td>1.097</td>
<td>4:48:00</td>
<td>287.83</td>
<td>0.467</td>
</tr>
<tr>
<td>3.4</td>
<td>0.906</td>
<td>4:48:27</td>
<td>288.38</td>
<td>0.471</td>
</tr>
<tr>
<td>2.6</td>
<td>0.713</td>
<td>4:48:47</td>
<td>288.73</td>
<td>0.475</td>
</tr>
</tbody>
</table>
Drift Period Analysis from REPT A

Time\text{injection} = 286.2 \pm 0.3 \\
\phi_{\text{injection}} = -1.50 \pm 0.15 = 274.00 \pm 90 \\
\phi_{s/c} = 0.47 \text{ rad.} = 27^{\circ}
Shock arrival calculated from WIND compared to injection time from REPT observations

Assume Nominal Magnetopause at 11Re, i.e. 70125 km

Distance in X (GSE) travelled by shock

\[ \Delta X = X_{\text{Wind}} - X_{\text{MP}} \]

\[ = 1612674 - 70125 = 1542549 \text{ km} \]

Time of traversal \[ = 1542549 \times 0.88/510 \]

where 0.88 is cosine of shock normal angle \( \theta \)

Time of traversal \[ = 2661 \text{ sec} = 44 \text{ min} \]

Time of shock at WIND = 4:00UT

propagated time to MP nose = 4:44UT
from REPT measurements = 4.46UT
Shock Arrival calculated from WIND position and shock measurements.

\[ V_{dt} = \frac{dx}{dt} \]

\[ V_{dt}/dx = \cos \theta \]

\[ \Rightarrow dt = \frac{dx \cdot \cos \theta}{V} \]
Drift Period Analysis from REPT A

REPT A 90° electrons: 17 March 2015

- 6.3 MeV
- 5.2 MeV
- 4.2 MeV
- 3.4 MeV
- 2.6 MeV

$\Phi_{\text{injection}} = -0.47 \pm 0.15 = 333.10^\circ \pm 9^\circ$

$\Phi_{\text{s/c}} = 0.47 \text{ rad.} = 27^\circ$

$\text{Time}_{\text{injection}} = 286.3 \pm 0.3$
REPT A flux profiles  90° pitch angle

2.6 MeV  4:48:44

3.4 MeV  4:48:23

4.2 MeV  4:47:50

5.2 MeV  4:47:39

Ashley Jones
• THEMIS impact times:
  – THD: 04:44:08 UT
  – THE: 04:44:19 UT
  – THA: 04:44:34 UT

• Notes:
  – THEMIS in the sheath at the impact
  – They all observed more intense sheath after impact and then were thrust into the solar wind as bow shock compressed
  – Shock transit time through sheath is a major unknown...
Shock Analysis: WIND measurement

17 Mar 2015

WIND propagated to MP nose 4:44UT
Consistent with SOHO and THEMIS
Summary and Conclusions

- Shock response of electrons show several interesting features
  - prompt injection of ~1 to 6 MeV electrons
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