Model and Data Deficiencies

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Background

• ESA* performed an independent validation of AE9/AP9
  – Compared AP9 with data and other models
  – One conclusion was that AP9 proton fluxes are significantly higher than data and other models, especially for LEO and at low energy (< 10 MeV)

• IRENE team wanted to determine possible reasons and resolutions

• This study focuses on the low energy (< 20 MeV) LEO protons
  – This is a very difficult population to measure
  – We expect RBSP/RPS to provide the “definitive” measurements for > 50 MeV
  – What can we learn about lower energies?

Background

- **AP9** predicts much larger fluxes of low energy (< 10 MeV) protons than **AP8** at low altitudes

- **AP8 MAX** is based largely on data from Azur
  - Flew in 1969 – 1970 (0.3 years near solar maximum): very short time span
  - AP8 only uses 1 month of data (November 1969)
  - 1.5 – 104 MeV in 7 channels (ΔE/E_{mid} ≈ 0.7)
  - D. Heynderickx/ESA processed & cleaned the data, have provided data to IRENE team
  - Very clean data set, low altitude measurements at 90° pitch angle

- **AP9** below 10 MeV is based mainly on CRRES PROTEL
  - Flew in 1990 – 1991 (1.3 years near solar maximum): short time span
  - 1 – 100 MeV in 24 channels (ΔE/E_{mid} ≈ 0.2)
  - Much data for low L is based on high-altitude pitch angle resolved measurements

- **AP9 implicitly uses data from S3-3** (0.1 – 2 MeV) via templates
  - Vampola published a model based on S3-3; low-altitude fluxes were much higher than AP8
# Proton Data Sets - Spectral

## AP9 v1.35

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO</td>
<td>0.1 0.2 0.4 0.6 0.8 1 2 4 6 8 10 15 20 30 50 80 100 150 200 300 400 700 1200 2000</td>
</tr>
<tr>
<td>MEO</td>
<td></td>
</tr>
<tr>
<td>HEO</td>
<td></td>
</tr>
<tr>
<td>GEO</td>
<td></td>
</tr>
</tbody>
</table>

- CRRES/PROTEL
- ICO/Dosimeter
- HEO-F3/Dosimeter
- HEO-F1/Dosimeter
- TSX5/CEASE
- Polar/IPS
- Polar/HISTp
- TacSat-4/CEASE

*(S3-3/Telescope)*

**Indicates threshold detector. Spectral inversion required for differential fluxes.**

**Indicates incomplete spectral or spatial coverage in LEO.**

## AP9 Future Versions

- Azur
- RPSP/RBSPICE
- RBSP/MagEIS (lo)
- RBSP/MagEIS (hi)
- RBSP/KEPT
- RBSP/RPS
- POES

## AP8 (Partial list relevant to LEO)

- Azur
- Injun 5
- OV3-3
- OV3-4
- P11-AS (APS & AP8)
- Relay 1 (APS & AP8)
# Proton Data Sets - Temporal

## AP9 v1.35
- CRRES/PROTEL
- ICO/Dosimeter
- HEO-F3/Dosimeter
- HEO-F1/Dosimeter
- TSX5/CEASE
- Polar/IPS
- Polar/HISTp
- TacSat-4/CEASE
- (S3-3/Telescope)

## AP9 Future Versions
- Azur
- RPSP/RBSPICE
- RBSP/MagEIS (lo)
- RBSP/MagEIS (hi)
- RBSP/REPT
- RBSP/RPS
- POES

## AP8 (Partial list relevant to LEO)
- Azur
- Injun 5
- OV3-3
- OV3-4
- P11-AS (APS & APB)
- Relay 1 (APS & APB)
AE9/AP9 Team performed several analyses to investigate reasons for differences, with primary emphasis:

**What is the spectral shape of LEO protons between 1 and 30 MeV?**

- **“Binspectra” plots**
  - Plot energy spectra in each AP9 bin for all data sets used
  - Plot model as well
  - We have added additional data sets not currently in AP9 (e.g., Azur, S3-3)
  - These show uncertainty of measurements and model in each bin

- **S3-3 analysis**
  - Data showed very high fluxes for L < 1.9
  - Although S3-3 data have not been used directly in AP9, they were included in templates
  - Analysis focused on identifying potential contamination

- **Review other data sets and analytical models**
  - Injun 5, AP8, SIZM, Blanchard & Hess, ...

- **TacSat-4 data analysis**
  - Attempt to deduce spectral shape from counts in different CEASE channels
  - Intent is to determine whether TacSat-4 data is consistent with a spectral shape like Azur
  - This analysis is not covered in this talk
CRRES, TacSat-4, TSX5 agree reasonably well, S3-3 is in line

Azur is below other data, different spectral shape

Lm≈1.45

X = S3-3

Δ = Azur
TacSat-4 & Azur agree reasonably well, CRRES is out.
Binspectra Plots

Many data sets, narrow confidence intervals

$X = S3-3$
$\Delta = Azur$

API9V12, KPhi
$K^{1/2} = 0.9 \log_{10} \hat{\phi} - 0.05$
$L^* = 2.12308$
$i_2 = 10, i_3 = 31, l_{full} = 1390$
$\text{red} = 851, \text{iail} = 21251-21275$

50% Flux, 20.0 MeV
95% Flux

Template (Arbitrary Units)
S3-3 Analysis

- Flew in 1976 – 1979 (about 6 years after Azur, rising part of solar cycle)
- 236 x 8048 km x 97.5° orbit
- Proton telescope housed within magnetic electron spectrometer
  - 0.08 – 3.2 MeV, 5 channels, $\Delta E/E_{\text{mid}} \approx 0.7$
- Data showed very high fluxes for $L < 2$
- Data formed the basis for a low-energy model by Vampola
- Although S3-3 data have not been used directly in AP9, they were included in templates
  - Templates are used to interpolate/extrapolate data during construction of flux maps
- Analysis focused on identifying potential contamination
S3-3 Variation with L

$K^{1/2} < 0.025; \alpha = 90° \pm 5°$
Spectral Shapes: Selesnick et al., 2007

- Selesnick model shows spectra peaking at 50 – 80 MeV for $L < 1.4$
- At higher $L$, spectra below 20 MeV are power-law-like, with modulation over solar cycle
- Azur shows spectra peaking at 5 – 10 MeV up to $L > 1.5$
Selesnick vs. Azur

- Azur and Selesnick model show very different spectral shapes
- Azur has steeper $L$-gradients than SIZM (this is a known issue in model)
Claflin & White (1974)

- Solves diffusion equation including Coulomb energy loss, nuclear inelastic scattering, secular decrease of internal field
- Uses solar-cycle averaged atmosphere
- Extended to lower energies (~ 2 MeV) for comparison with Azur and OV3-4
- For $E < 10$ MeV, basically flat for $L < 1.25$, peaks at 6 - 8 MeV for higher $L$

Fig. 8. Computed inner belt proton energy spectra, 2-500 MeV. The dashed line shows the boundary condition at $L = 1.7$ based on the data of Hovestadt et al. [1972] and Thede [1969]. The solution used $D_{L} = 9 \times 10^{-7}L^{1.5-4.0}$ and a free electron density higher than the model density by a factor of 5.
Spectral Shapes: Other Data

- Data from Injun 5 in 1968 – about 1 year prior to Azur
  - This data set was used in AP8
  - Different L values correspond to different K
  - Note minimum in spectrum for $E \approx 2$ MeV, peak at $E \approx 6$ MeV at low L

- Data from Dial, ESRO 2 (Fischer et al., 1977) shows spectra peaked near 10 – 20 MeV

Injun 5, 1968 (Pizzella and Randall, 1971)
Spectral Shapes: AP8 & Older Data

- This plot from the AP8 report shows the evolution of model spectra at $L = 1.2$
- Note that these are integral, omnidirectional fluxes
- Early model AP-5 did have higher fluxes at lower energies
  - AP-5 covered 0.1 – 4 MeV, assumed an exponential spectral shape (in integral flux)
- Relay 1 (1963) measured 3 MeV fluxes about 9 x Azur (1970) at $L \approx 1.7$
- Vette probably modified the shape based on Injun 5 and Azur
- This illustrates the uncertainty and difficulty in developing global models including many data sets and a large energy range
Summary of Results

• Binspectra plots
  – There are often large differences among data sets
  – Azur is sometimes the odd one out
  – S3-3 is generally in line with other data sets
  – Agreement among data sets improves above $L \approx 1.5$

• S3-3
  – No reason to doubt large fluxes for $L < 1.9$
  – May be a transient phenomenon, but fairly stable over 2.8 years of data (1976 – 1979)

• Other data and models
  – Azur and contemporary data sets (1967 – 1971, Injun 5, Dial, ESRO 2) show spectra peaked at 5 – 20 MeV
  – Physics-based models indicate a range of spectral shapes, but these are mostly for energies > 10 MeV
  – Models provide little guidance for lower energies—spectrum below 10 MeV could be flat or power law (or something else)

• TacSat-4 Tests
  – TacSat-4/CEASE response appears to be inconsistent with Azur spectral shapes
Miscellaneous Points

• For $E < 10$ MeV, AP9 is largely driven by data from CRRES/PROTEL
  – Much work was performed to remove initial contamination of measurements at $E < 10$ MeV (including after release of CRRESPRO model)
  – Note that in many cases AP9 fluxes are more like CRRES active data
• Measurements of $< 10$ MeV protons in inner zone are very difficult, primarily due to contamination from penetrating protons
• The fact that Azur is lower than other data sets indicates that the others could be contaminated (but not beyond a reasonable doubt)
• AP9 data sets from 1990 and later have been cross-calibrated with GOES
  – However, cross-calibration is uncertain for $E < 10$ MeV
• Fluxes vary over multiple dimensions (e.g., $E$, $K$, $\Phi$, $t$; perhaps MLT, …)
  – Slicing and dicing for comparison (e.g., comparing energy spectra at one $K/\Phi$) can be misleading, especially in regions with large flux gradients, due to uncertainty in coordinates as well as measurements themselves
Conclusions (1 of 2)

• We trust the data in AP9, model agrees with data
• We also trust Azur data
• Most likely hypothesis is that Azur (and contemporary measurements) and S3-3 represent two different geophysical states
Conclusions (2 of 2)

• Need to explain and model the discrepancies and natural variability
  – Clean measurements of < 20 MeV protons in IZ
  – Extend theory to lower energies
  – Better methods for cross-calibration at lower energies

• Include solar cycle variations
  – Theory (e.g., SIZM, …)
  – Data (e.g., POES, SAMPEX, …)
Backup Charts
Azur

- Data from Nov. 1969 – Mar. 1970 (0.3 years near Solar Max)
- 384 x 3145 km x 102.9° orbit; 1.5 – 104 MeV
  - 6 channels, $\Delta E/E_{\text{mid}} \approx 0.7$
- Magnetically stabilized, so it always measures $j_{\text{perp}}$
- A fairly large SPE occurred in Nov. 1969, right at launch; several smaller events occurred during the mission
Fischer et al. (1977)

- **Dial:**
  - 326 x 1629 km x 5.5°

- **ESRO 2:**
  - 334 x 1085 km x 97.2°

- **Azur (Moritz):**
  - Single channel, 0.25 – 1.65 MeV
  - Separate experiment from Hovestadt
Valot (1972)

- Valot: ESRO 2
- Pizzella & Randall: Injun 5
- Naugle & Kniffen: Emulsion stack (Sept. 1960)
- Mihalov & White: KH 7-10 (1964-045A); 149 x 307 km x 95.5°
Spectral Shapes: Blanchard & Hess (1966)

- These figures from Blanchard and Hess show model spectra at low L over the solar cycle.
- Here we see some flattening at low energies 3 – 5 years after solar min, power-law at other times.
- Note that Blanchard & Hess, Selesnick et al., and other models are all for E > 10 MeV.
- Claflin & White (1974) predict relatively flat spectra below 10 MeV.
REPT vs. Models – 26 MeV

26 MeV

\( I_{\text{omni}} \) (\#/cm^2-s-MeV)

\( L_m \)

- REPT
- V1.20 95th
- V1.20 mean
- V1.20 25th
- V1.05 mean
- AP8min
Summary of ESA Findings (Relevant to LEO Protons)

- AP9 vs. Azur: AP9 mean overestimates except around 10 MeV, spectral shape does not agree with data and other models, also overestimates extent of SAA region
- This plot compares AP9 with AP8 for a polar LEO orbit
- At 1 MeV, AP9 is up to a factor of 10 higher than AP8
Version 1.20 – Database Updates

- **New data set (first new data to be added):**
  - TacSat-4/CEASE proton data—captures new observations of elevated 1-10 MeV protons
  - Additional plasma data: THEMIS/ESA

- **New proton templates**
  - Incorporate E/K/Φ and E/K/hₘᵟᵣₚₚ profiles observed by RBSP/Relativistic Proton Spectrometer
  - Extend proton energies to 2 GeV

- **Low altitude taper**
  - Force fast fall-off of flux for hₘᵟᵣₚₚ < 100 km
  - Cleans up radial scalloping at altitudes below ~1000 km

- **Low altitude fluxes are reduced, but differences remain**
Binspectra Plots

Lm ≈ 1.17
X = S3-3
Δ = Azur
Binspectra Plots

\[ L_m \approx 1.54 \]

\[ X = S_3 - 3 \]

\[ \Delta = \text{Azur} \]
Binspectra Plots

X = S3-3
Δ = Azur
S3-3 PADs: L=1.4

Measured near the equator, pitch angle determined by the pitch angle of the detector axis

Using $j_{\text{perp}}$ measurements, equatorial pitch angle determined using $B/B_{\text{min}}$

Equatorial Pitch Angle vs. Flux (#/cm$^2$-s-sr-keV)

$L = 1.4 \pm 0.01; K^{1/2} < 0.01$

Counts vs. Equatorial Pitch Angle

Measured near the equator, pitch angle determined by the pitch angle of the detector axis

Using $j_{\text{perp}}$ measurements, equatorial pitch angle determined using $B/B_{\text{min}}$

Equatorial Pitch Angle vs. Flux (#/cm$^2$-s-sr-keV)

$L = 1.4 \pm 0.01; \alpha_{\text{LC}} > 85^\circ$

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$L = 1.3 \pm 0.01; \alpha_{\text{LC}} > 85^\circ$
Spectral Shapes: Selesnick et al., 2007

- Same as previous slide, but off the equator
Epilogue: RBSP

• RBSP < 20 MeV protons (MagEIS and RBSPICE) do not have a requirement for measurements in inner zone
• REPT (20 – 100 MeV) measurements in inner zone require significant data processing to remove contamination from penetrating protons
• RPS measurements in inner zone are clean