LEO Protons in AP9

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Ξιλοκαστρο, Ελλαδα

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Background

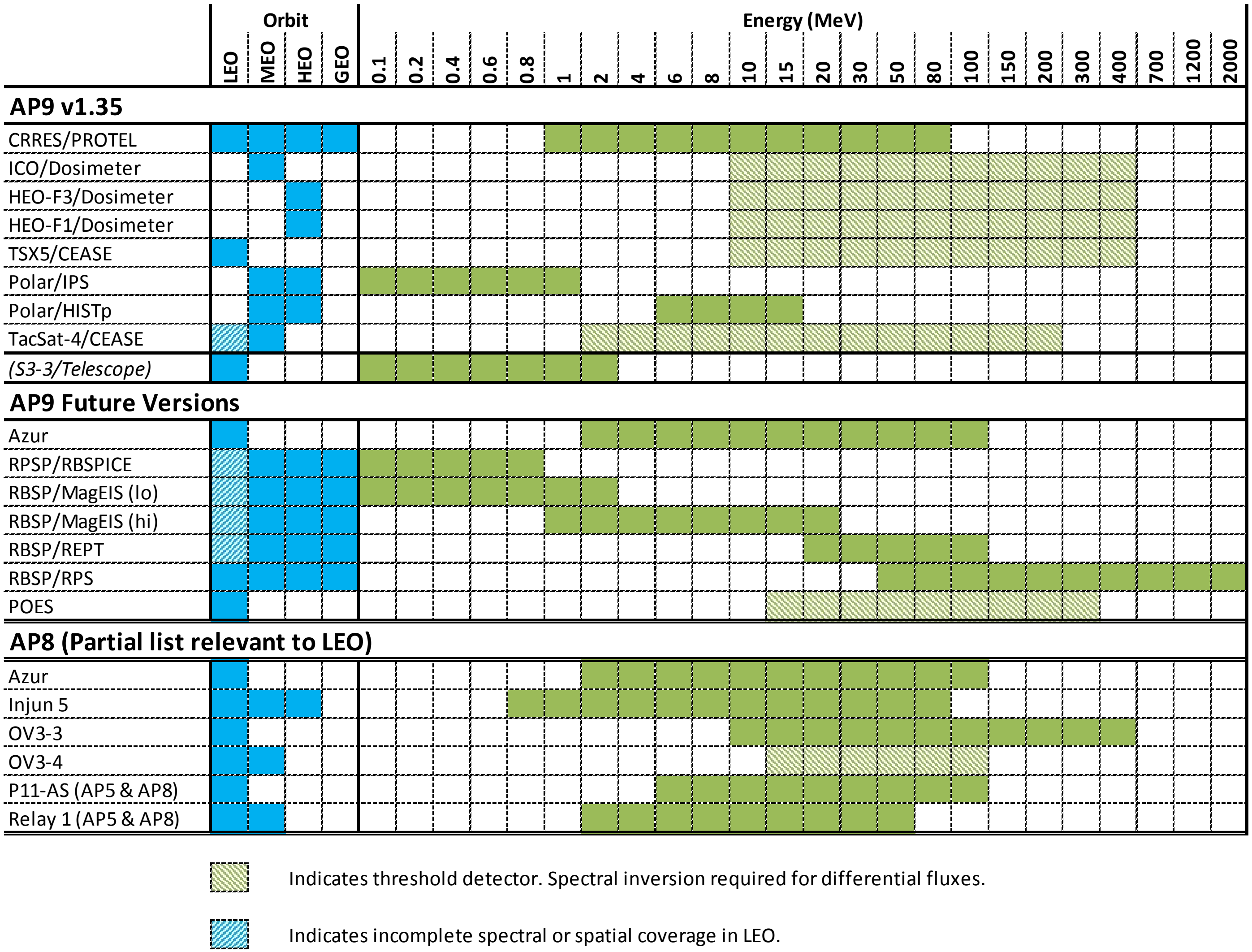
- ESA* performed an independent validation of AE9/AP9
  - Compared AP9 with data and other models
  - One conclusion was that AP9 proton fluxes are significantly higher than data and other models, especially for LEO and at low energy (< 10 MeV)
- IRENE team wanted to determine possible reasons and resolutions
- 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?

*Heynderickx, D., and P. Truscott, "NARMI Technical Note 2: Validation and Comparison Results," 27 October 2014.

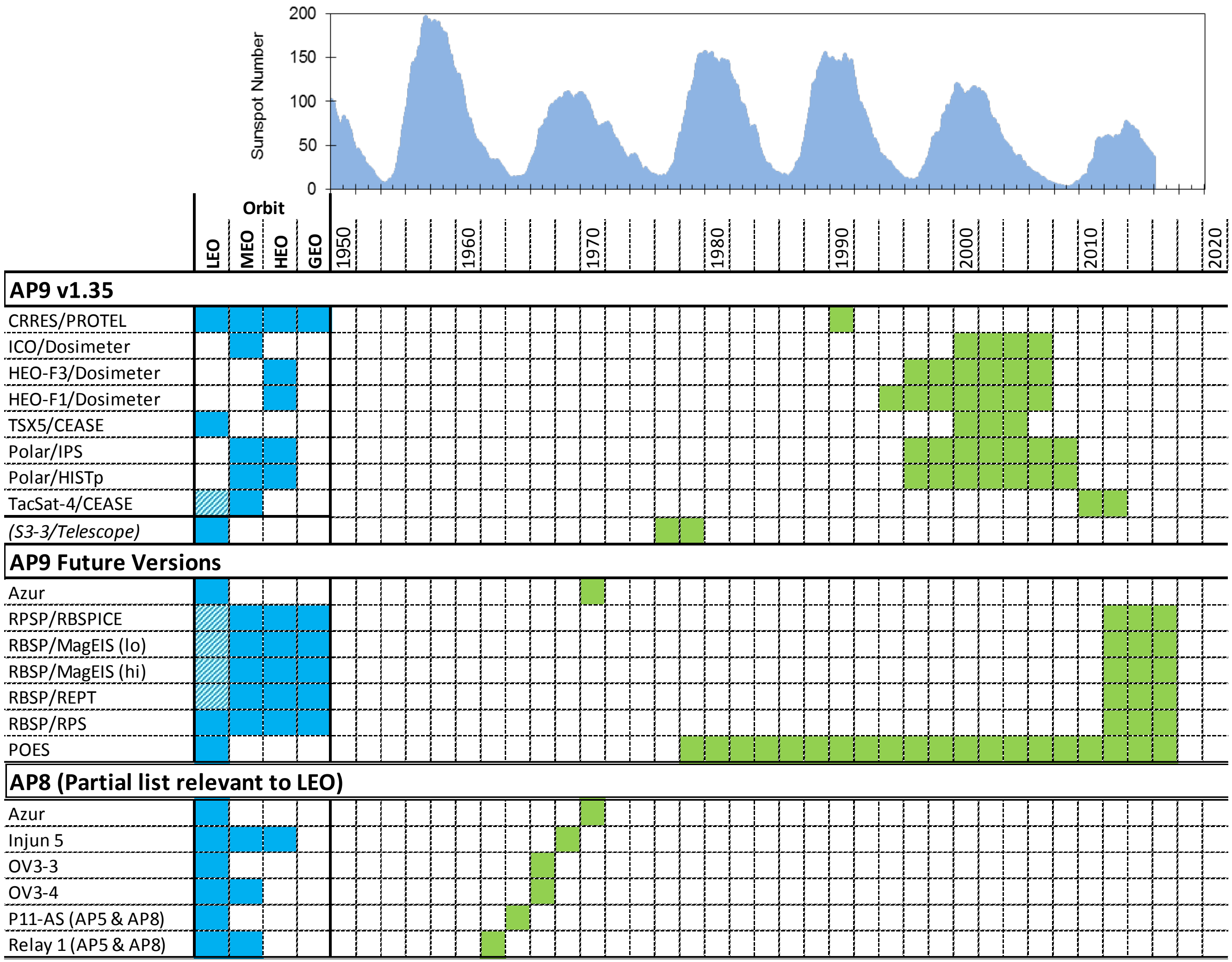
Background

- **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 ($\Delta E/E_{mid} \approx 0.7$)**
  - **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 ($\Delta E/E_{mid} \approx 0.2$)**
  - **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**

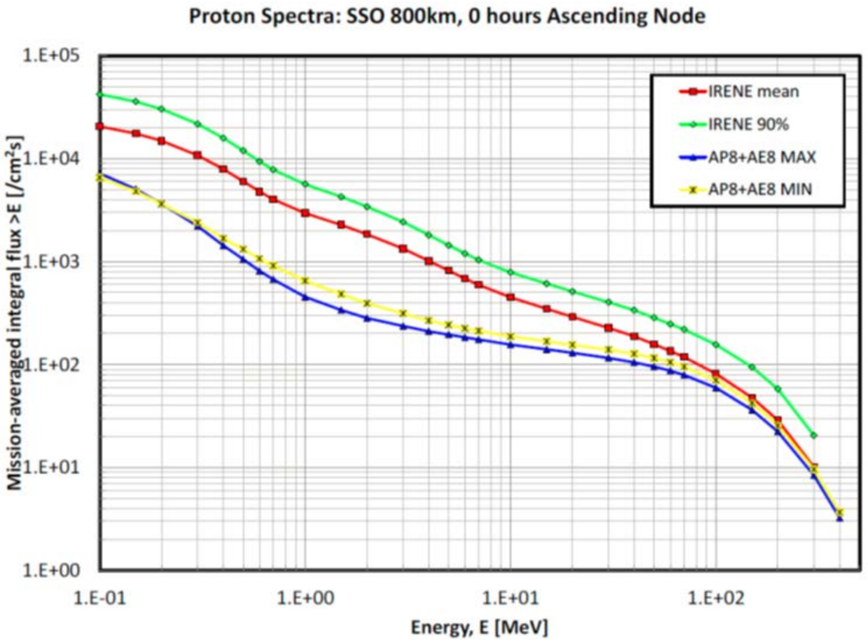
Proton Data Sets - Spectral



Proton Data Sets - Temporal



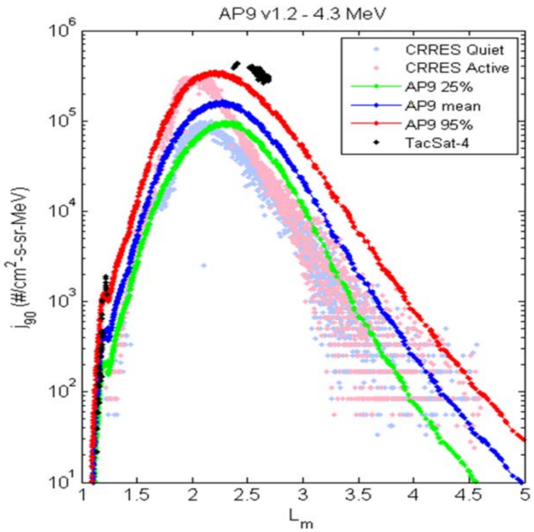
Summary of ESA Findings (Relevant to LEO Protons)

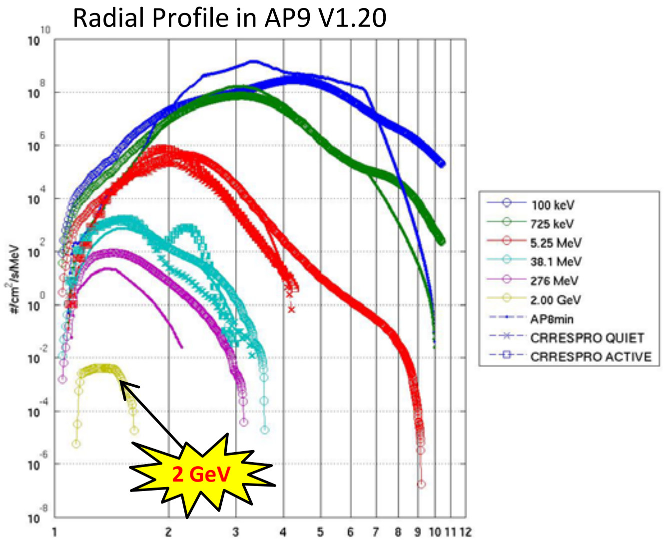


- **AP9 vs. Azur: AP9 mean overestimates except around 10 MeV, spectral shape does not agree with data and other models,also overestimates extent of SAA region**
- **This plot compares AP9 with AP8 for a polar LEO orbit**
- **At 1 MeV, AP9 is up to a factor of 10 higher than AP8**

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/h_{min} profiles observed by RBSP/Relativistic Proton Spectrometer
  - Extend proton energies to 2 GeV
- **Low altitude taper**
  - Force fast fall-off of flux for h_{min} < 100 km
  - Cleans up radial scalloping at altitudes below ~1000 km
- **Low altitude fluxes are reduced, but differences remain**





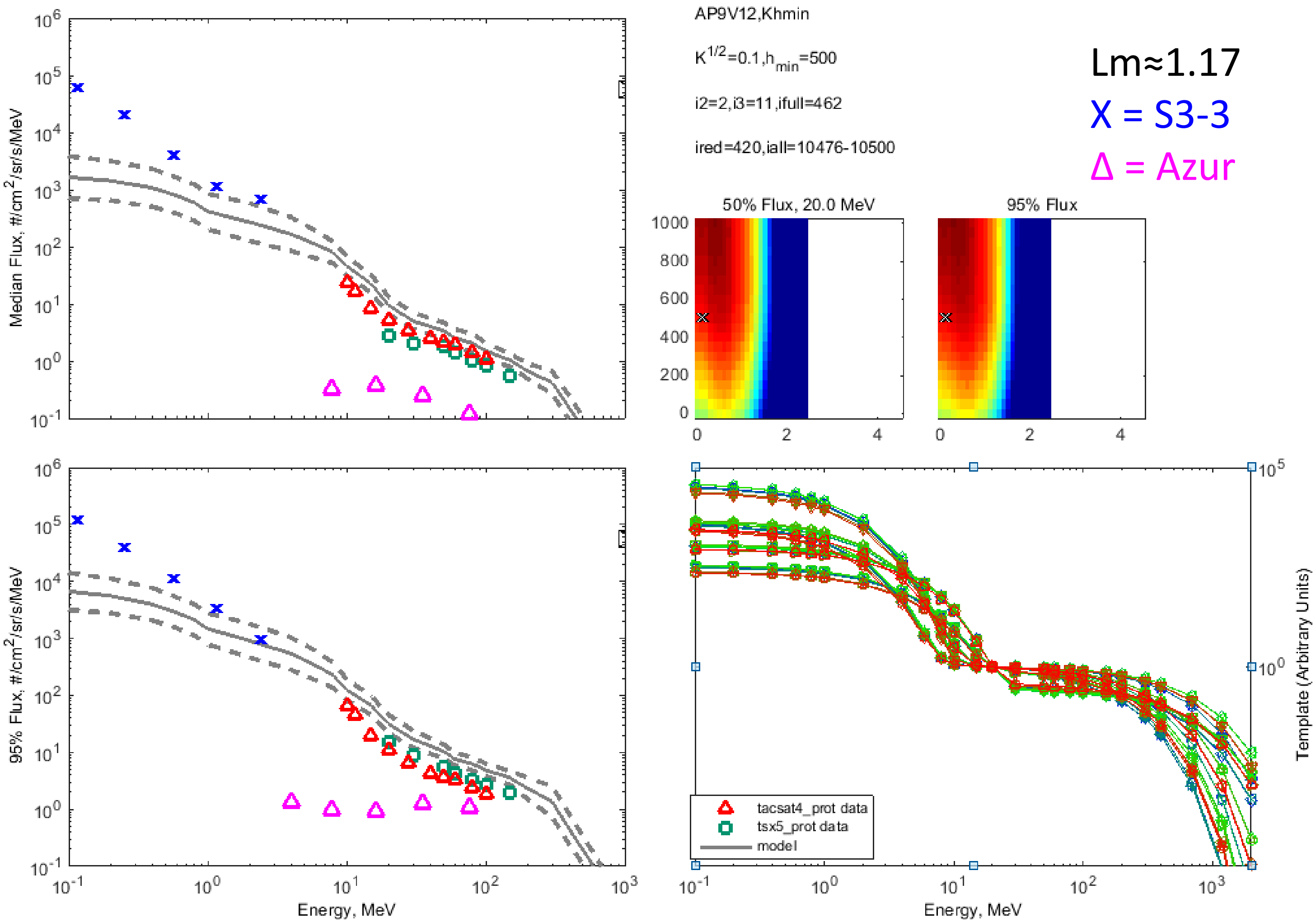
Analyses Performed

AE9/AP9 Team performed several analyses to investigate reasons for differences, with primary emphasis:

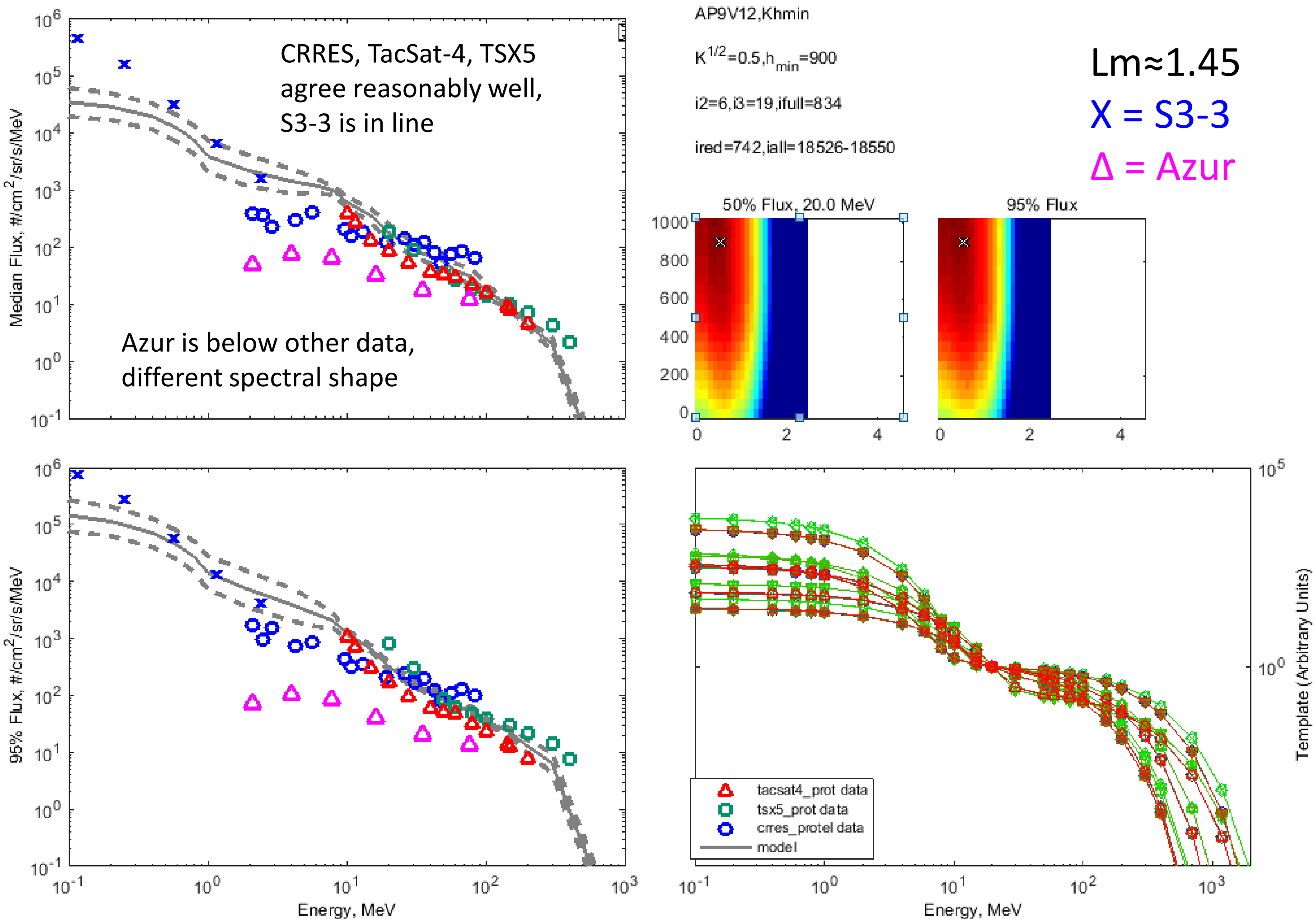
What is the spectral shape of LEO protons between 1 and 30 MeV?

- **"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

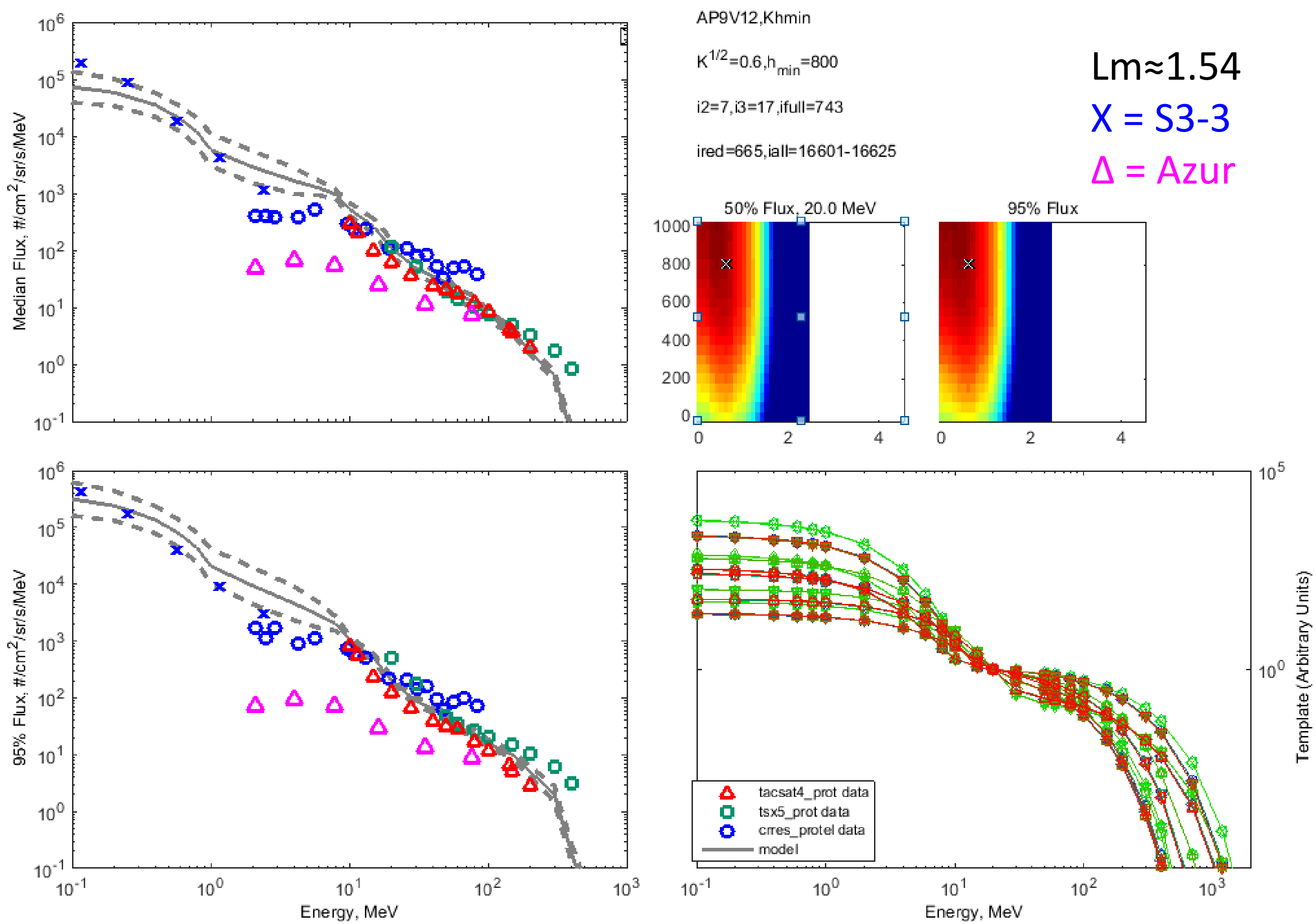
Binspectra Plots



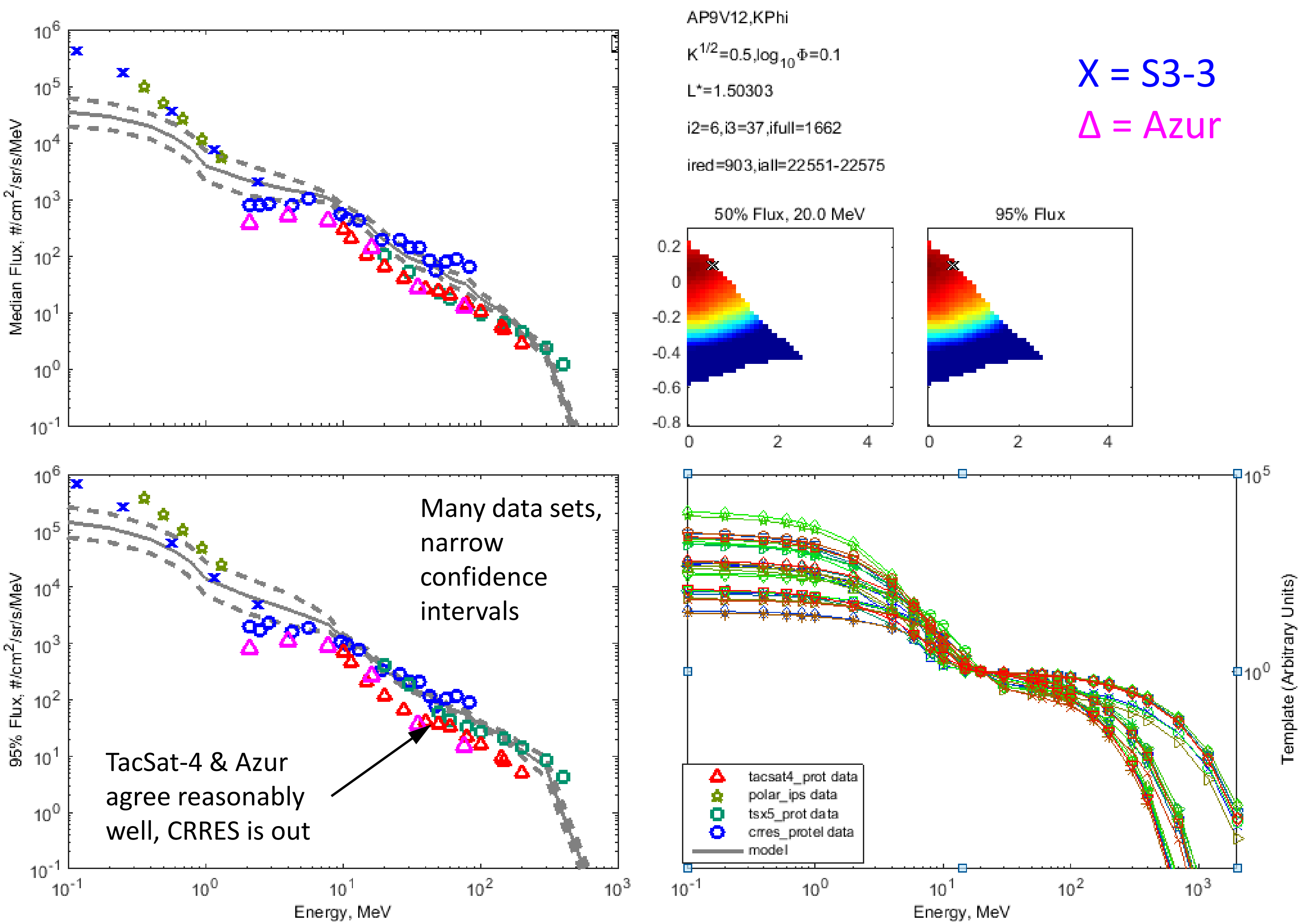
Binspectra Plots



Binspectra Plots



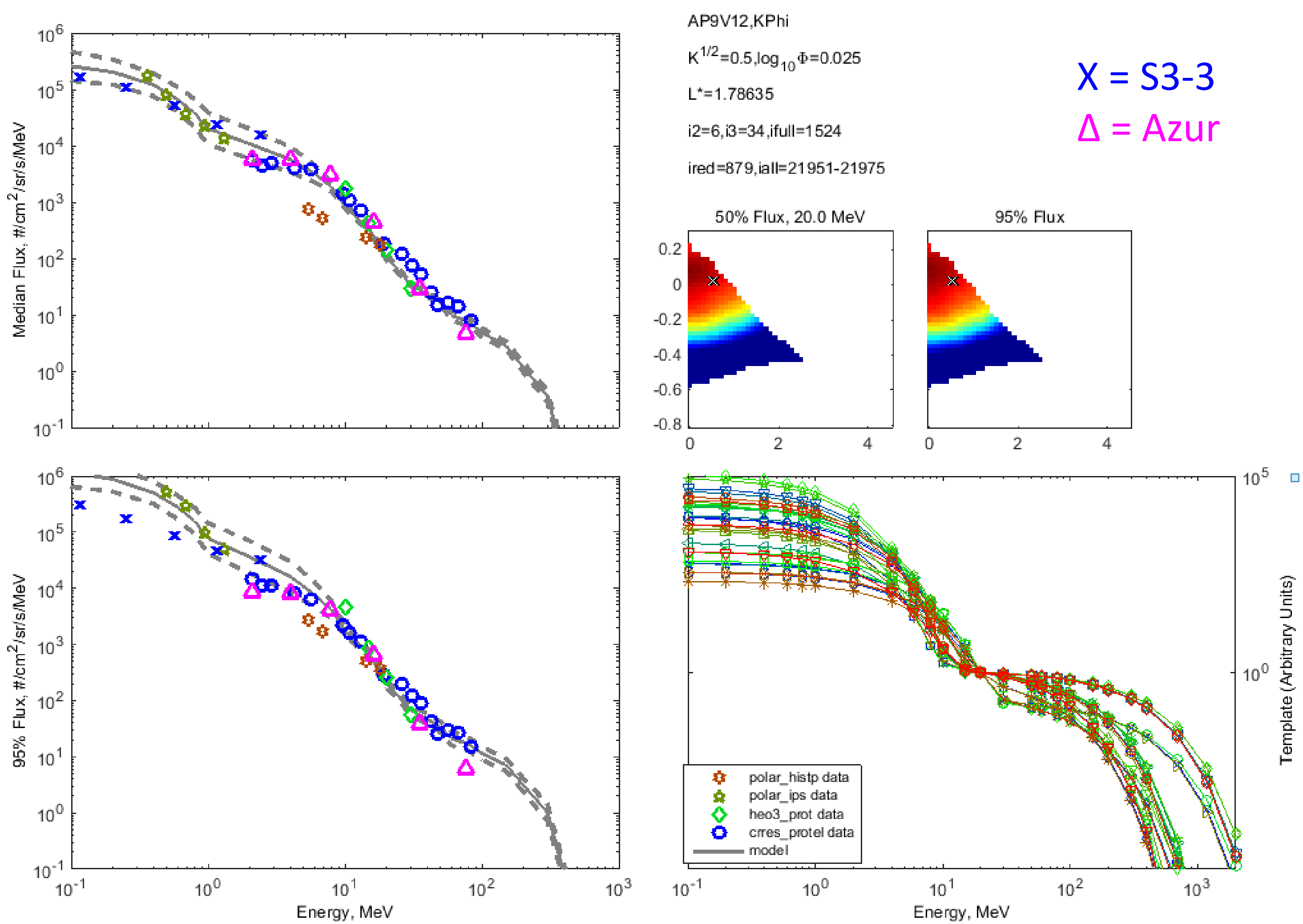
Binspectra Plots



X = S3-3

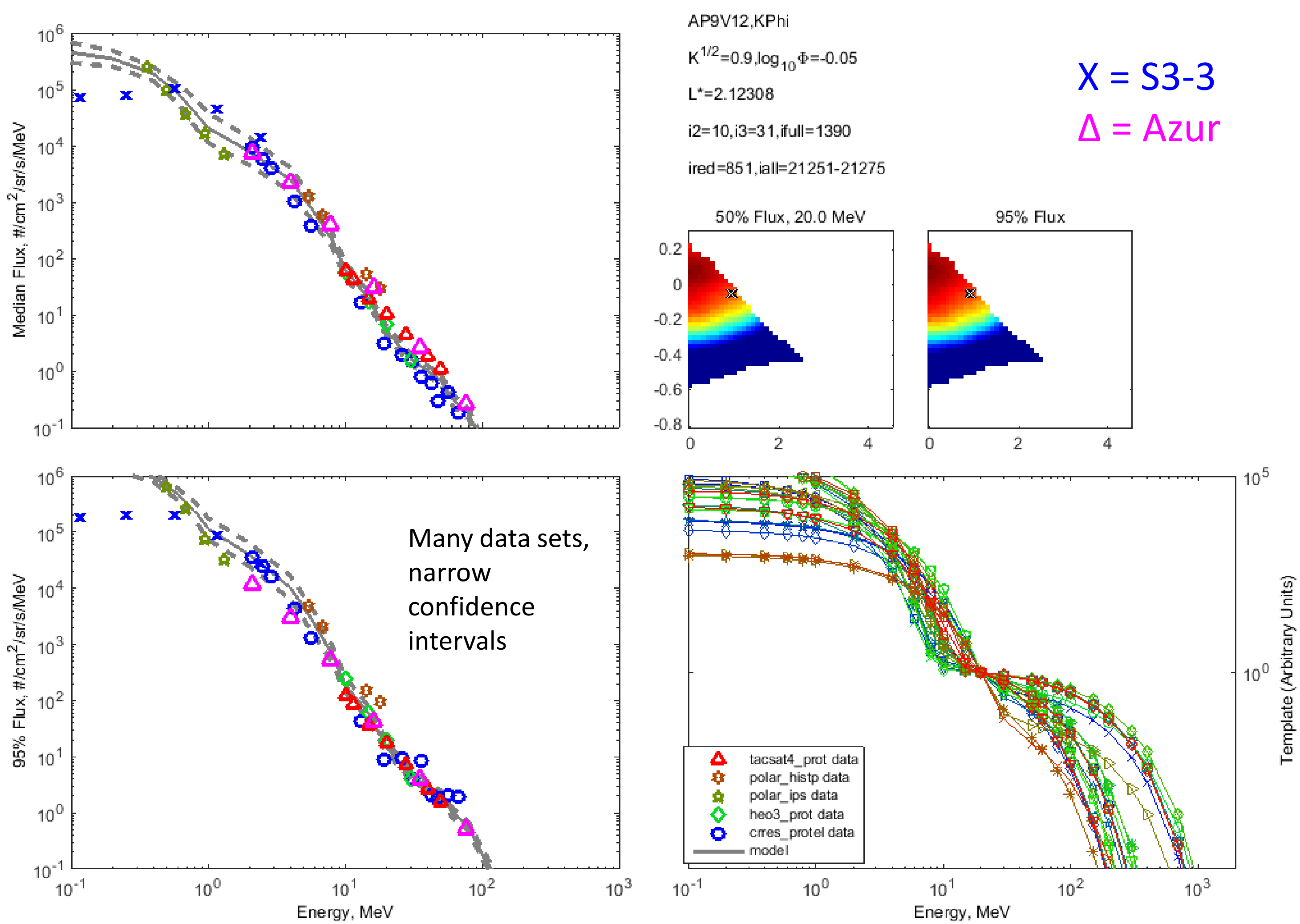
Δ = Azur

Binspectra Plots



AFRL

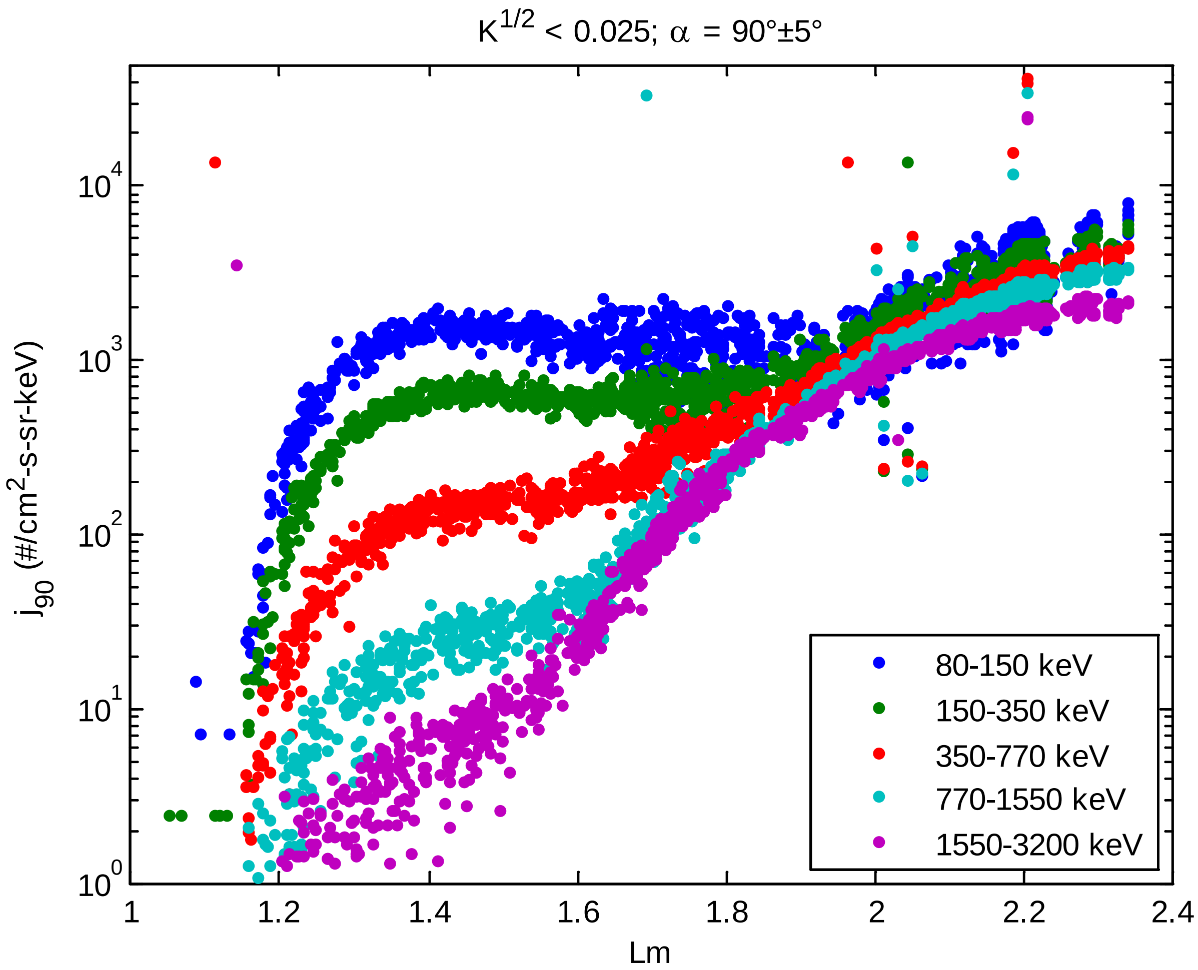
Binspectra Plots



S3-3 Analysis

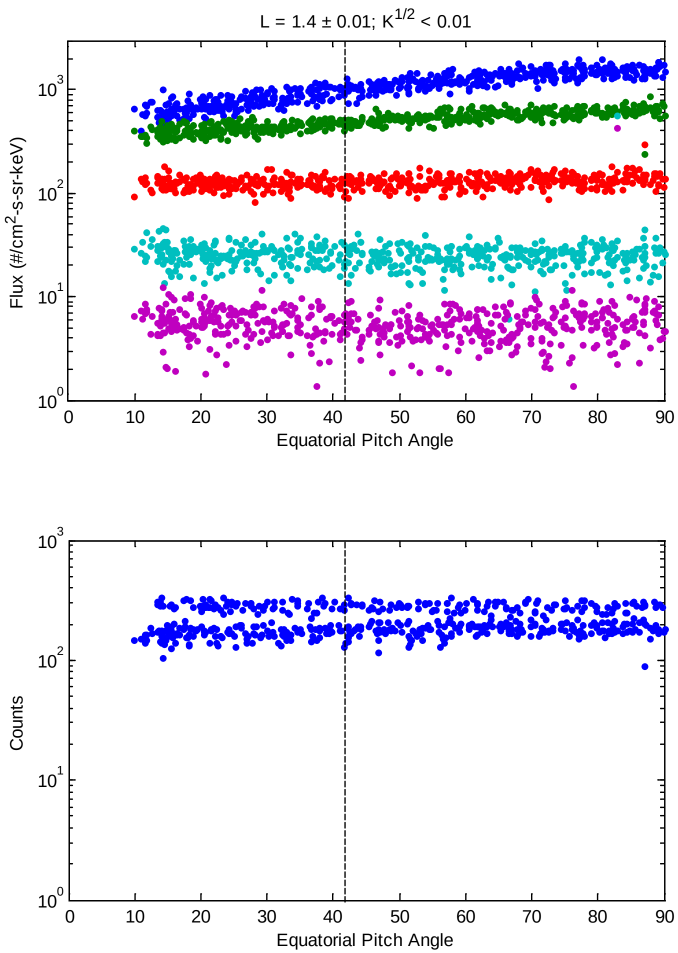
- Flew in 1976 – 1979 (about 6 years after Azur, rising part of solar cycle)
- 236 x 8048 km x 97.5° orbit
- Proton telescope housed within magnetic electron spectrometer
  - 0.08 – 3.2 MeV, 5 channels, $\Delta E/E_{mid} \approx 0.7$
- Data showed very high fluxes for L < 2
- Data formed the basis for 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

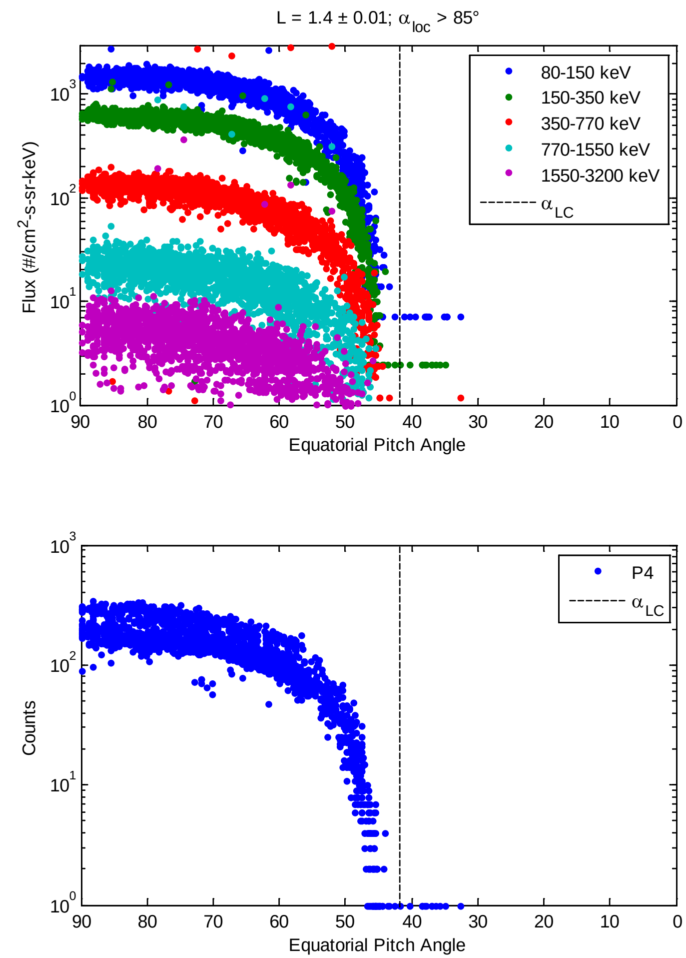


S3-3 PADs: L=1.4

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



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



S3-3 PADs: L=1.3

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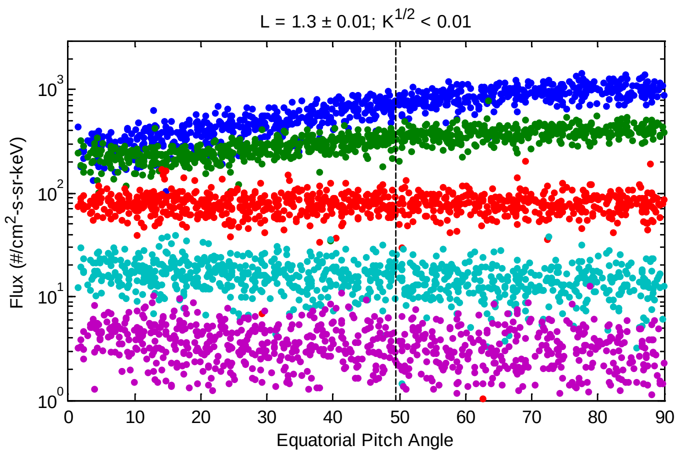
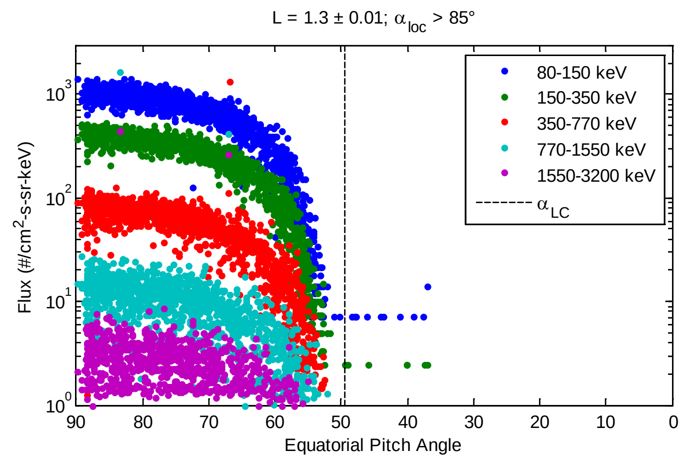
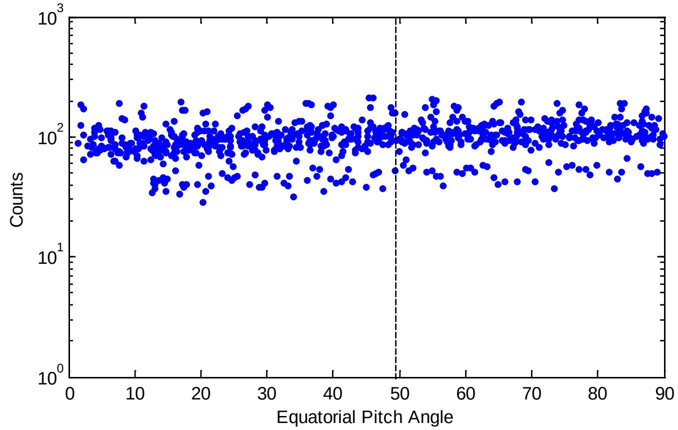
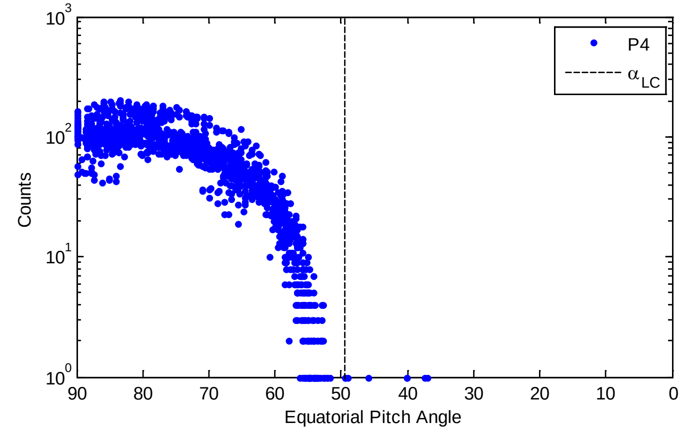
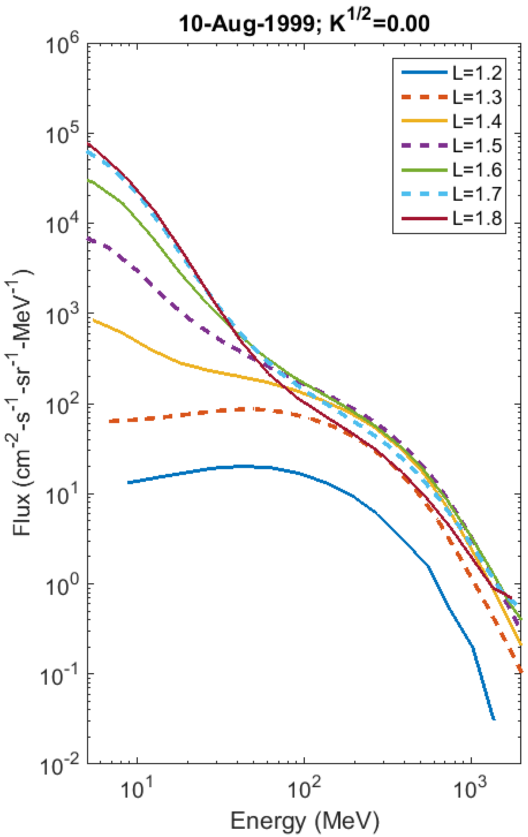


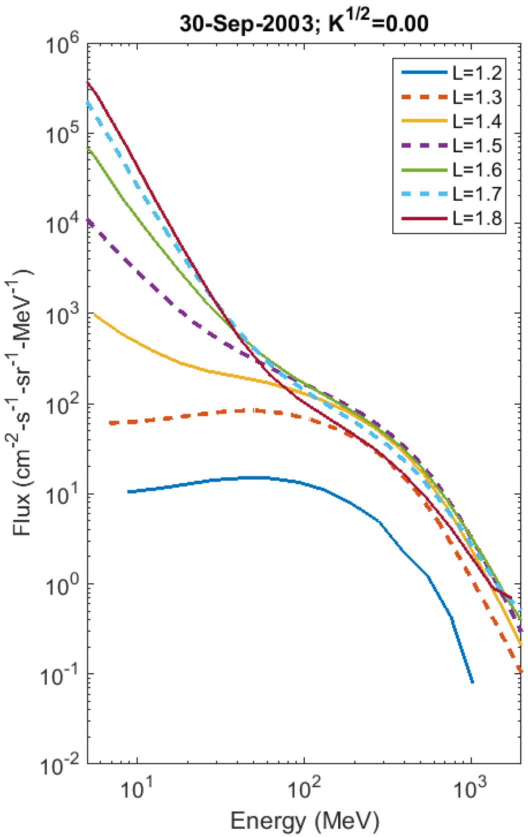






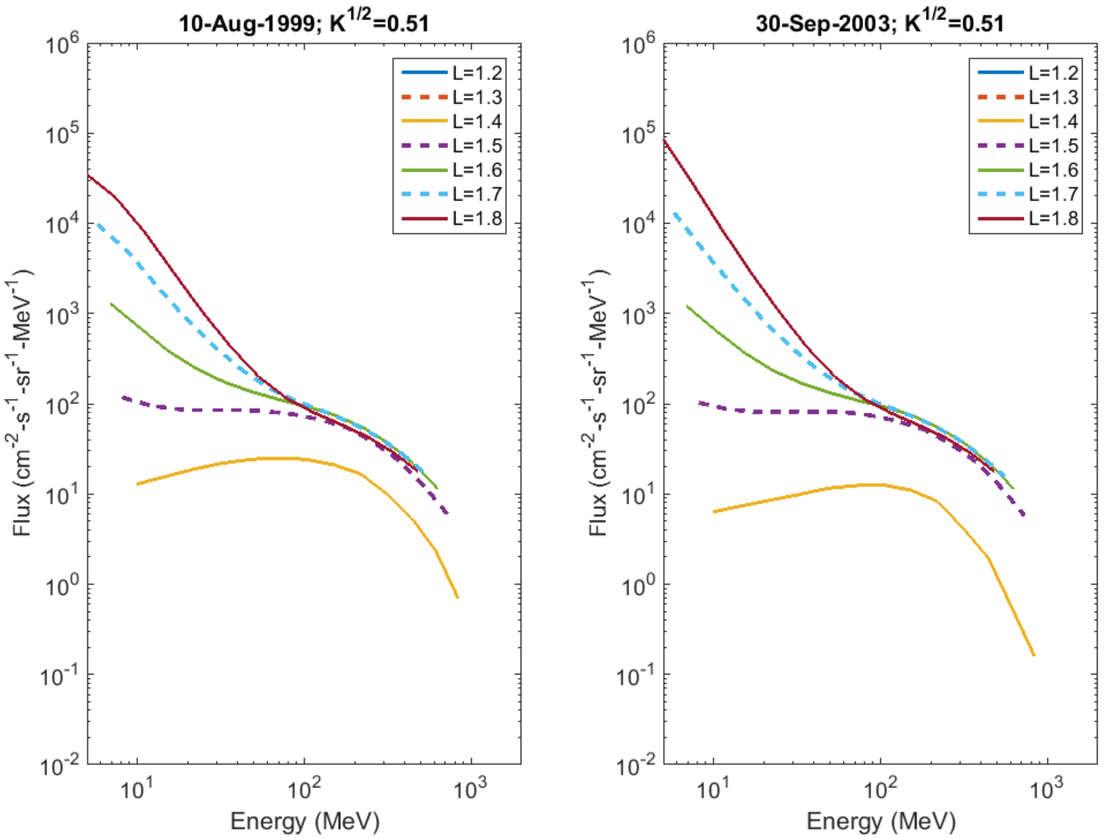
Spectral Shapes: Selesnick et al., 2007





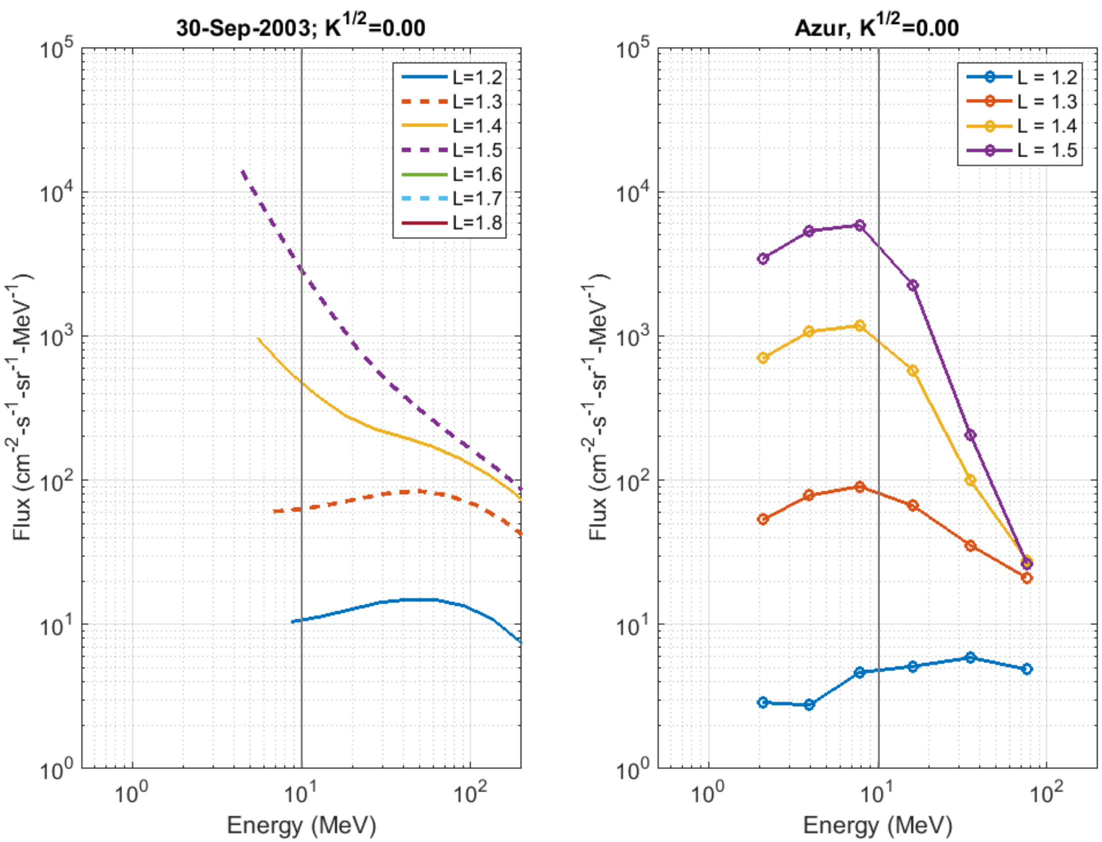
- **Selesnick model shows spectra peaking at 50 – 80 MeV for L < 1.4**
- **At higher L, spectra below 20 MeV are power-law-like, with modulation over solar cycle**
- **Azur shows spectra peaking at 5 – 10 MeV up to L > 1.5**

Spectral Shapes: Selesnick et al., 2007



- **Same as previous slide, but off the equator**

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)

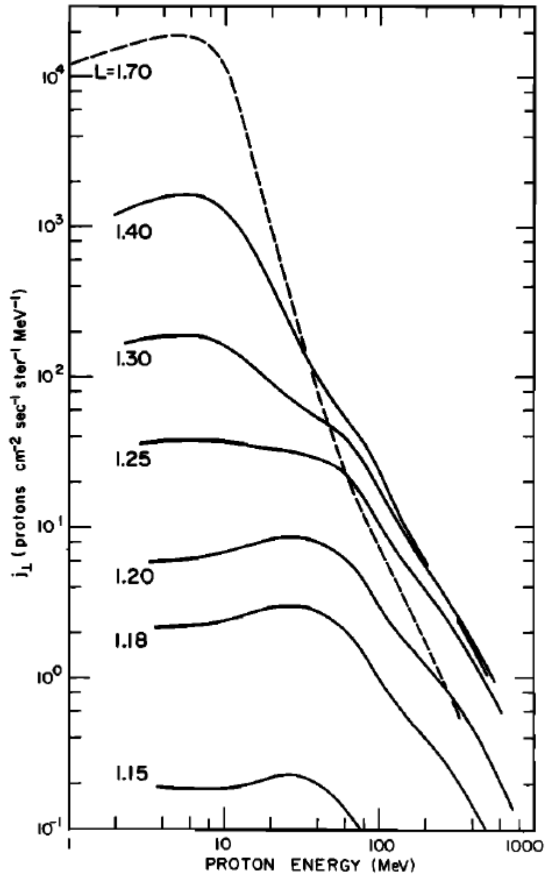


Fig. 8. Computed inner belt proton energy spectra, 2–500 MeV. The dashed line shows the boundary condition at $L = 1.7$ based on the data of *Hovestadt et al.* [1972] and *Thede* [1969]. The solution used $D_{LL} = 9 \times 10^{-7} L^{11.4} \mu^{-0.7}$ and a free electron density higher than the model density by a factor of 5.

- **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**

Spectral Shapes: Other Data

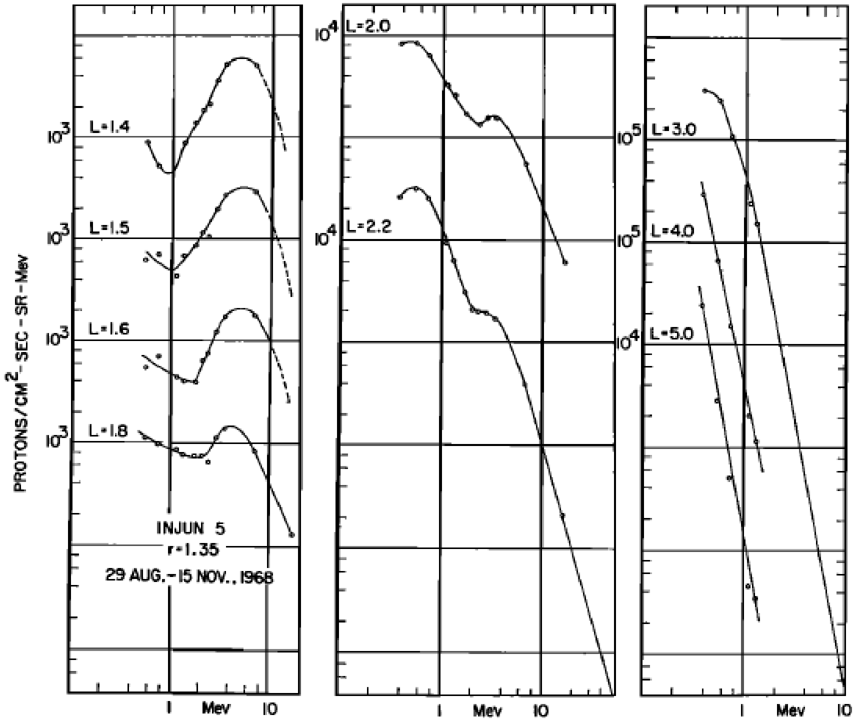


Fig. 2. Experimental proton differential energy spectra at $r = 1.35$ and various L values.

Injun 5, 1968 (Pizzella and Randall, 1971)

- **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 ≈ 2 MeV, peak at E ≈ 6 MeV at low L**
- **Data from Dial, ESRO 2 (Fischer et al., 1977) shows spectra peaked near 10 – 20 MeV**

Spectral Shapes: AP8 & Older Data

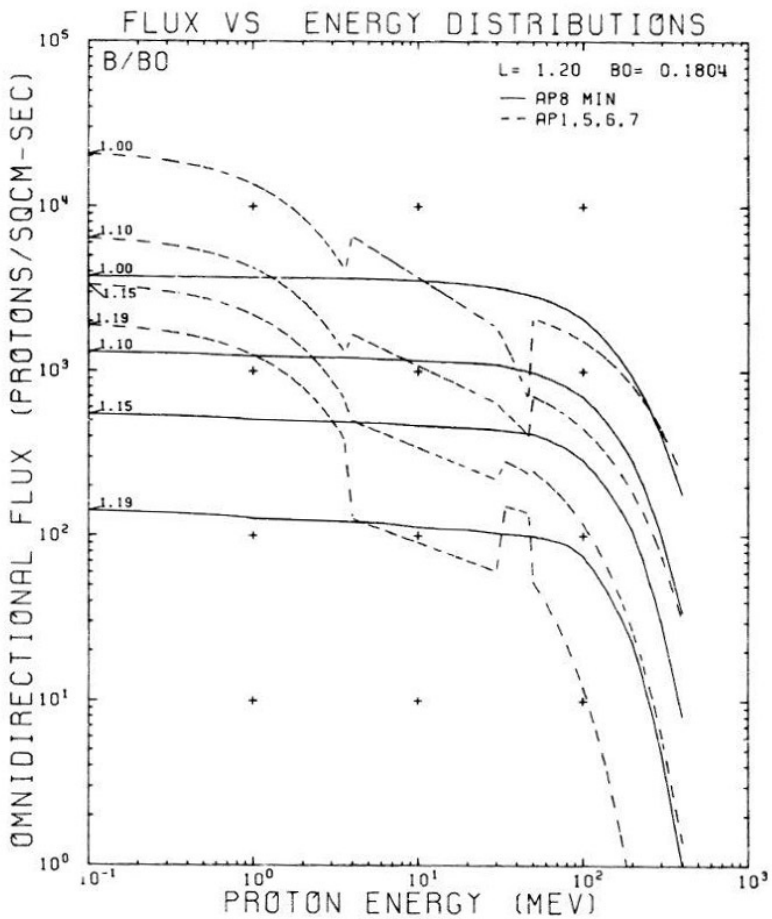


Figure 144. AP8MIN and AP-1, -5, -6, and -7 Flux vs Energy Comparison Plot for L = 1.20 R_E

- 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 ≈ 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 ≈ 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, Φ, t; perhaps MLT, …)**
  - **Slicing and dicing for comparison (e.g., comparing energy spectra at one K/Φ) 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)

- We expect that including Azur data (due in Version 1.5) will reduce AP9 fluxes, unclear how much
  - Confidence intervals will also change
- We are also developing new templates which should improve spectral shapes and altitude gradients
- Including solar cycle variations will also help
- Need to eventually explain 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

Epilogue: RBSP

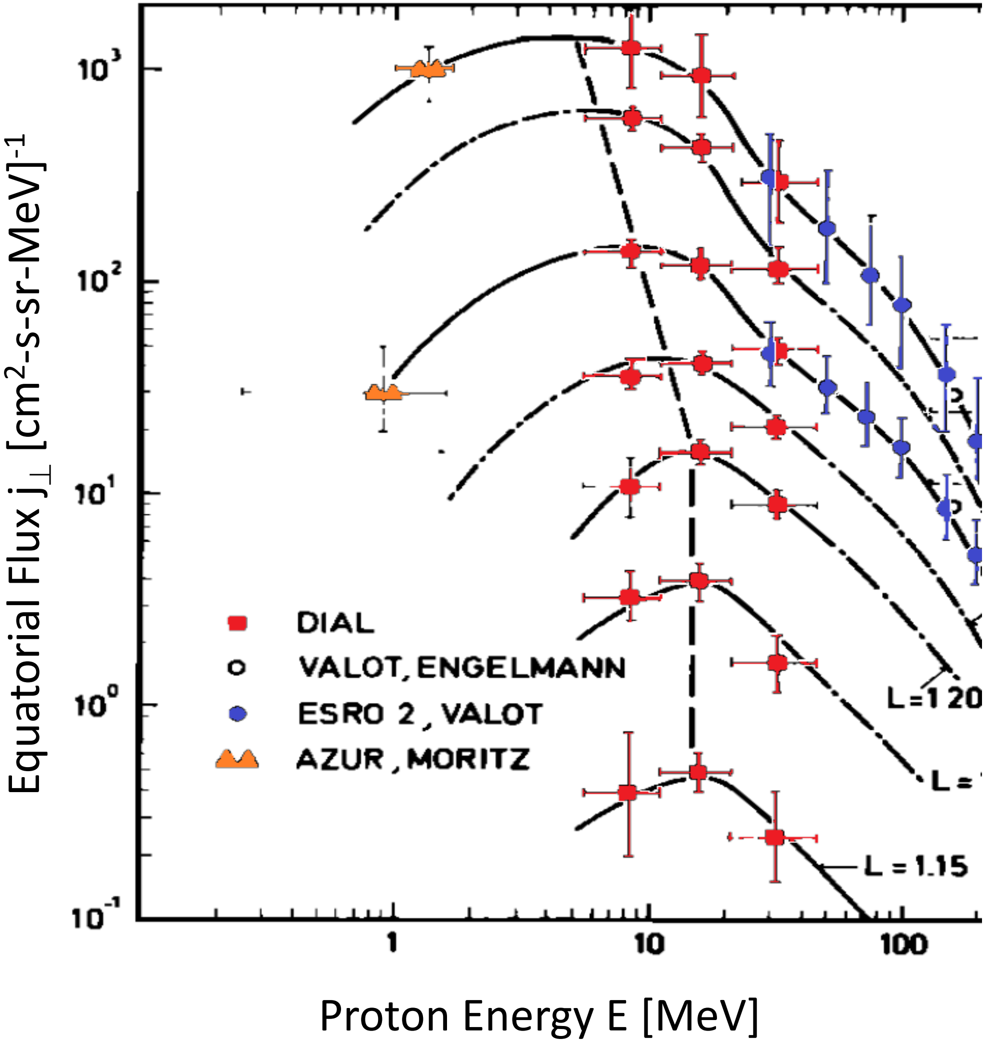
- **RBSP < 20 MeV protons (MagEIS and RBSPICE) do not have a requirement for measurements in inner zone**
- **REPT (20 – 100 MeV) measurements in inner zone require significant data processing to remove contamination from penetrating protons**
- **RPS measurements in inner zone are clean**

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, $\Delta E/E_{mid} \approx 0.7$**
- **Magnetically stabilized, so it always measures j_{perp}**
- **A fairly large SPE occurred in Nov. 1969, right at launch; several smaller events occurred during the mission**

Fischer et al. (1977)



- **Dial:**
  - **Mar. 1970 – May 1970**
  - **326 x 1629 km x 5.5°**
- **ESRO 2:**
  - **Oct. 1967 – May 1971**
  - **334 x 1085 km x 97.2°**
- **Azur (Moritz):**
  - **Single channel, 0.25 – 1.65 MeV**
  - **Separate experiment from Hovestadt**

Valot (1972)

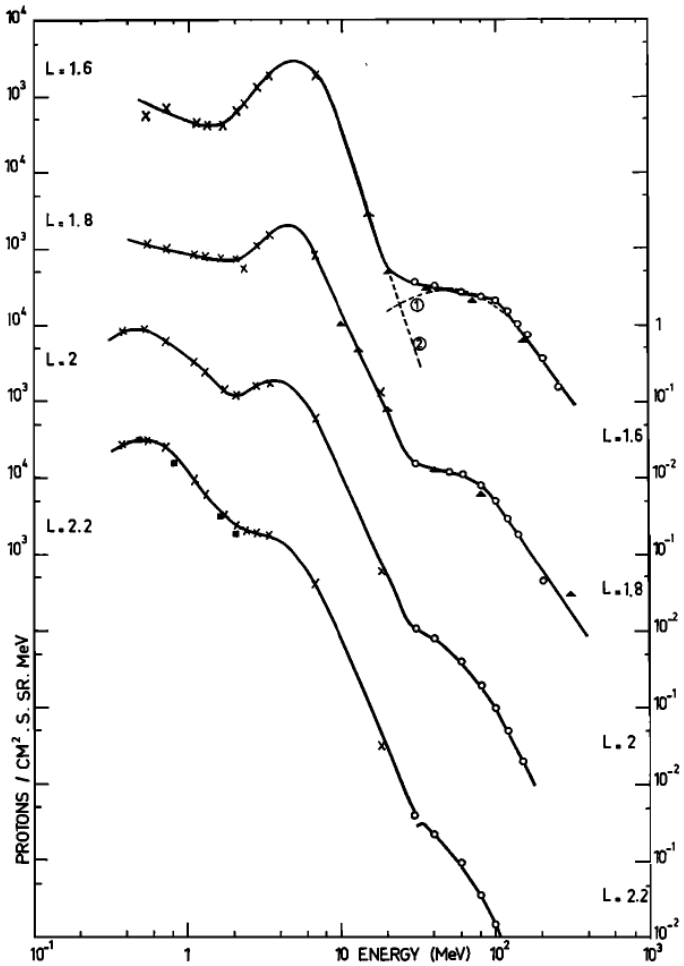


Fig. 8. Spectra between 0.3 and 300 Mev. Remarks and discussion are made in the text. Circles indicate Esro 2 data; crosses, data of *Pizzella and Randall* [1971]; triangles, data of *Naugle and Kniffen* [1963]; and squares, data of *Mihalov and White* [1966].

- **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)

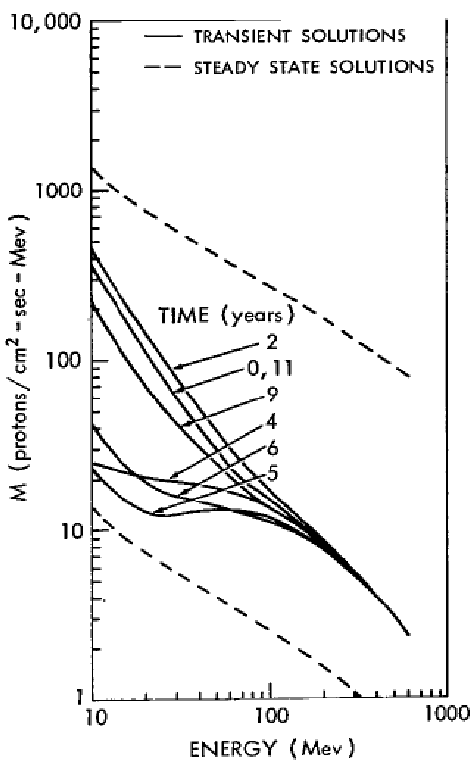


Figure 42—Proton energy spectra at different times in the solar cycle for L = 1.188, B = .1884, h_{min} = 650.

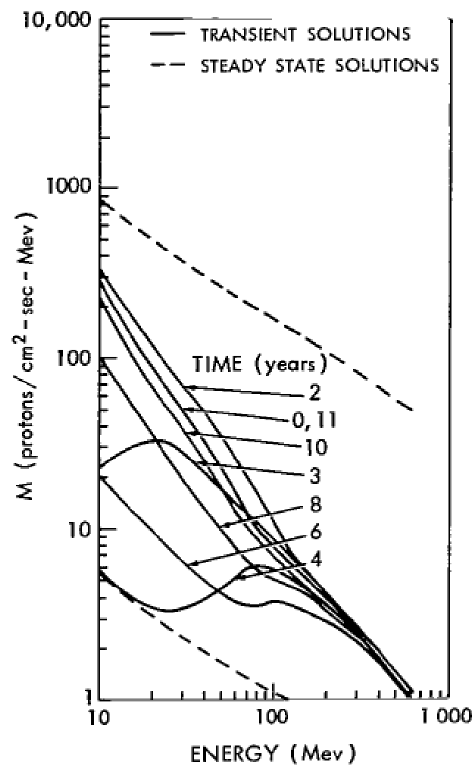


Figure 43—Proton energy spectra at different times in the solar cycle for L = 1.188, B = .193, h_{min} = 580.

- **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