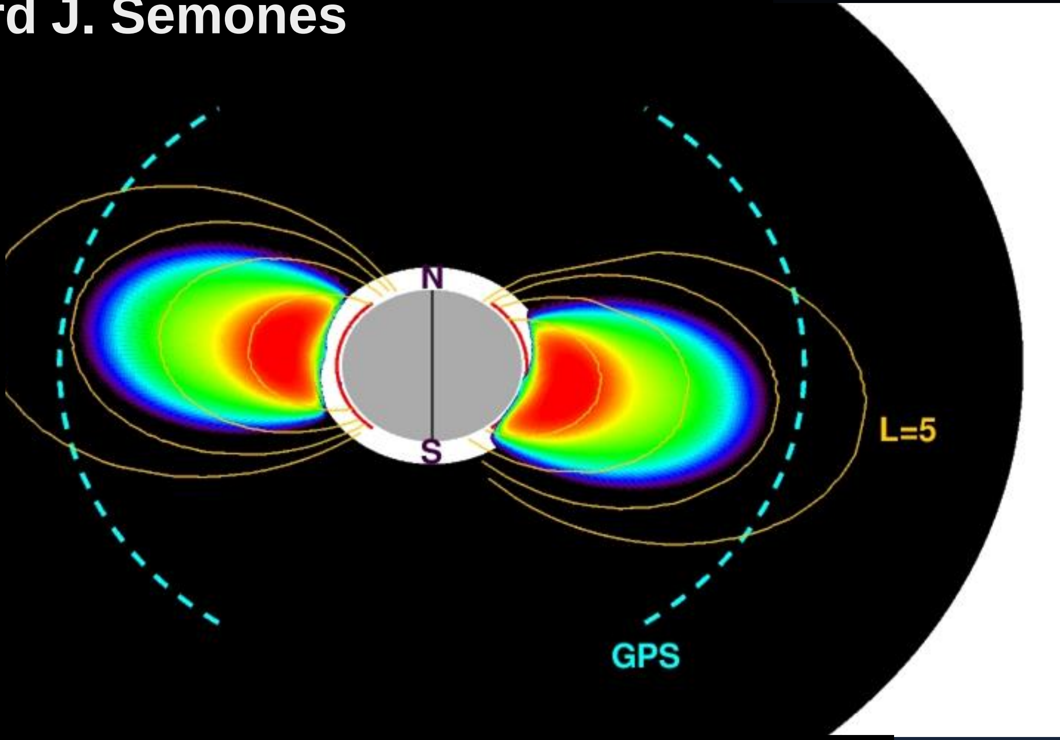
A Dynamic Near-Earth Trapped Proton Model for Mission Analysis

Xiaojing Xu, Steve R. Blattnig, Francis F. Badavi,
Martha S. Clowdsley, Edward J. Semones

Space Radiation Group
NASA Langley Research Center



The 27th Workshop on Radiation Monitoring for the International Space Station
09/2024, Boulder, Colorado

Outline

- **Background**
  - Importance of trapped proton environment
  - Time variations in the trapped proton environment
  - Simulation of the year 2013 environment by existing models (AP8, AP8-DT, IRENE-AP9)
- **Development of a dynamic trapped proton model**
  - **Model structure and derivation of functions**
    - Geomagnetic field confinement
    - Collisional loss of particles to atmosphere
  - **Fitting to the flux observations** (RPS-b 2013, POES 1998-2013)
  - **Model validation** (with the environment recorded in AP8)
  - **Proton flux spectrum**
- **Discussion and summary**

Importance of trapped proton environment

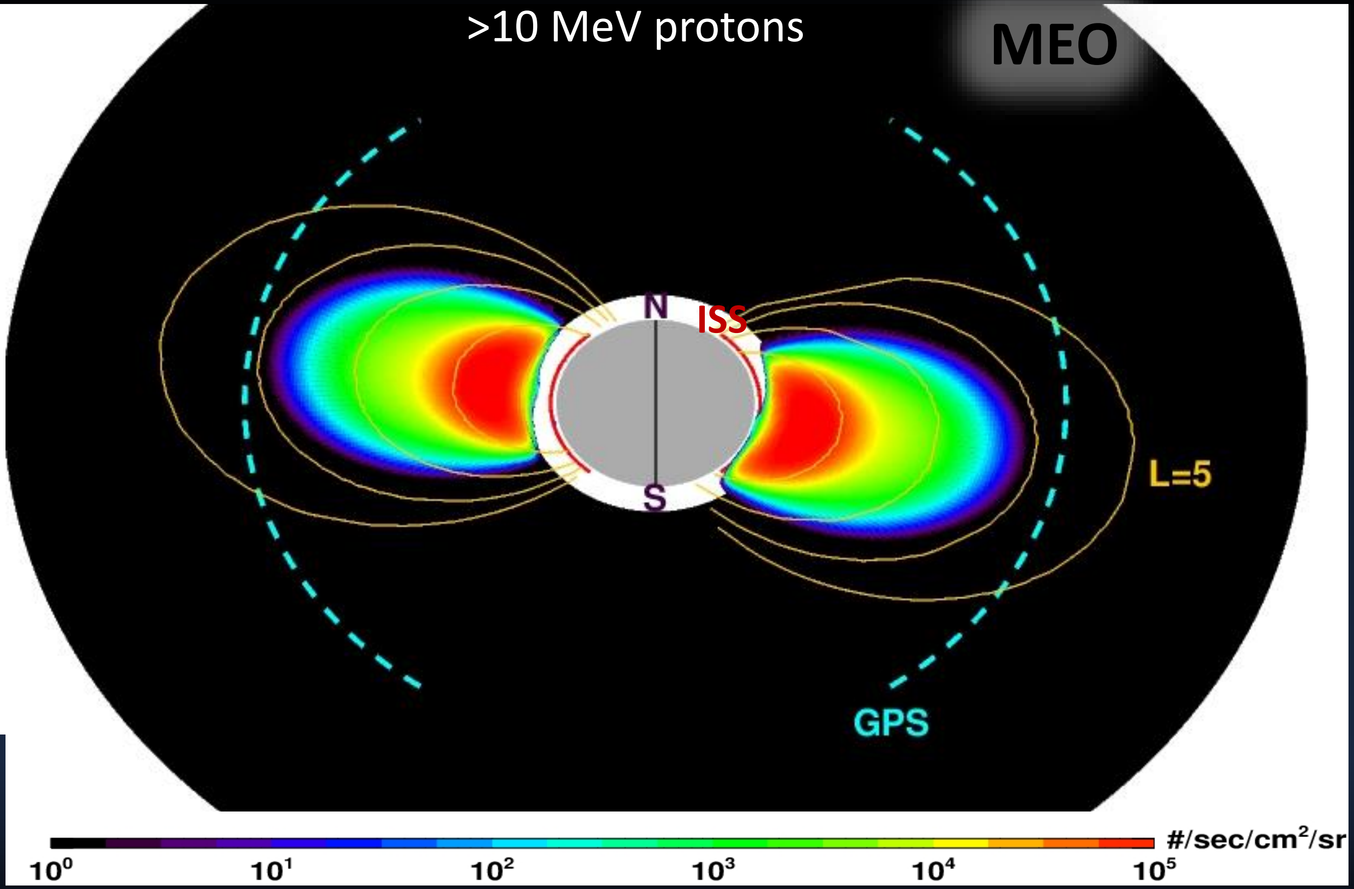
Trapped by: Earth's magnetic field

Proton Energy: 100 KeV to several hundred MeV

Extension: from a few hundreds to 20,000 km
- LEO (200-2,000 km, the white band)
- MEO (2,000-36,000 km, the black area)

Radiation hazard:
- Instrument failures or adversary events
- health risk

120°E-60°W cross-section of the proton radiation belt

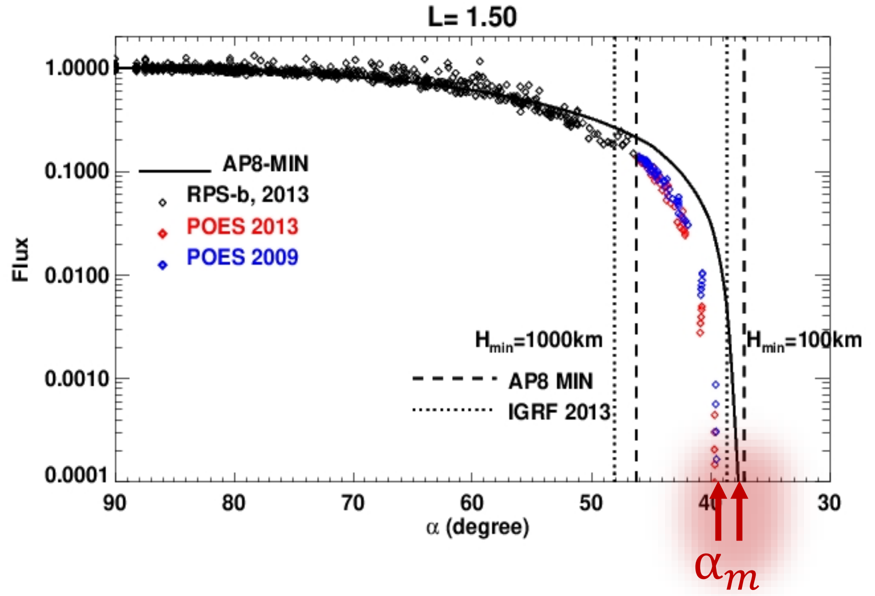


Time variations in trapped proton environment

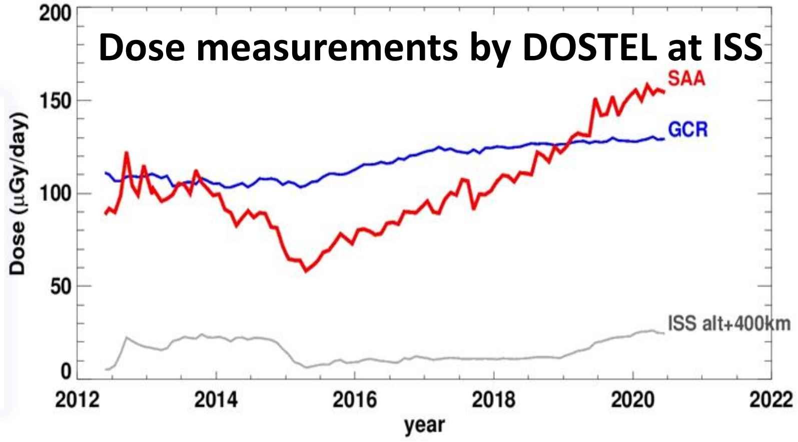
Geomagnetic field changes

- Decreasing dipole moment
- Increasing offset of geographic and geomagnetic centers

- Decreasing trend in H_{min} of particle drift shells
  - Particles with mirror points in low altitudes:
    - increased collisional loss rate
  - Increased drift loss cone angle α_m
    - some locations no longer open for particle trapping



Solar cycle modulations



Radiation from trapped protons at ISS orbit (SAA)

- Significant contributions
- Strong time variations (during 10 years of period, mainly due to solar cycle modulations)

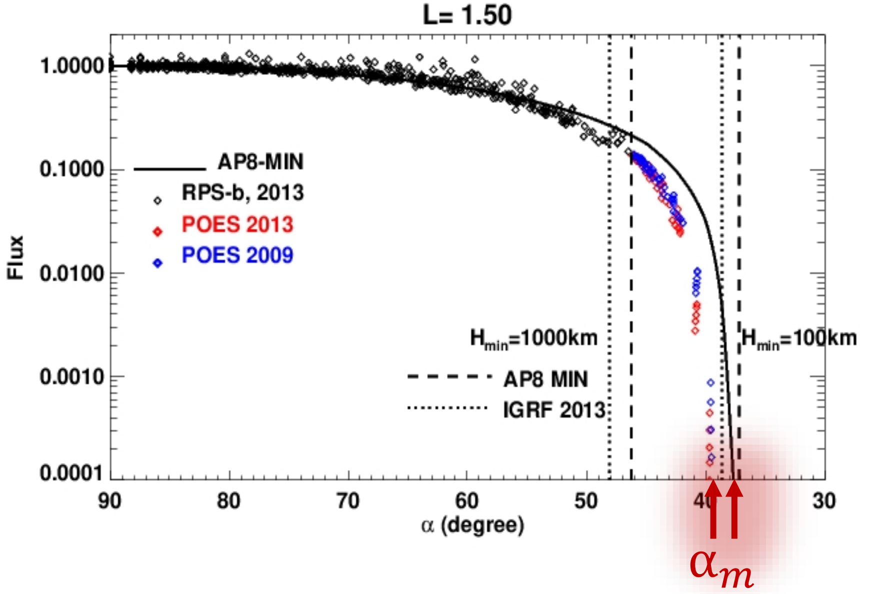
- Time variation at low altitudes caused by both **geomagnetic field changes** and **solar cycle modulations**

Time variations in trapped proton environment

Geomagnetic field changes

- Decreasing dipole moment
- Increasing offset of geographic and geomagnetic centers

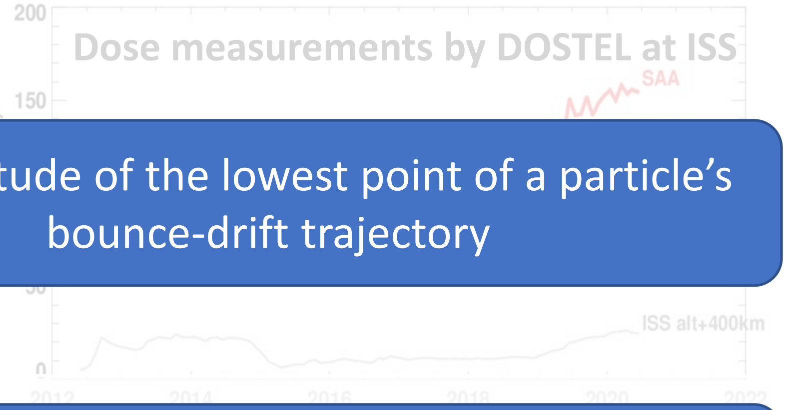
- **Decreasing trend in H_{min} of particle drift shells**
  - **Particles with mirror points in low altitudes:**
    - increased collisional loss rate
  - **Increased drift loss cone angle α_m**
    - some locations no longer open for particle trapping



Hmin: altitude of the lowest point of a particle's bounce-drift trajectory

α_m: the smallest equatorial pitch angle allowing the particle to finish the longitudinal drift

Solar cycle modulations



...rbit (SAA)

- Strong time variations (during 10 years of period, mainly due to solar cycle modulations)

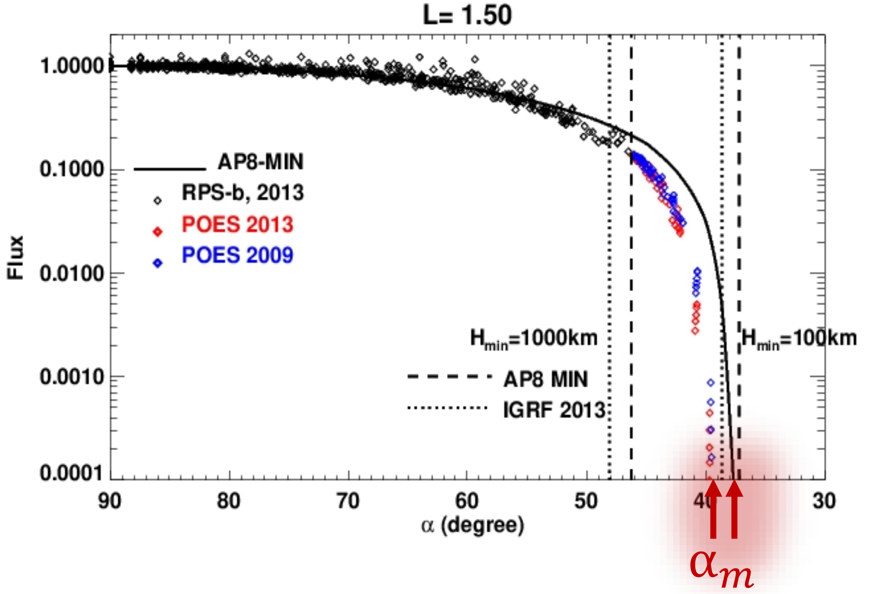
- Time variation at low altitudes caused by both **geomagnetic field changes** and **solar cycle modulations**

Time variations in trapped proton environment

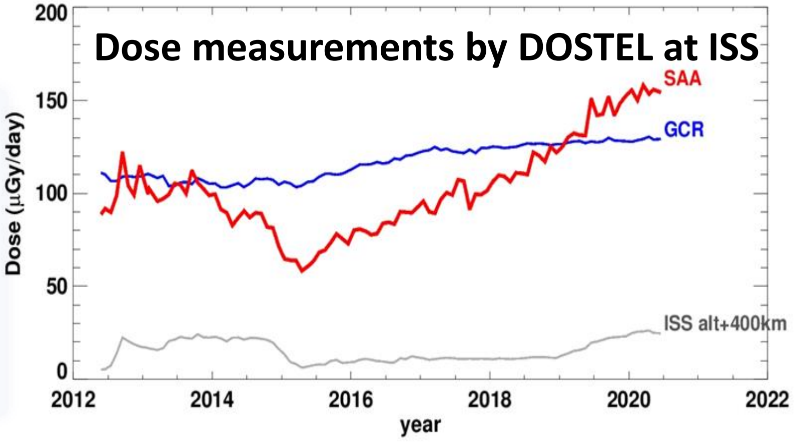
Geomagnetic field changes

- Decreasing dipole moment
- Increasing offset of geographic and geomagnetic centers

- Decreasing trend in H_{min} of particle drift shells
  - Particles with mirror points in low altitudes:
    - increased collisional loss rate
  - Increased drift loss cone angle α_m
    - some locations no longer open for particle trapping



Solar cycle modulations



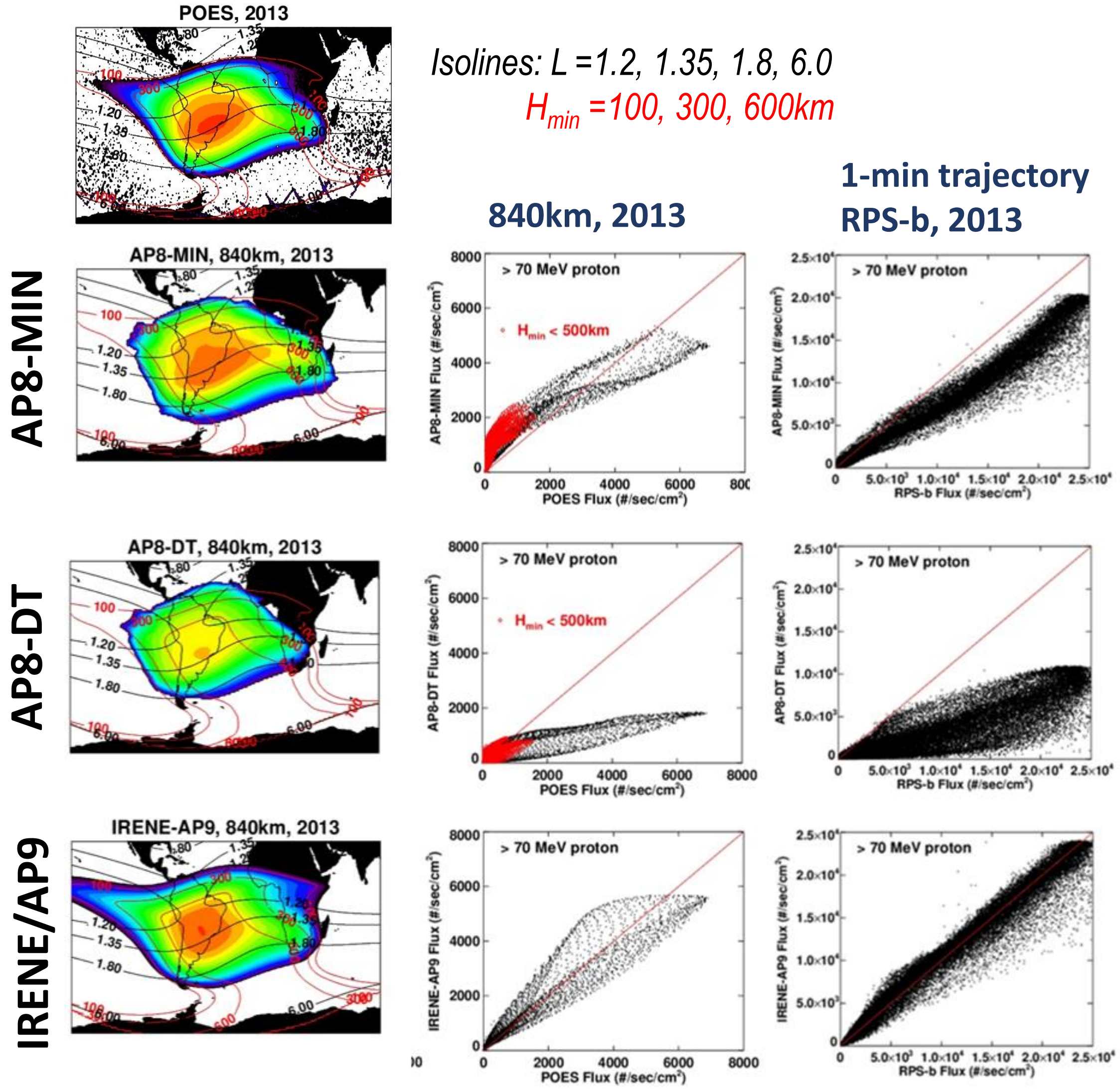
Radiation from trapped protons at ISS orbit

- Significant contributions
- Strong time variations (during 10 years of period, mainly due to solar cycle modulations)

- Time variation at low altitudes caused by both **geomagnetic field changes** and **solar cycle modulations**

Performance review of existing models

AP8, AP8-DT, IRENE-AP9



AP8-MIN:

- static model, based on ~1965 observations
- simulations shown here are computed by coupling AP8 flux table with IGRF field (2013)

AP8-Design Tool

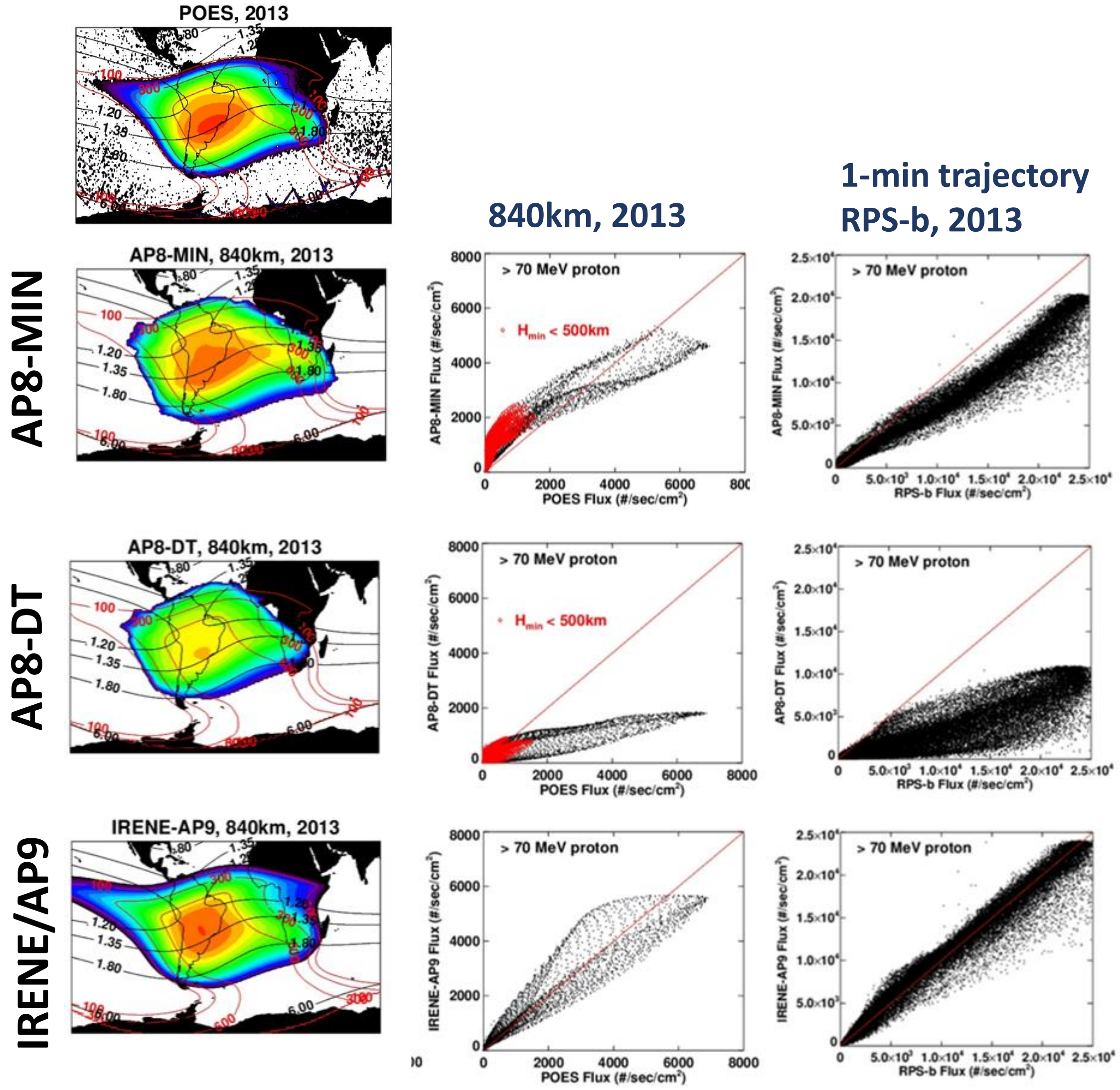
- developed for mission analysis at ISS and space shuttle altitudes
- AP8 field shifted to match the SAA center of later epoch
- flux scaled down by ~0.54

IRENE/AP9 (V1.57):

- uses IGRF; separated flux tables for high and low altitude regions
- developed for space craft design; provides statistical percentile based on several decades

Performance review of existing models

AP8, AP8-DT, IRENE-AP9



AP8-MIN:

- Erroneous estimations at low altitudes when coupling its flux tables with the geomagnetic field of later epochs

AP8-Design Tool

- The strategy to improve the simulations at the ISS altitude leads to erroneous estimations at any other locations

IRENE/AP9 (V1.57):

- Time dependency is not provided
- Some uncertainties (unlikely related to solar modulations) in the low region

Development of a new trapped proton model:
geomagnetic field model and observation database

Geomagnetic field description

IGRF

Flux observations

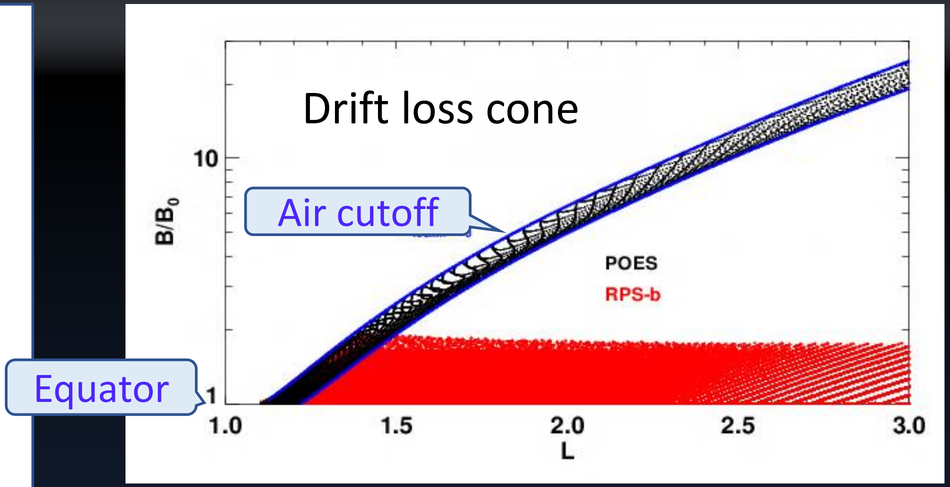
RPS onboard Van Allen Probe (b)

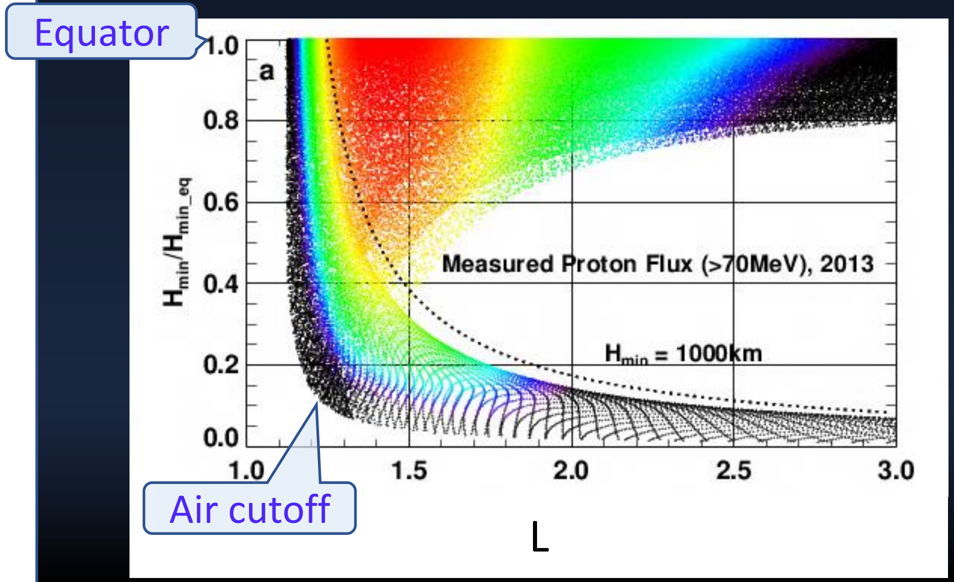
Orbit: highly eccentric, 10.2°, a few hundred km to ~7 times Earth radius
Measurement timing: 2013, 1-minute cadence

SEM2/POES (cross-calibrated to RPS-b)

Orbit: 98°, 840 km;
Measurement timing: yearly averages for 1998-2013

- Coverage of two most interesting regions (the center region and the SAA) with high quality data
- Solar cycle modulation (POES)





Model structure:
essential components: N_0, g and r functions

Model structure: $f\left(E, L, \frac{B}{B_0}(or\ h), s\right) = N_0(E,L) * g\left(E, L, \frac{B}{B_0}(or\ h)\right) * (1 - r(E,h,s))$

H_{min}

Solar activity indicator

Adiabatic

Collisional loss
Violation of adiabatic

N_0: equatorial flux intensity
$N_0(L,E)$

g function: relative flux intensity along the field lines

A: $g_b\left(E, L, \frac{B}{B_0}\right) = J(E,L,B)/J(E,L,B_0)$ (Roederer 1970, Selesnick 2014; Ni 2015)

$$J(E,L,B) = 4\frac{B}{B_0}\int_{\sqrt{1-\frac{B_0}{B_m}}}^{\sqrt{1-\frac{B_0}{B}}} j_0(E,L,cos(\alpha_i))\frac{cos(\alpha_i)}{\sqrt{1-\frac{B}{B_0}(1-cos^2(\alpha_i))}}d(cos(\alpha_i))$$

$$j_0(E,L,cos(\alpha_i)) = j_0(L)(sin(\alpha_i))^{k(E,L)}$$

$cos(\alpha_m)$

B:

$$g_h(E,L,h) = \left(\frac{h - h_m}{h_{eq}(L) - h_m}\right)^{\eta(E,L)}$$

h_m: H_{min} of the drift shell (L, α_m)

particle collisional loss r function

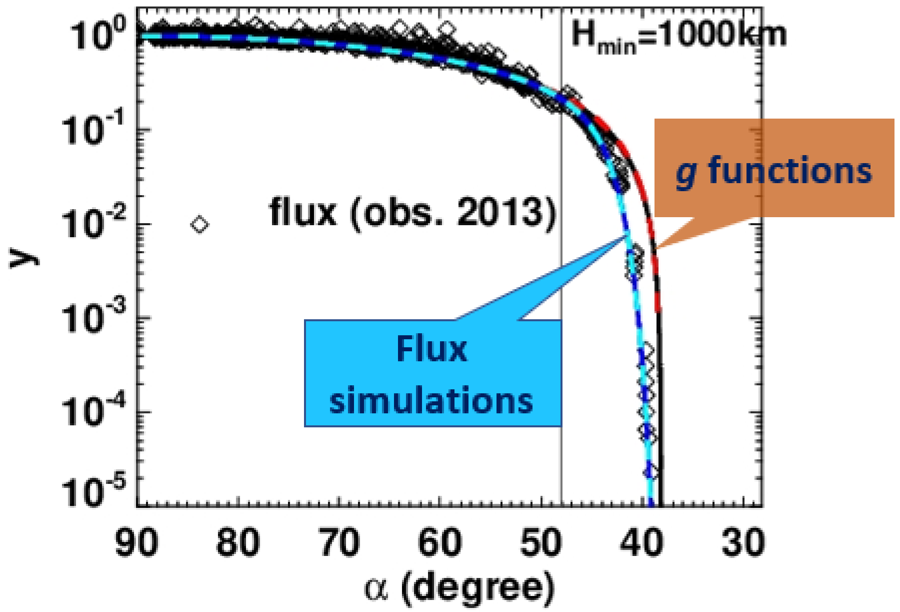
$$r(E,h,s) = 1 - e^{-a*\hat{\rho}(E,h,s)}$$

$$\hat{\rho}(E,h,s) = e^{-[(\frac{h}{z(h,s)})^{b(E)}]}$$

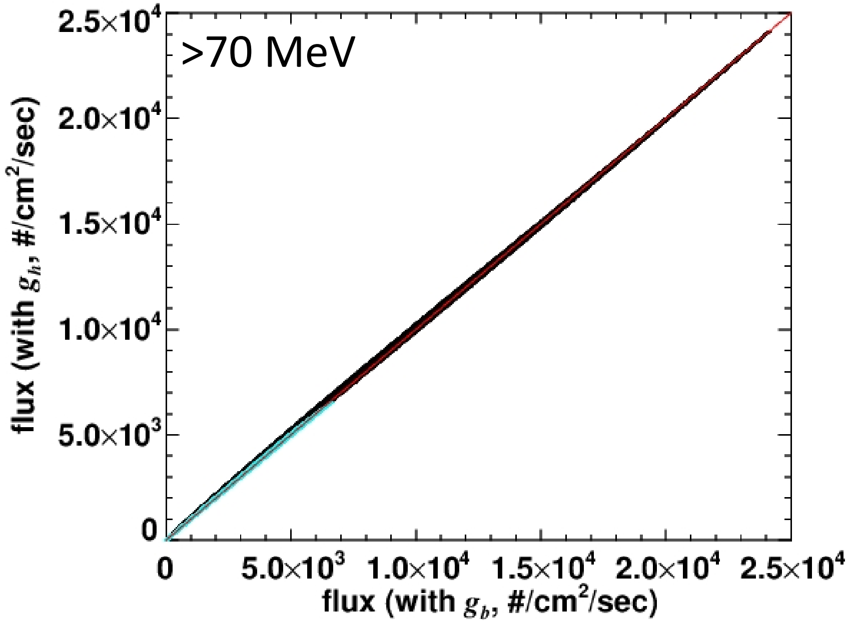
Solar cycle modulation effects ride on the collisional loss function

Regression process:
Close performance of the g functions

Flux intensity (>70 MeV) along the field line (year 2013, L=1.5)

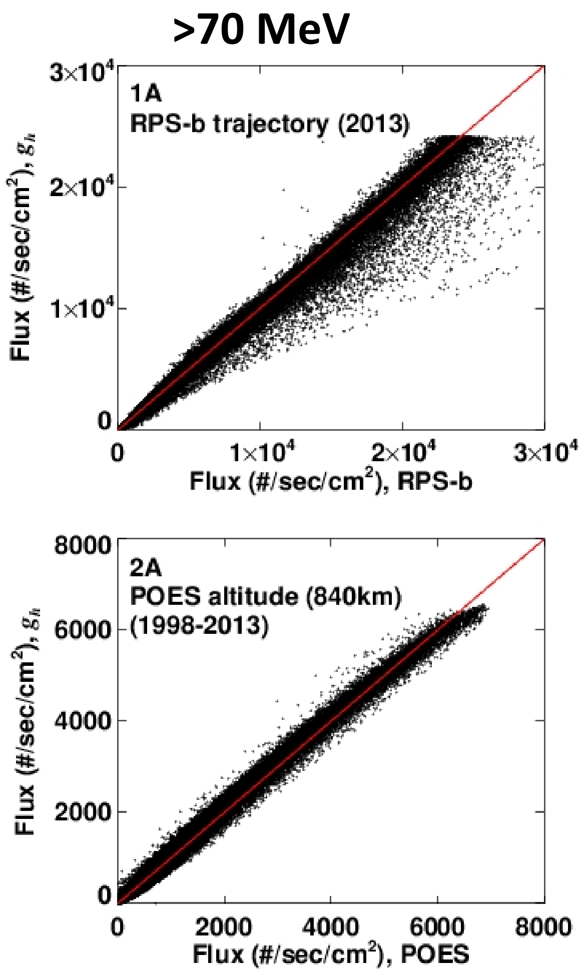


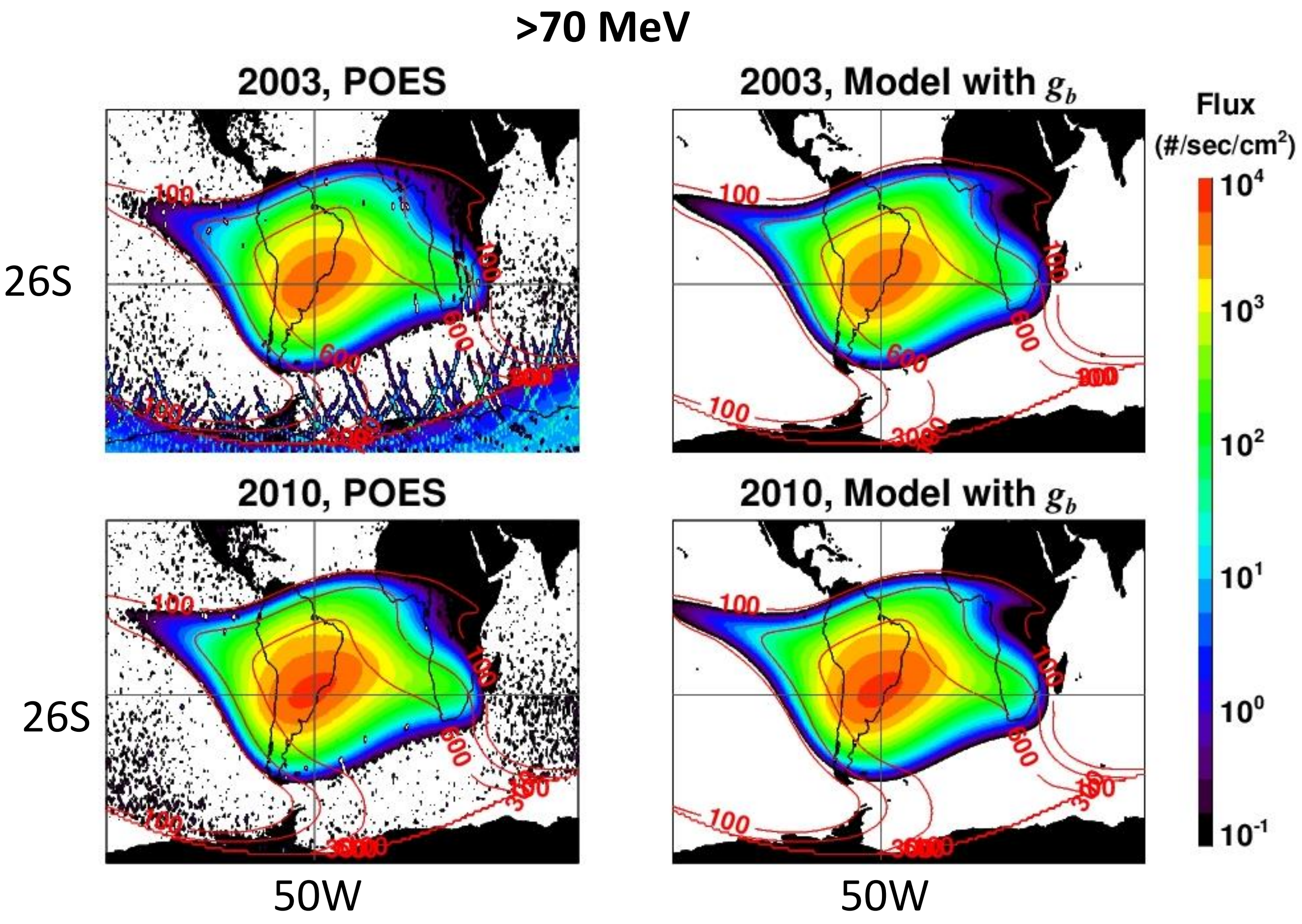
Comparison of the model simulations with the estimation by g_b and g_h functions



- optimized g_b and g_h functions: very close to each other
- model simulations and observations agree well

Model results:
fitting to the observations (1)

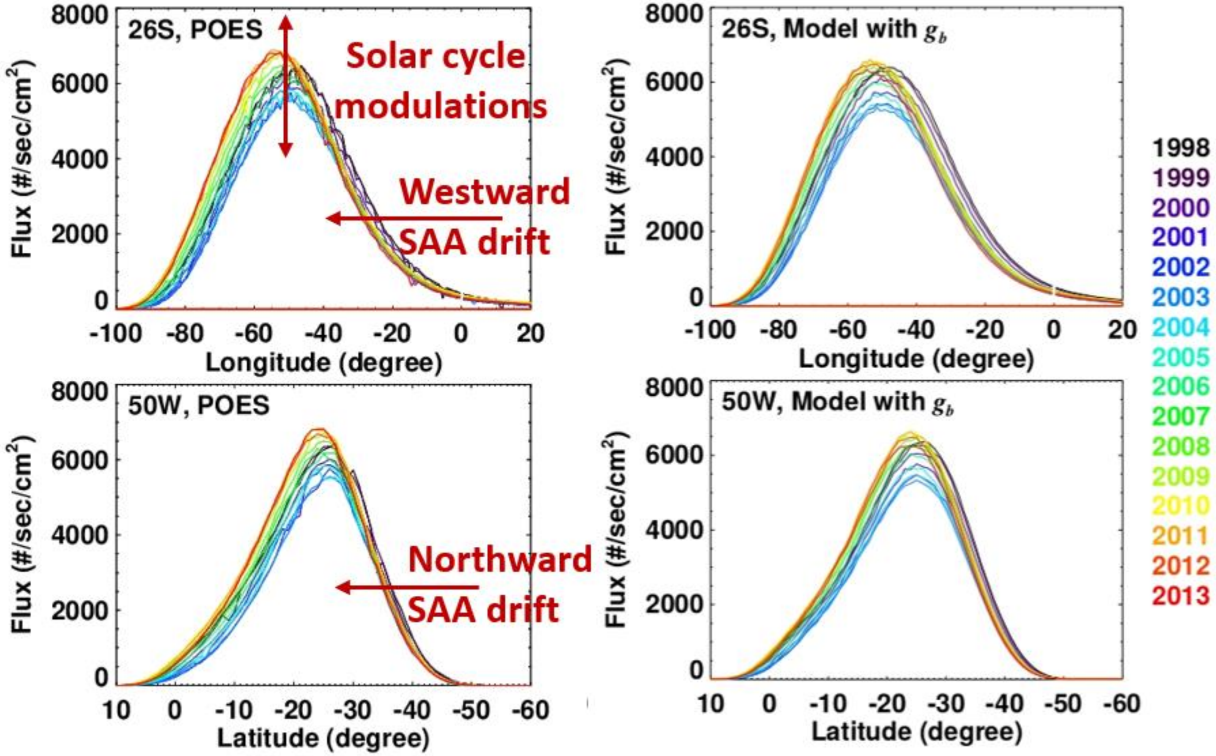




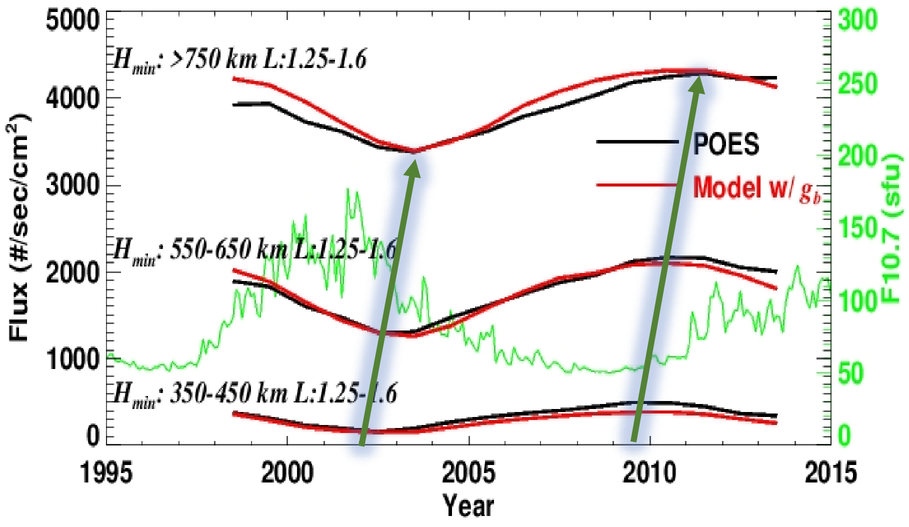
- Model estimations and observations by RPS-b and POES agree well
- Solar cycle modulations well simulated

Model results:
fitting to the observations (2)

Observations **Model Estimations**



Time variations in flux density



- SAA drift and solar cycle modulations are well simulated
- Model's coupling with IGRF is successful

- Solar cycle modulation is well simulated, including the "delayed response" at locations with relatively high H_{min}

Model Validation
time dependency of the environment

Q: How far into the future will the model provide accurate simulations?
A: Estimate by how far back the model can reproduce historical environments.

If the model accurately reproduces the environment 50 years in the past, then we can hypothesize that it should be accurate for predictions 50 years in the future.

Validation of model's time dependence with the environment recorded in AP8

Validation dataset requirement:

- Far enough from model's construction database observation time

AP8:

- Significant variations in the environment since AP8 (1965, 1970)

Difficulties with AP8

- Large uncertainties; coarse spatial resolution
- Cross-calibration between AP8 and model (or RPS-b) cannot be performed

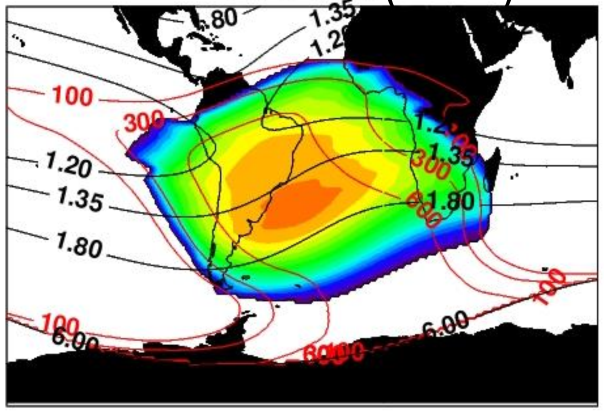
Validations:

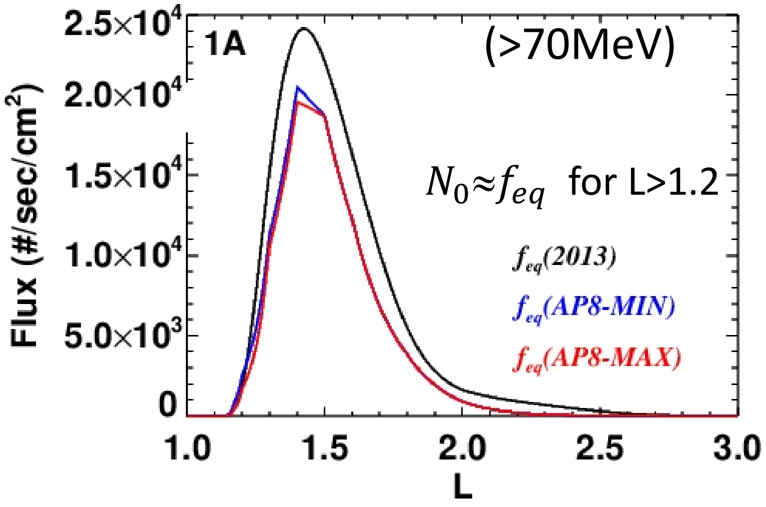
1) N_0

2) Performance of g and r functions, by comparing $\hat{f}$ the relative flux intensity (normalized to f_{eq})

$$\hat{f}\left(L,\frac{B}{B_0},s\right)=\frac{f(L,\frac{B}{B_0},s)}{f_{eq}(L,s)}=\frac{g\left(L,\frac{B}{B_0}\right)*\left(1-r(h,s)\right)}{1-r\left(h_{eq},s\right)}$$

AP8-MIN (840km)





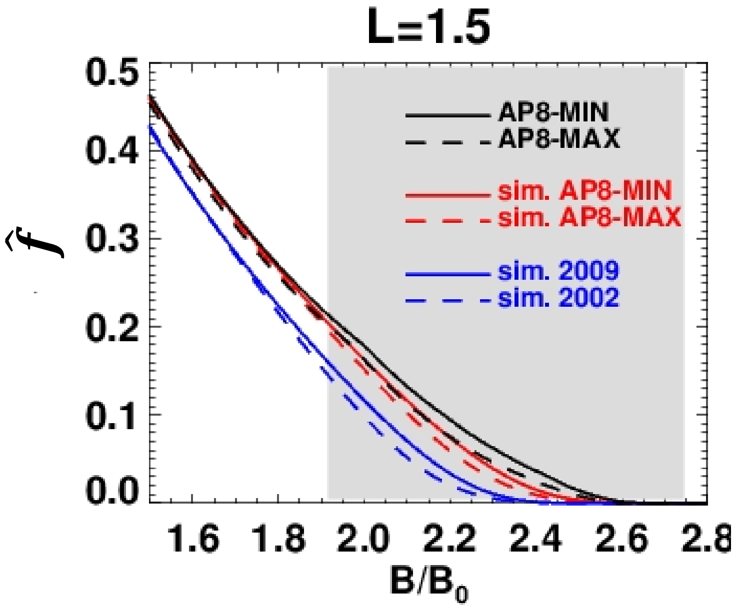
Model validation:
performance of the g and r functions

flux intensity normalized to f_{eq}:

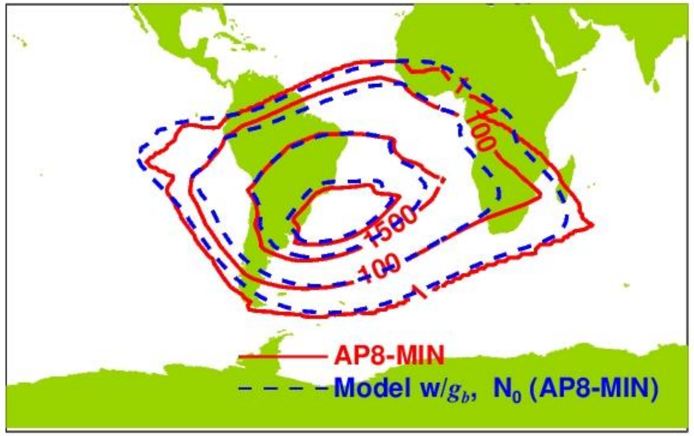
$$\hat{f}\left(L,\frac{B}{B_0},s\right)=\frac{f\left(L,\frac{B}{B_0},s\right)}{f_{eq}(L,s)}=\frac{g\left(L,\frac{B}{B_0}\right)*\left(1-r(h,s)\right)}{1-r\left(h_{eq},s\right)}$$

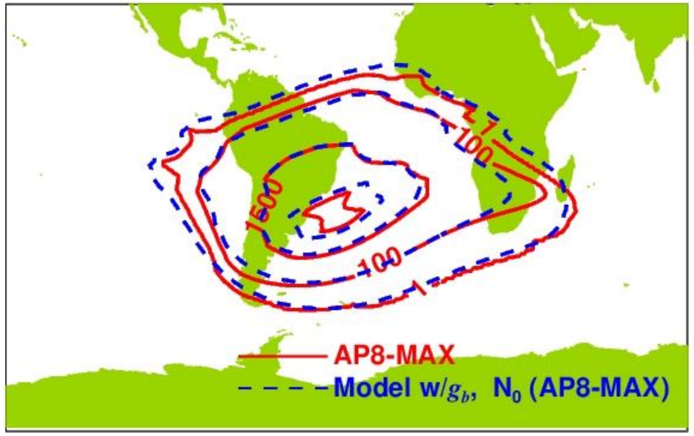
flux intensity with g and r functions and f_{eq} imported from AP8:

$$f_{AP8}\left(L,\frac{B}{B_0},s\right)=\frac{f_{eq}(L,AP8)}{1-r\left(h_{eq},s\right)}*g\left(L,\frac{B}{B_0}\right)*\left(1-r(h,s)\right)$$



840 km, >70MeV



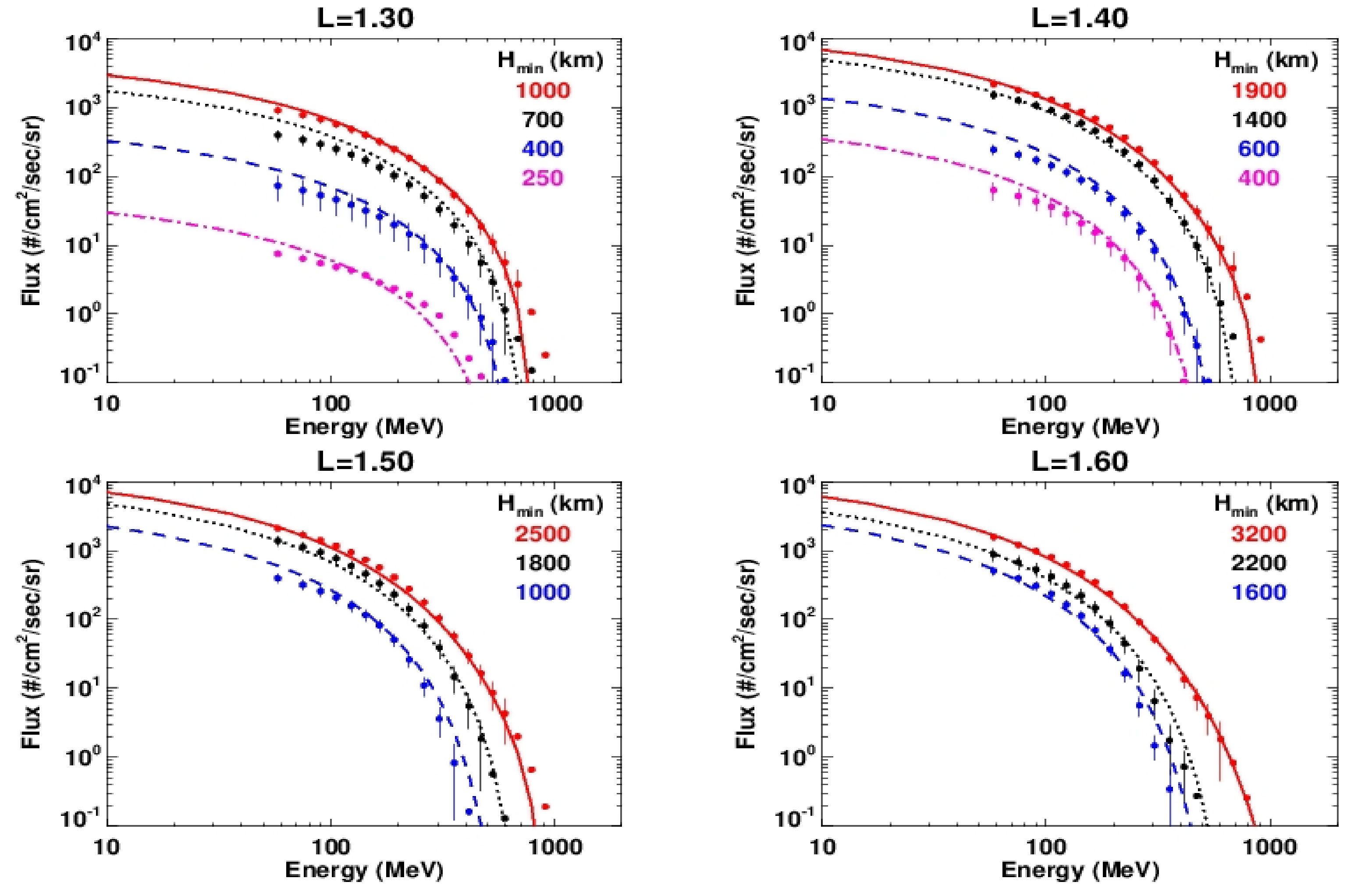


- Significant changes in flux intensity distribution due to geomagnetic field changes since AP8 times
- The variations are well simulated by the *g* and *r* functions.

Model results:

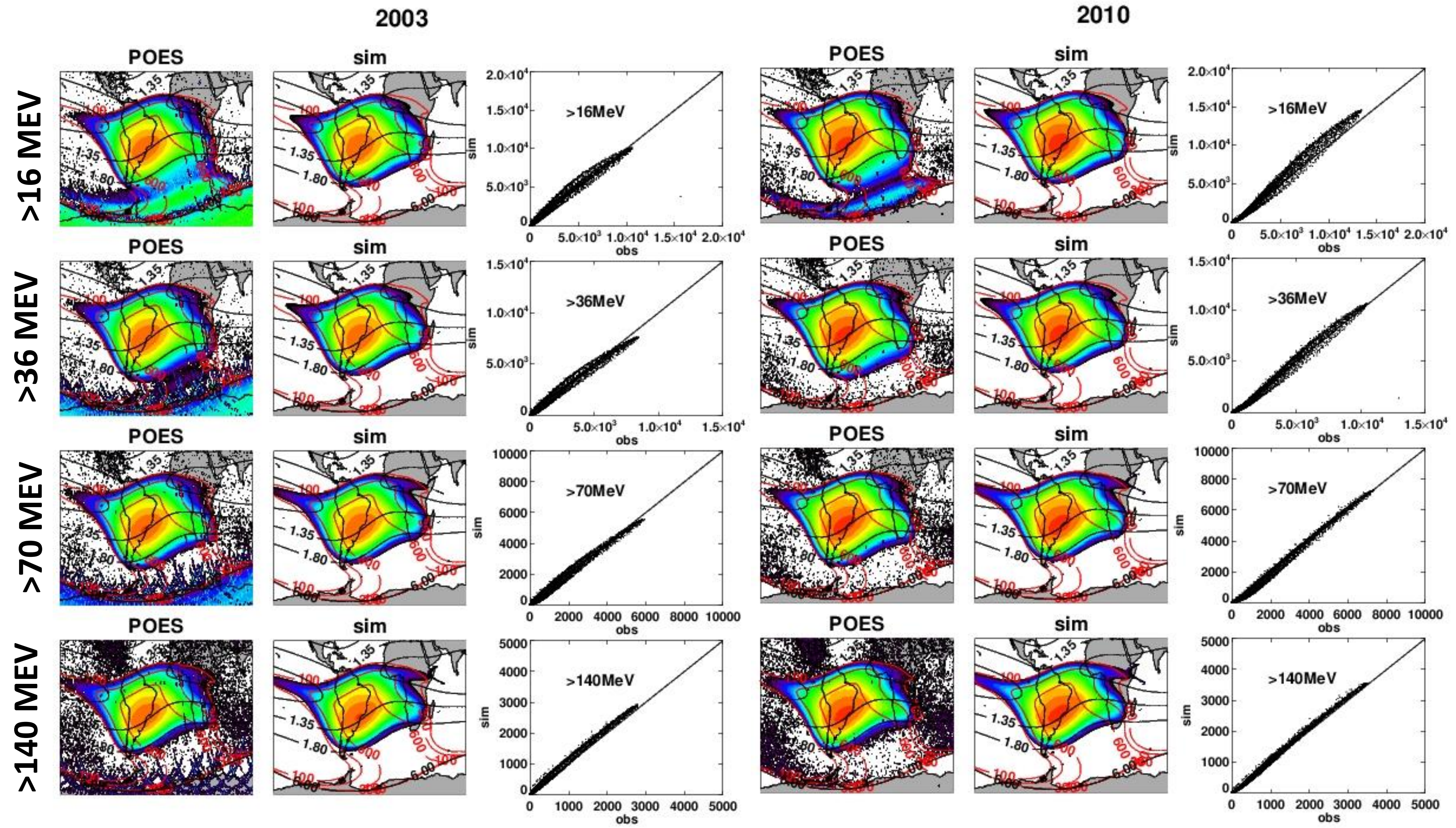
fitting to the energy spectrum observed by RPS-b

Comparison with RSP-b 2013 observations



* Preliminary results

Model results:
fitting to POES observations (4 energy channels)

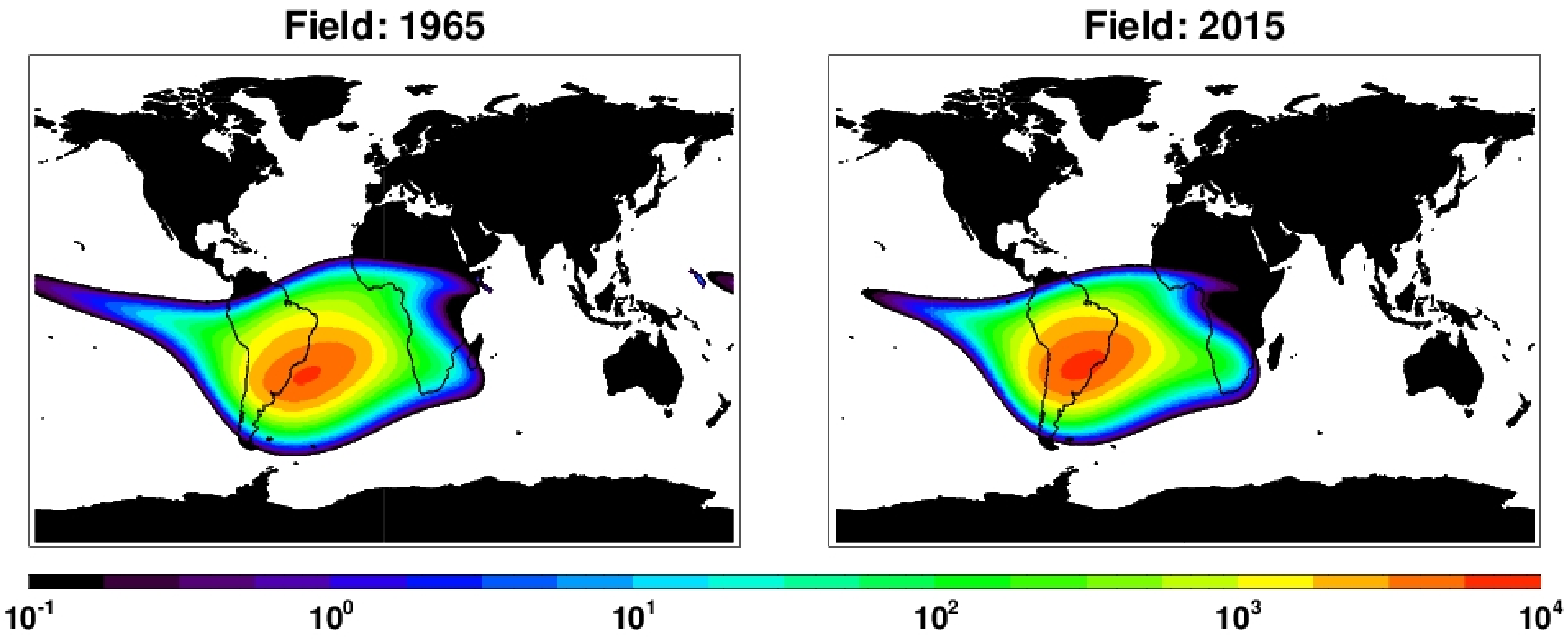


- Larger uncertainties for protons with lower energies, especially at L > 2.0 shells
- Appears to be solar proton injection related

**each energy change has its own color bar to fully use the full color spectrum (preliminary results)*

Discussion:
50 years' changes in SAA

>70MeV proton at 840 km, with a solar minimum modulation as in 1965



- **Drift of SAA toward northwest; decrease in total area**
- **10% increase in the peak flux intensity**
- **5-6% increase in the total flux**

Summary

- **A global dynamic near-earth trapped proton model is developed**

  Energy range: 0.1-1000 MeV; **L range:** 1.0-4.0; **Geomagnetic field: IGRF**

  Three essential components

  - Equatorial flux intensities $N_0(E, L)$
  - The $g(E, L, \alpha)$ functions for the relative flux intensity along the field lines
  - The $r(E, s, h)$ function for particle collisional loss to atmosphere

- **The model simulates well the time variation in the trapped proton environment**

  - AP8 (1965, 1970), POES (1998-2013), RPS-b (2013): 50 years

- **Meet the needs for mission analysis**

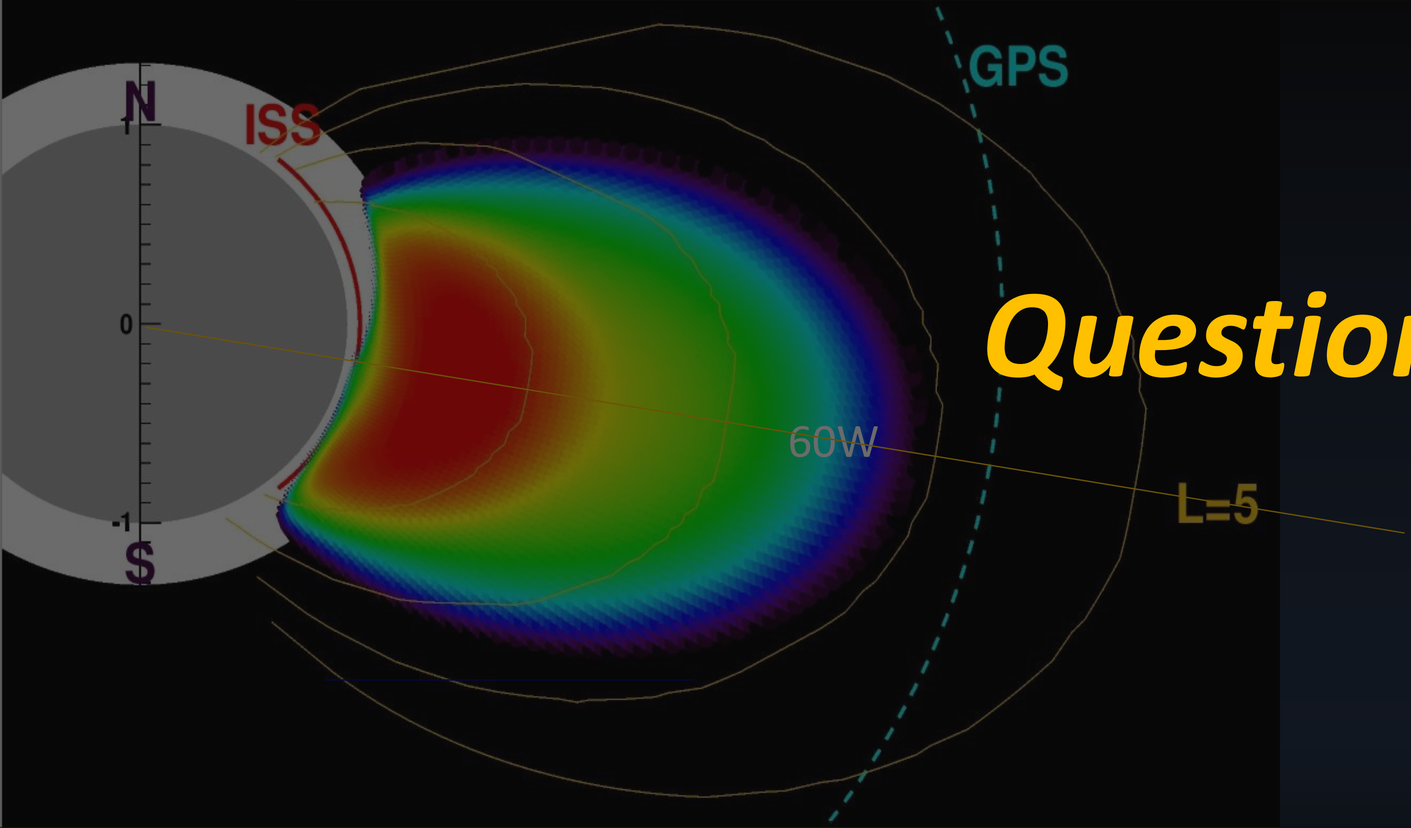
  - predicts spatiotemporal variation of the environment with accuracy over a long-time span

	AP8	AP8-DT	IRENE/AP9	New model
Changing geomagnetic field	No	No	Yes	Yes
Solar cycle modulations	Yes	Yes	No	Yes

- **Future work:**

  - Evaluate model simulated environment with dose measurements inside of ISS and Orion
  - Reduce the model flux uncertainties at L>2.0 shells

A Dynamic Near-Earth Trapped Proton Model for Mission Analysis

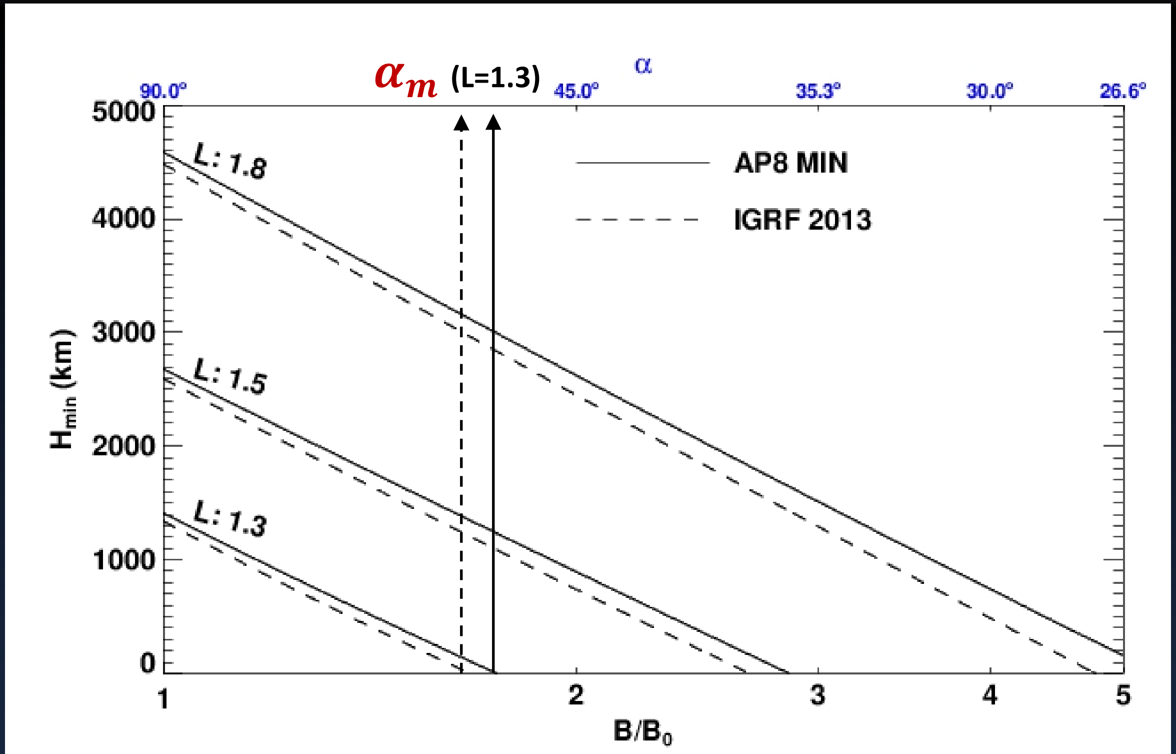


Questions?

A Dynamic Near-Earth Trapped Proton Model for Mission Analysis

Back-up slides

Decreasing trend in H_{min} of drift shells



Model development:
collisional loss to atmosphere

$$r(h,s) = 1 - e^{-a*\hat{\rho}(h,s)}$$
*** reaction rate function based on collision theory

$$\hat{\rho}(h,s) = e^{-[(\frac{h}{z(h,s)})^{b}]}$$
*** scaled air density at satellite altitudes

$z(h,s)$: atmosphere scale height, h is H_{min} of the location

$$z(h,s) = z_1 + z_2 * s(h)$$
*** solar cycle modulation dependency

$$s(h) = \overline{F10.7[(t-m(h))..t]}$$
*** averaged F10.7 over a time of ***m***

$m(h)$: 12 months for $H_{min} \approx 300$ km locations
48 months for $H_{min} \approx 800$ km locations
*** delayed response at higher H_{min} locations

b: fine tuning component

Optimized *k(L)*, *η(L)* and *r(h, s)* for >70 MeV protons