Jet Propulsion Laboratory
California Institute of Technology

Radiation Environment Models used for JPL Space Missions

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June 25, 2019
SEESAW II
Toulouse, France

Information for discussions only.

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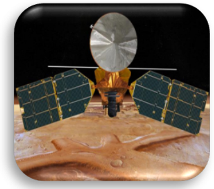
20 Spacecraft and 8 Instruments in Operation Across the Solar System and Beyond


1977
Voyagers 1 & 2


2001
Mars Odyssey


2003
Opportunity


2003
Spitzer


2005
Mars Reconnaissance Orbiter

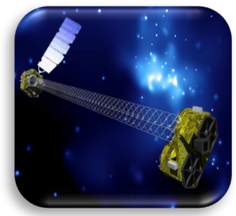

2006
CloudSat


2008
Jason 2

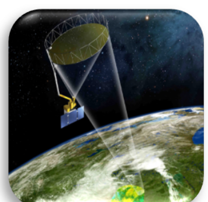

2009
NEOWISE

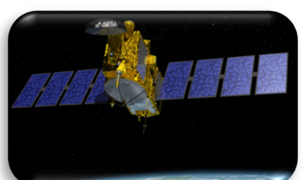

2011
Juno

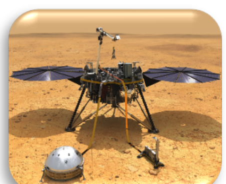

2011
Curiosity


2012
NUSTAR

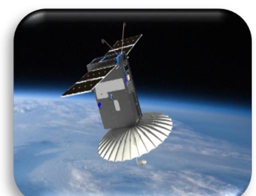

2014
OCO-2

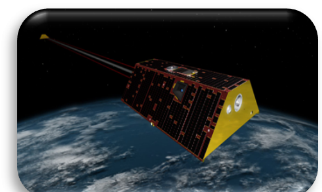

2015
SMAP


2016
Jason 3


2018
InSight


2018
MarCO


2018
RainCube


2018
Grace Follow-On

Instruments

Earth Science

• MISR (1999) • AIRS (2002) • MLS (2004) • ASTER (2009) • OPALS (2014) • ECOSTRESS (2018) • CAL (2018) • OCO-3 (2019)

Planetary

• MARSIS (2003)

JPL Missions

- Robotic Solar System Exploration
  - Mars
  - Outer Planets
    - Gas Giants
    - Ice Giants
    - …
  - Deep Space
    - Asteroids
    - …
- Earth Science
  - Mostly LEO orbits
  - …
- Astrophysics
  - Spitzer
  - WISE
  - Hubble (instrument)
  - JWST (instrument)
  - …
- ….

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- ….

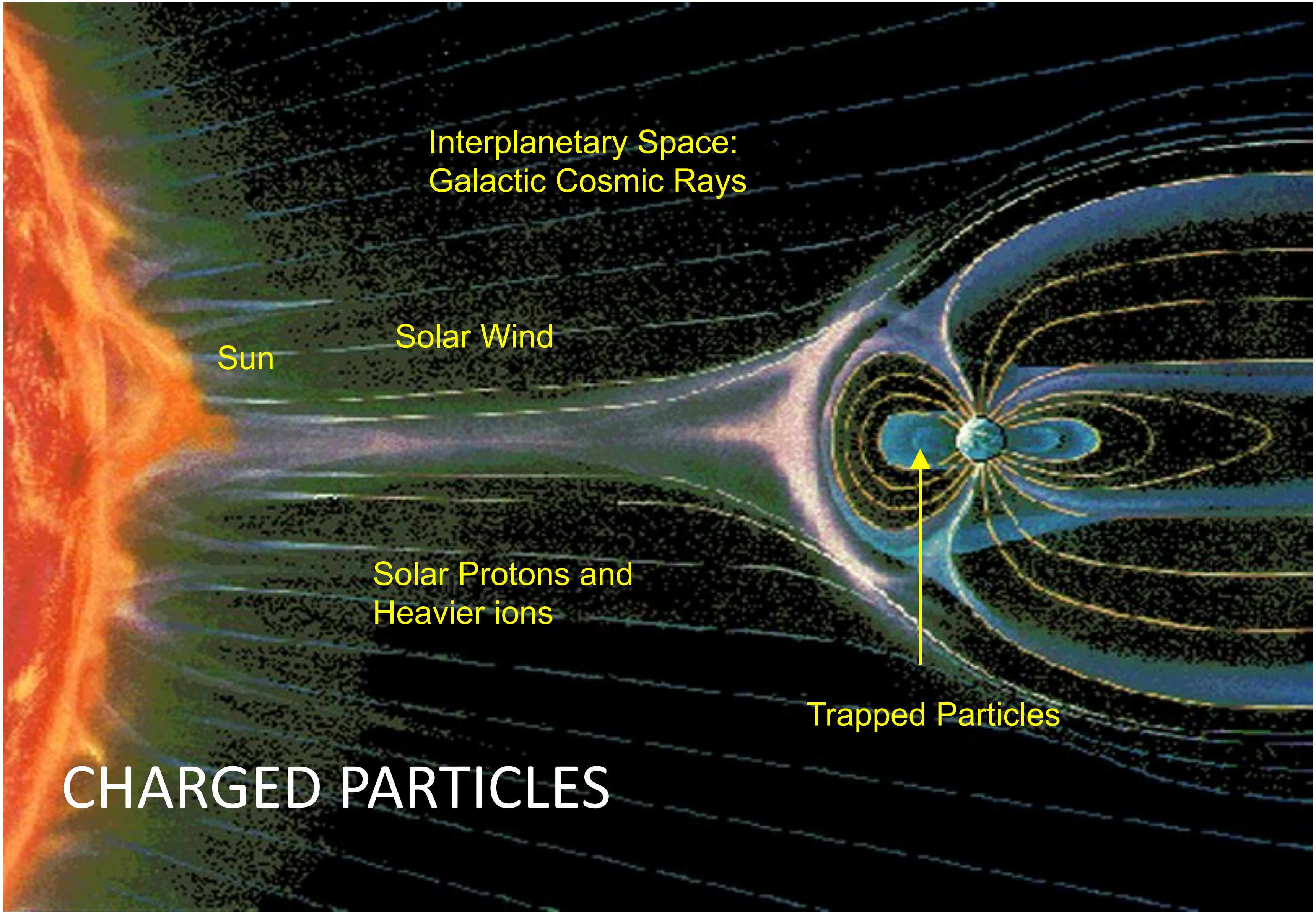
Earth Missions – In Development

Mission	Orbit	Comments
NISAR	Polar sun-synchronous 747 km altitude	Joint mission with ISRO
Seninel-6	66° Inclination 1336 km altitude	Joint mission with CNES
Sphere-X	Low Earth sun-synchronous ? km altitude	
SWOT (Surface Water Ocean Topography)	77.6° Inclination 891 km altitude	

Earth Missions – In Operation

Mission	Orbit	Launch
ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer)	Sun synchronous 705 km altitude	Dec 18, 1999
AIRS (Atmospheric Infrared Sounder)	Polar sun-synchronous 705.3 km altitude	May 4, 2002
Microwave Limb Sounder on Aura	98.7° sun synchronous 705 km altitude	July 15, 2004
CloudSat	98.3° sun synchronous 705 km altitude	April 28, 2006
Jason-2 (OSTM)	66° Inclination 1336 km altitude	June 20, 2008
NEOWISE	sun-synch orbit 525 km	Dec 14, 2009
NuSTAR	6 deg inclination 650 km x 610 km	June 13, 2013
OCO-2	98.3° sun synchronous 700 km altitude	July 2, 2014
SMAP	Polar sun-synchronous 685 km altitude	Jan 31, 2015
Jason-3	66° Inclination 1336 km altitude	Jan 17, 2016
GRACE-FO	Near-circular 89° 490 km altitude	May 22, 2018

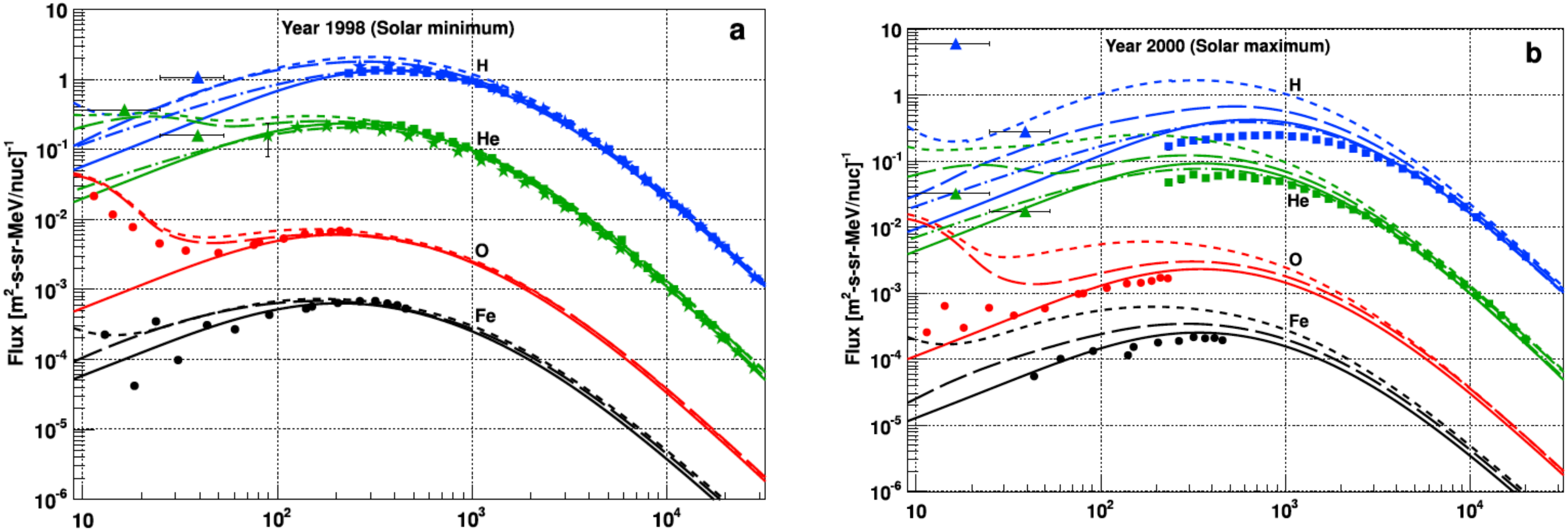
The Space Radiation Environment



Environment Models

Environment	Models (Present)	Models (Future)
GCR	CREME96	?
SEP	JPL	?
Trapped • Earth • Jupiter • Saturn • Uranus • Neptune	 • AE8/AP8 • GIRE3 • SATRAD • UMOD • NMOD	 • ? • ? • ? • ? • ?

GCR Model Comparison



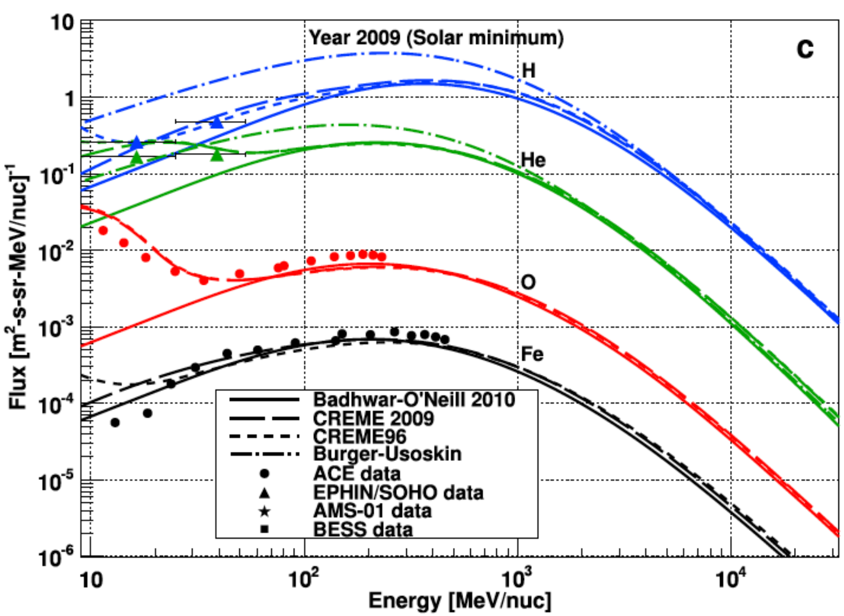


Figure 2. Comparison of H (blue lines), He (green lines), O (red lines) and Fe (black lines) GCR differential energy spectra described by Burger-Usoskin (dotted-dashed lines), CREME96 (dotted lines), CREME2009 (dashed lines) and BON2010 (continuous lines) models with the AMS-01 (solid stars), EPHIN/SOHO (solid triangles), BESS (solid squares) and ACE - SIS and CRIS (solid circles) measurements during different solar activity extremes. (a) The flux distributions for the year 1998 (solar minimum), (b) for the year 2000 (solar maximum), and (c) for the year 2009 (solar minimum).

Mrigakshi et al, JGR 2012

CREME2009 (https://creme.isde.vanderbilt.edu/)

GCR Models – Chi-squared Test

Mrigakshi et al, JGR 2012

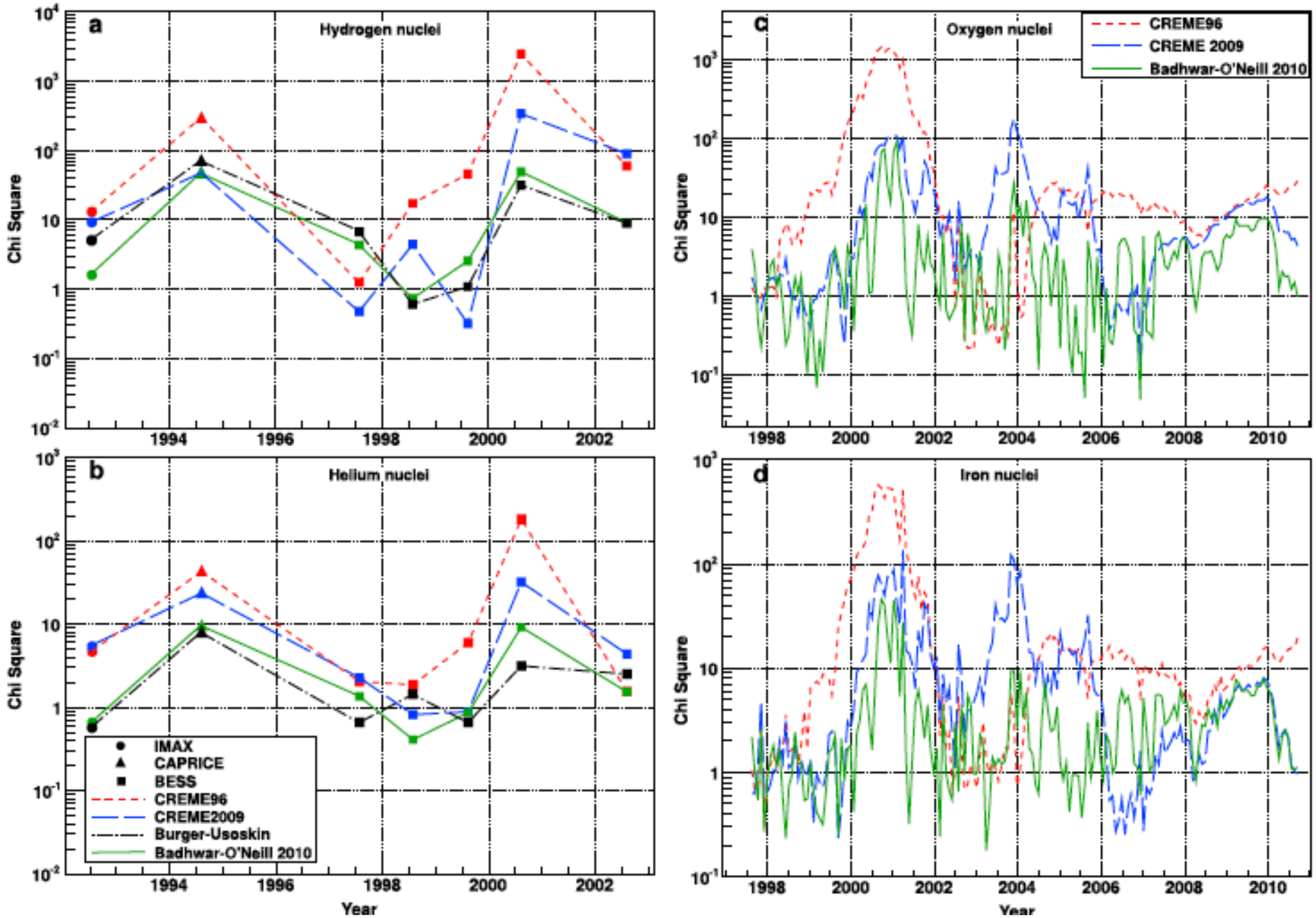


Figure 3. Chi-square to test the capability of Burger-Usoskin (black dashed-dotted lines), CREME96 (red dotted line), CREME2009 (blue dashed line) and BON2010 (green continuous line) models to describe the GCR H, He, O and Fe spectra. It was calculated with respect to the measurements from IMAX (solid circles), CAPRICE-1 (solid triangles) and BESS (solid squares) experiments for GCR H and He particles over an energy range of (a) 210 MeV/nuc to 24 GeV/nuc and (b) 230 MeV/nuc to 24 GeV/nuc. Whereas measurements from ACE/CRIS instrument were used to calculate the chi-squarefor GCR O and Fe particles over an energy range of (c) 80 MeV/nuc to 231 MeV/nuc and (d) 150 MeV/nuc–500 MeV/nuc.

Summary – GCR Model

- As for the GCR environment models, BO-2010 seems most accurate when compared to the measurements over the last decade or so.

- CREME96 still provides most comprehensive tools for practical applications.
  - How about Jim Adams' new SIRE2 tool??
  - Any European tool?

- Planned (or proposed) NASA efforts:
  - Move CREME-MC to the GSFC CCMC website
  - Update the BO model using the latest AMS data

Solar Energetic Particles (SEP)

- Fluence
- Peak Flux
- Heliocentric Radial Dependences
  - Fluence
  - Flux

SEP – Fluence

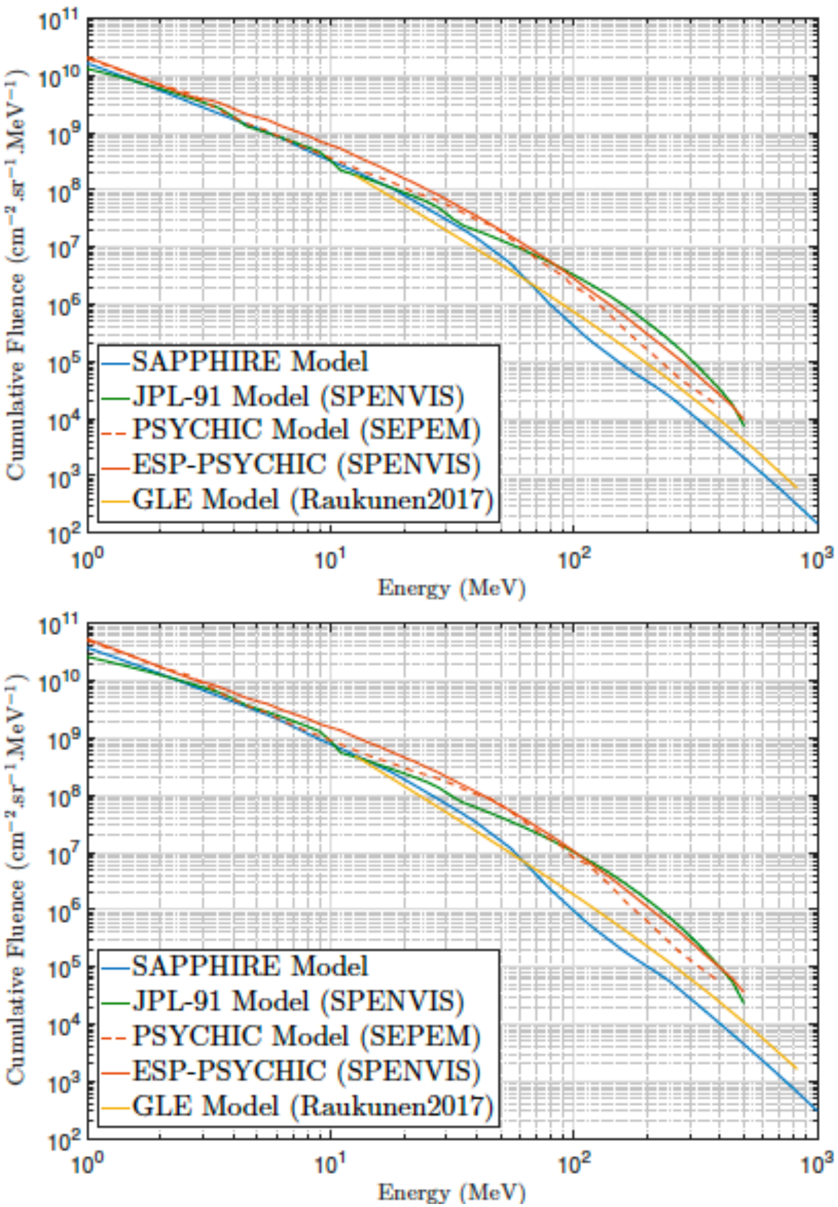


Fig. 12. Comparison of SAPPHIRE, PSYCHIC, JPL and GLE model outputs for a 2-year (top panel) and 7-year (bottom panel) solar proton cumulative fuence environment at a 95% confidence level.

Jiggens et al., Journal of Space Weather and Space Climate, 2018

Also see Jiggens et al., TNS, 2018

discussions only.

SEP – Peak Flux

- Use the CREME96 worst case peak flux models at 1 AU
  - Based on the 1989 October event

- >1 AU missions
  - Use 1/r^2 for fluence
  - Use the CREME96 peak flux at 1 AU for radiation "design"

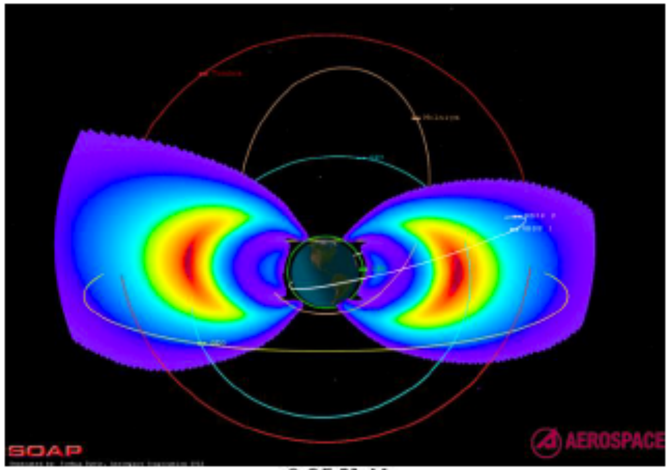
SEP Summary

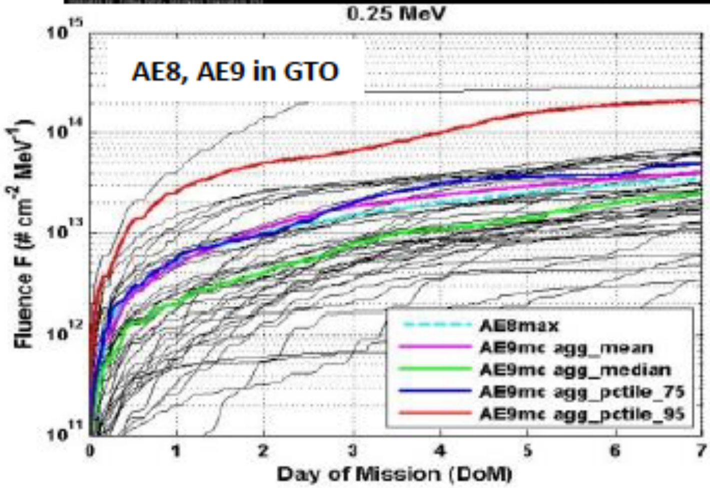
- As far as I know, there is no current study for updating the existing SEP models within USA.
  - SAPPHIRE may be a way to go in the future.
  - But we still see some discrepancies on the model output depending on modeling approaches.

- For JPL robotic missions, we would like to better understand the radial scaling law for both inner and outer solar system missions:
  - Both for fluence and for peak flux.
  - Collaboration with the Barcelona team?

Trapped Particles – AP9/AE9/IRENE

- AP9/AE9/IRENE specifies the natural trapped radiation environment for satellite design and mission planning
  - First released in 2012
  - Most current version: V1.55 (April 2019)
- It much improves on legacy models to meet modern design community needs:
  - Uses 45 long duration, high quality data sets
  - Full energy and spatial coverage – plasma added
  - Introduces data-based uncertainties and statistics for design margins (e.g.,95th percentile)
  - Dynamic scenarios provides worst case estimates for hazards (e.g., SEEs)
  - Architecture supports routine updates, maintainability, third party applications





Courtesy: Paul O'Brien (Aerospace) and Bob Johnston (AFRL)

AE8/AP8 vs. AE9/AP9/IRENE (Version 1.2)

Table 1. Summary of the AE8/AP8 and AE9/AP9/SPM Capabilities[a]

	AE8/AP8 [*Fung*, 1996]	AE9/AP9/SPM Version 1.20.003 [*Ginet et al.*, 2013]
Energy range	E: 0.04 MeV–7 MeV P: 0.1 MeV–400 MeV	E: 1 keV–10 MeV P: 1.15 keV–2 GeV
Spatial range	E: $1.2 < L < 11$ P: $1.15 < L < 6.6$	$0.98 < L^* < 12.4$ for AE9/AP9 (Here L^* is the Roederer's L shell parameter) $2 < L < 10$ for SPM
Data sets	24 satellites from early 1960s to mid-1970s	More than 37 data sets from 1976 to 2011 covering three solar cycles (TacSat-4/CEASE data, Time History of Events and Macroscale Interactions during Substorms/electrostatic analyzer data [*Johnston et al.*, 2014], and VAP RPS templates have been added in addition to Table 3 of Ginet et al.)
Statistics	Averages of solar maximum or minimum	Monte Carlo simulations providing average, mean, and percentiles

[a]"E" and "P" denote electrons and protons, respectively.

De Soria-Santacruz Pich and Jun, Space Weather, 2017

Comparison with Flight Data

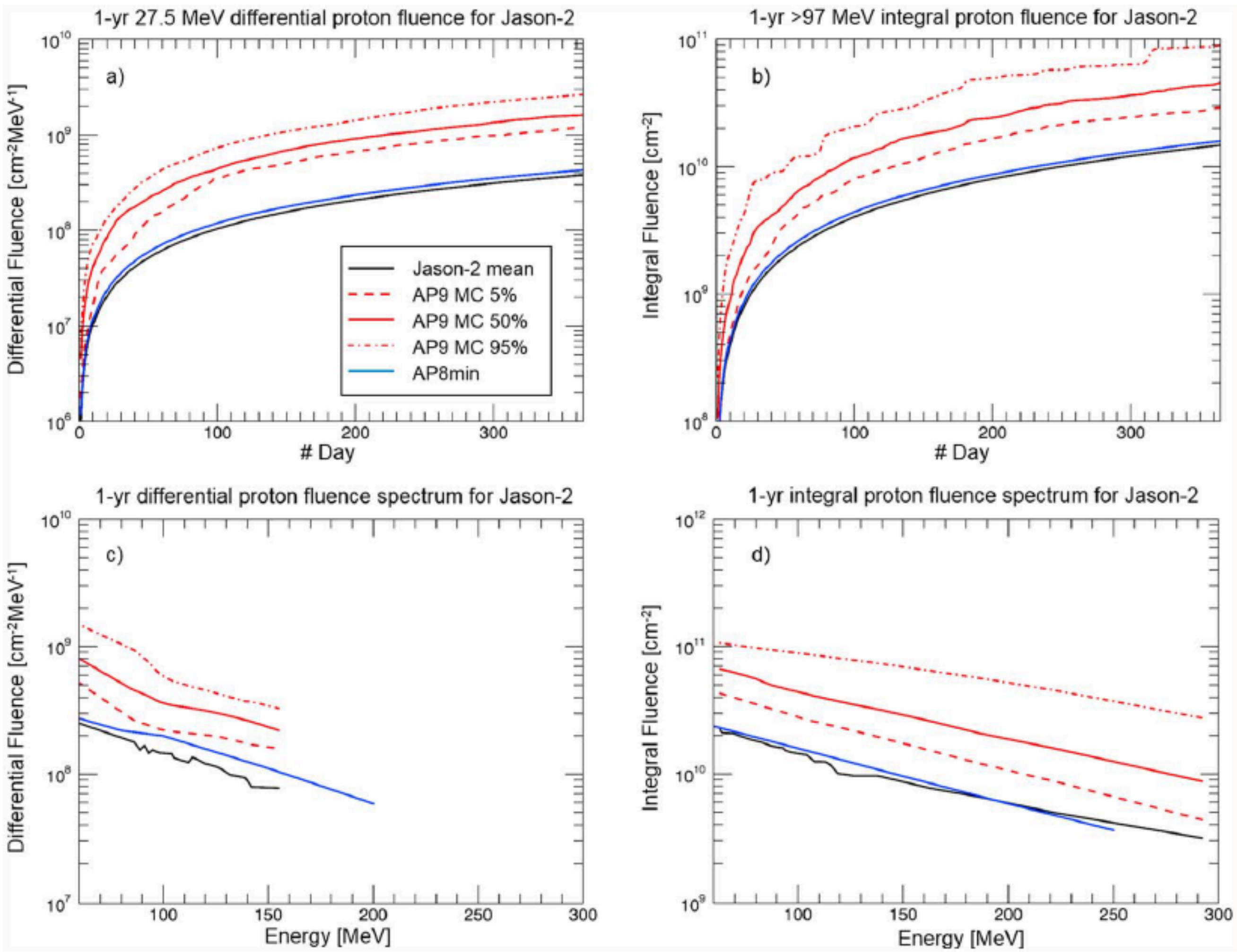


Figure 1. Comparison between Jason-2 proton fluence and the models. The Jason-2 data between June 1998 and June 1999 are used to calculate the cumulative fluence for (a) 27.5 MeV and (b) >97 MeV protons as a function of time. (c) Jason-2 differential channels are used to calculate the differential fluence spectrum. (d) Similarly, Jason-2 integral channels are used to obtain the integral fluence spectrum.

Jason-2: 1336km/66-deg

De Soria-Santacruz Pich and Jun, Space Weather, 2017

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Comparison with Flight Data

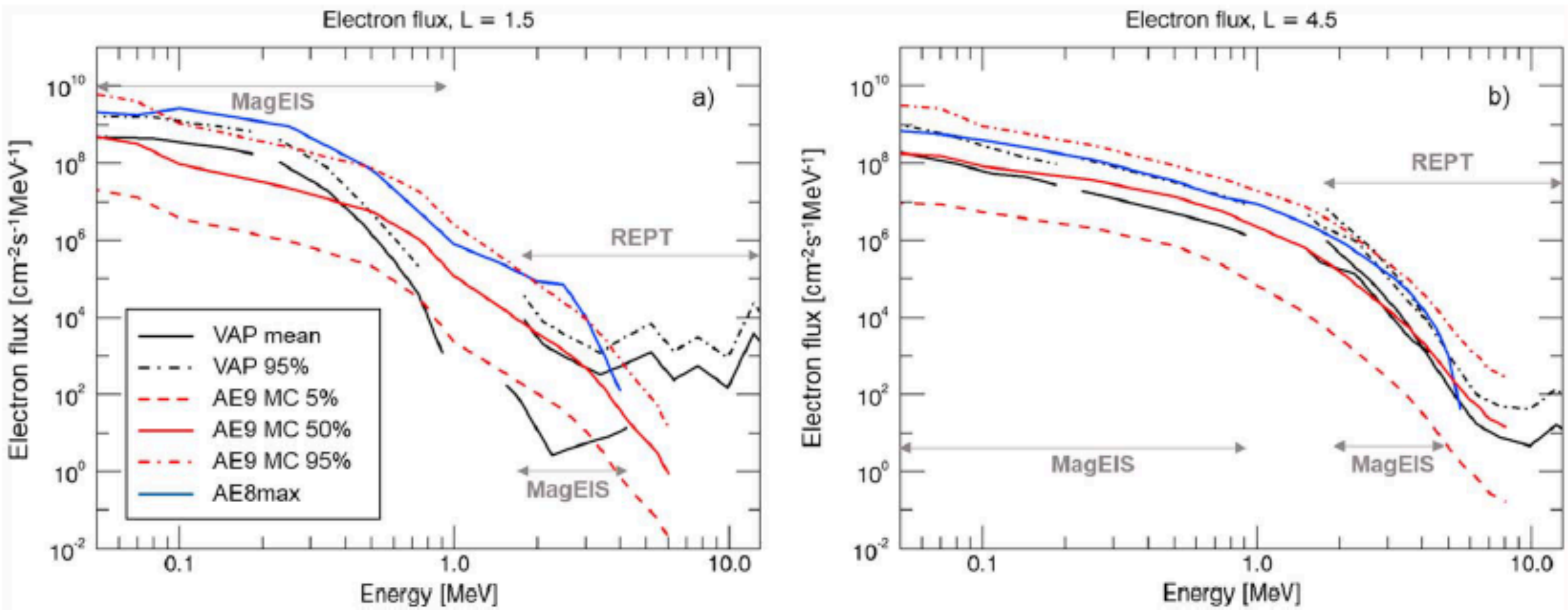
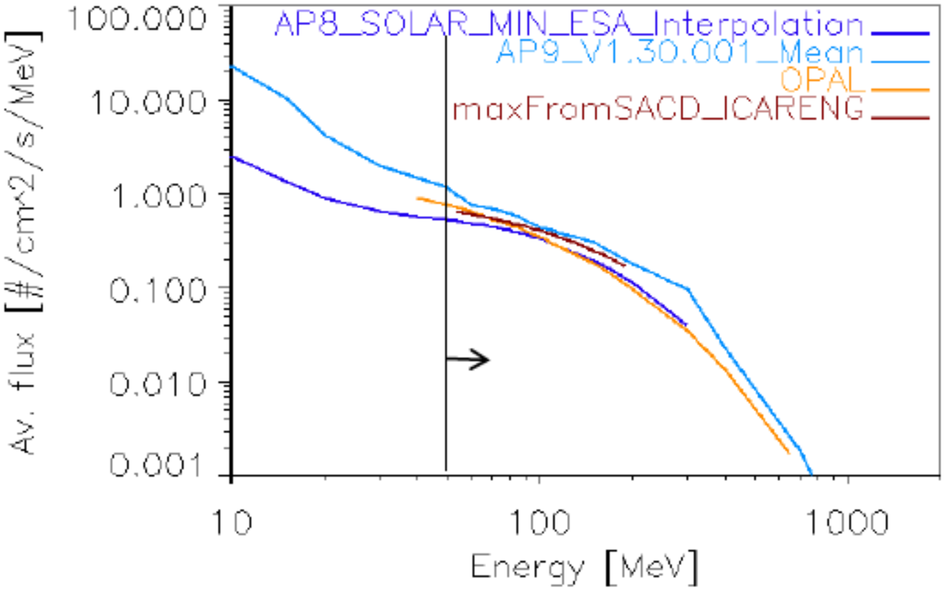


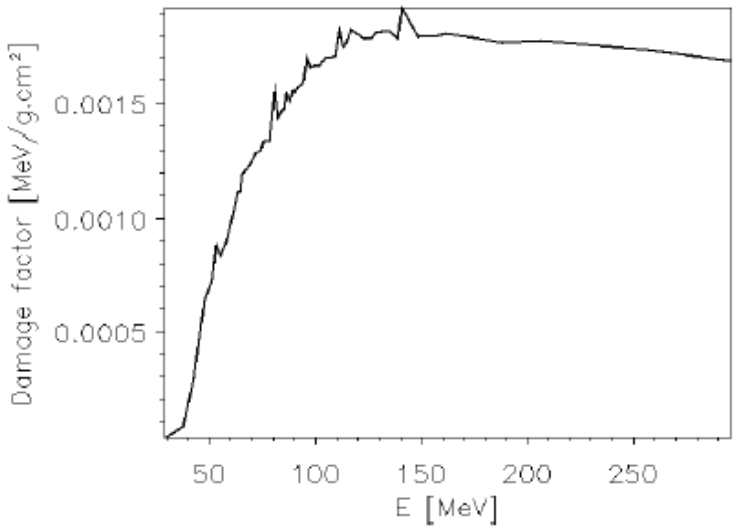
Figure 5. Comparison of electron differential flux spectra between the data from the MagEIS and REPT instruments onboard RBSP-A and the model outputs: (a) at $L = 1.5$ representing the inner belt and (b) at $L = 4.5$ representing the outer belt.

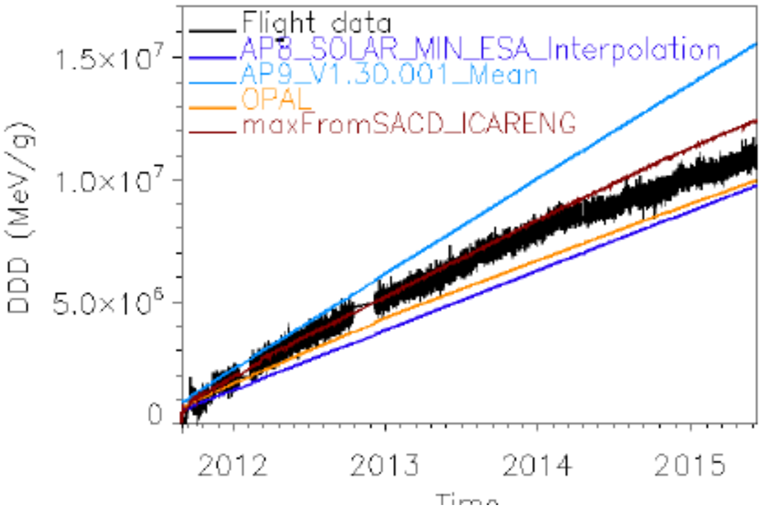
De Soria-Santacruz Pich and Jun, Space Weather, 2017

Comparison with Flight Data

Total displacement damage (DDD) at 660 km altitude (SAC-D, 660 km, 98°)







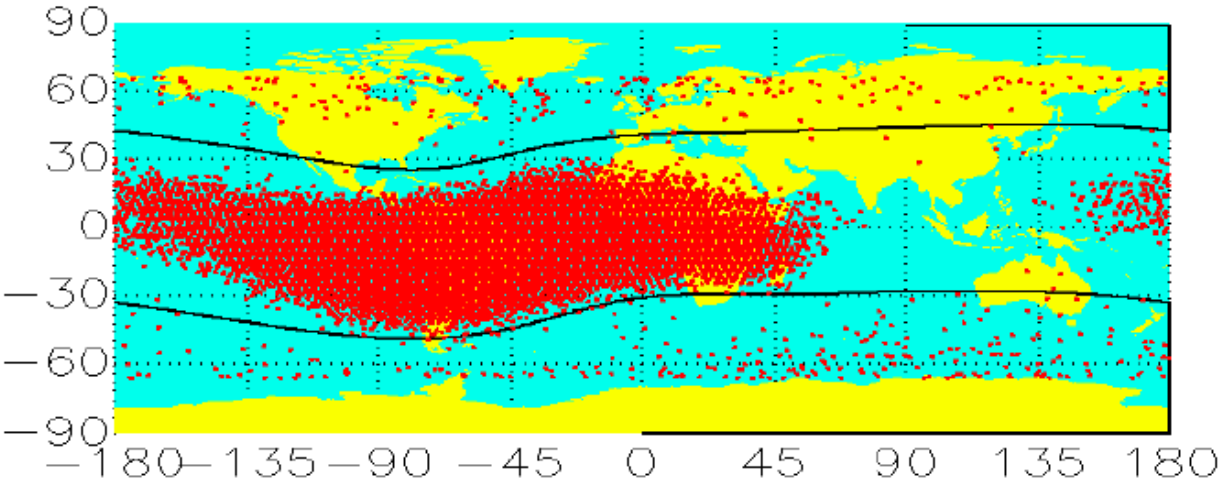
Model / data	Deviation (ratio prediction / flight data)
AP8 min	0.89
AP9 V1.30.001 Mean	1.42
OPAL	0.91
ICARE_NG	1.07

Information for discussions only.

Courtesy: S. Bourdarie, ONERA

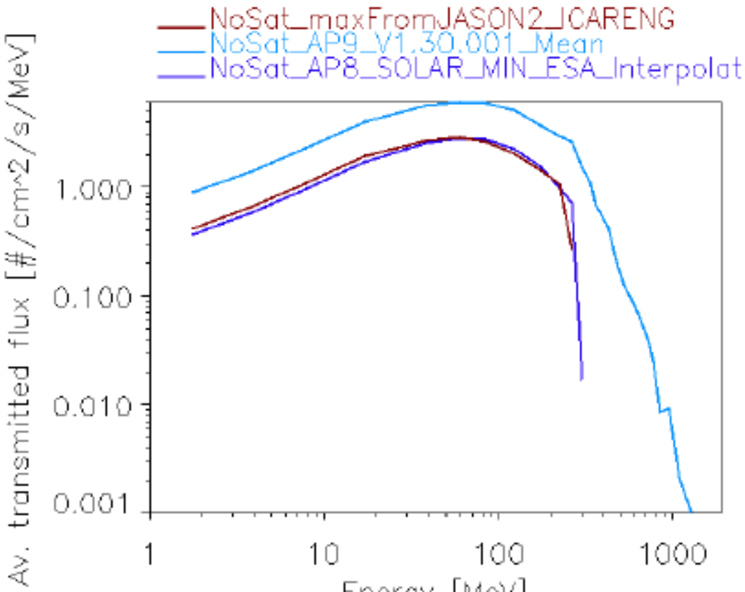
Comparison with Flight Data

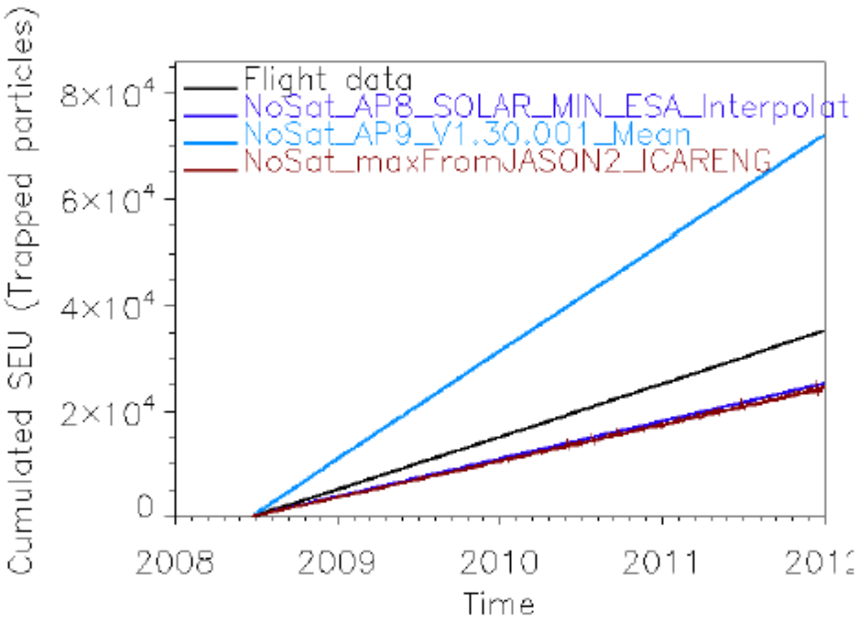
SEU rate from EDAC counter at 1336 km altitude (JASON-2, 1336 km, 63°)



L*<1.9 ⇒ 98.8%
L*>1.9 ⇒ 1.2%

10 SRAM (1MB SRAM M65608, 0.5µm CMOS process, developed by ATMEL)





2.10

0.72
0.70

Information for discussions only.

Courtesy: S. Bourdarie, ONERA

Summary -- Trapped Particles Model

- AP9/AE9/IRENE is a major step forward in describing the Earth trapped radiation environment
- However, there still exist some discrepancies when compared to flight data
  - Especially, LEO and slot region
- Continuous improvement is needed
  - More flight data would be valuable to improve the model

Environment Models

Environment	Models (Present)	Models (Future)
GCR	CREME96	?
SEP	JPL	SAPPHIRE (?)
Trapped • Earth • Jupiter • Saturn • Uranus • Neptune	 • AE8/AP8 • GIRE3 • SATRAD • UMOD • NMOD	 • AE9/AP9/IRENE (*) • GIRE4 with Juno data (+) • • •

(*)

- Continue to validate against on-orbit data – comparison between more of Jason-2/3 data and the latest AP9/AE9/IRENE version
- Will be used for selected missions (e.g., GEO)
- Waiting for community's acceptance based on wider and more comprehensive validation effort

(+)

- Just started working on noise background data available in PDS

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Summary

- Many models are being used to ensure adequate radiation design for space missions
- JPL is very interested in contributing in improving the existing models
  - Will eventually adopt new models
  - In the meantime, we are doing our due diligence to make sure we understand limitations and applicability of those new models
- Proper understanding of capabilities and limitations of those models is critical
  - Models and tools are continuously being updated with more in-flight data or through data assimilations
  - Validation and verification are important steps before using them for spacecraft design
- Open and sufficiently frequent communications within the (international) community is also important
  - Data sharing?

Thank You

Questions?

By the way, JPL is developing a new Web interface to run JPL environment models