Jet Propulsion Laboratory
California Institute of Technology

The Solar Particle Radiation Environment Requirements for JPL's Robotic Space Missions

Presented by Insoo Jun on behalf of

Natural Space Environments Group
Jet Propulsion Laboratory, California Institute of Technology

January 11, 2017

SPE Storm Shelter Meeting at LaRC

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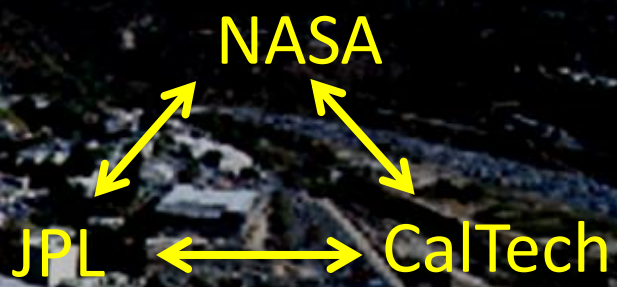
Topics

- Introduction toJPL and Natural Space Environments (NSE) Group
- JPL Missions
- Examples of Radiation Environments
  - Dose-depth curves for several missions to different targets
- JPL Solar Proton Model
- JPL Solar Proton Environment Specification for Missions

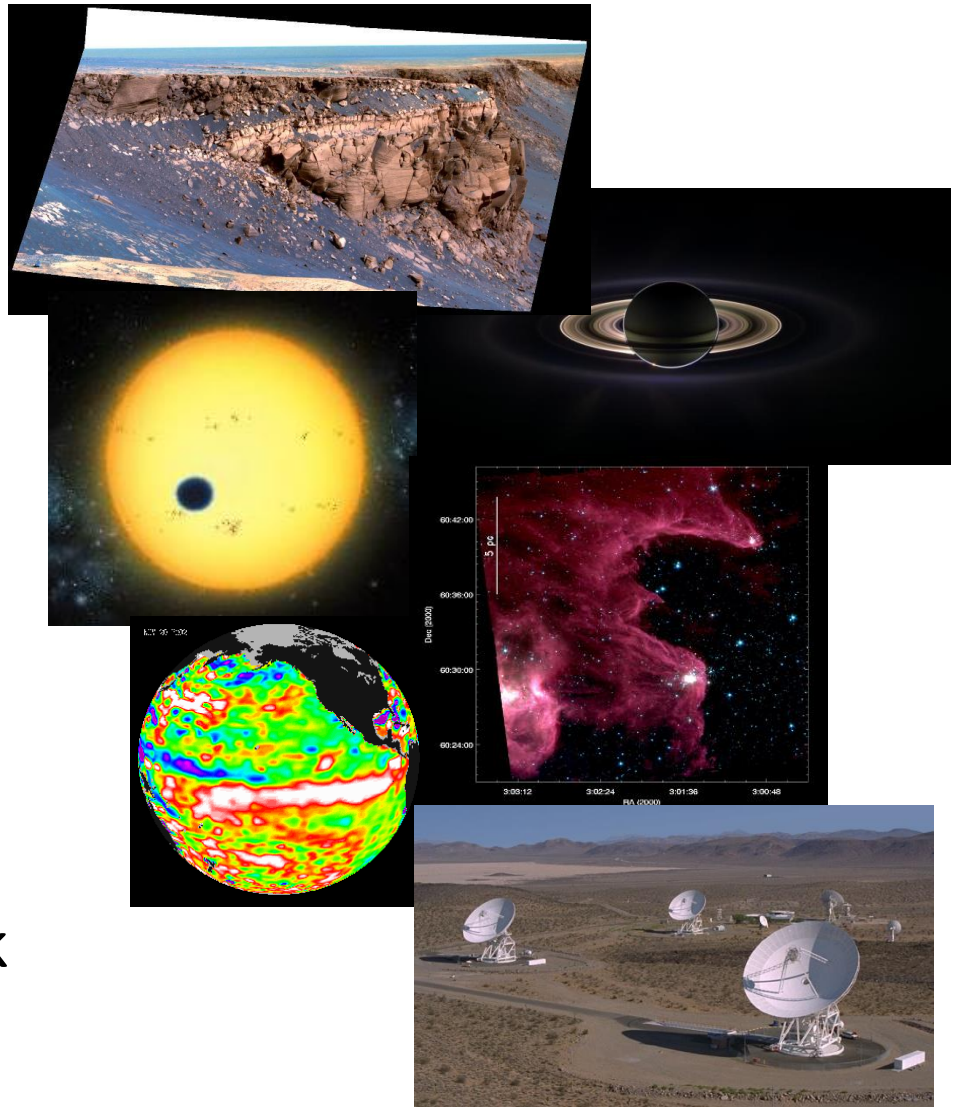
JPL is part of NASA and Caltech

- Federally (NASA)-owned "Federally-Funded Research and Development Center" (FFRDC)
- University (Caltech)-operated
- ~$2 billion business base
- >5,000 employees
- 177 acres (Includes 22 acres leased for parking)
- 139 buildings and 36 trailers
- 673,000 net square feet of office space
- 906,000 net square feet of non-office space (e.g., labs)



JPL's primary mission for NASA is robotic space exploration

- Mars
- Solar system
- Exoplanets
- Astrophysics
- Earth Science
- Interplanetary network



End-to-End Implementation

JPL's core competency is the end-to-end implementation of unprecedented robotic space missions. To sustain this skill, we develop and integrate some of the world's best capabilities in science, technology, and engineering on missions in all cost ranges. We do this by using our hands-on, experienced workforce and in partnership with other organizations.

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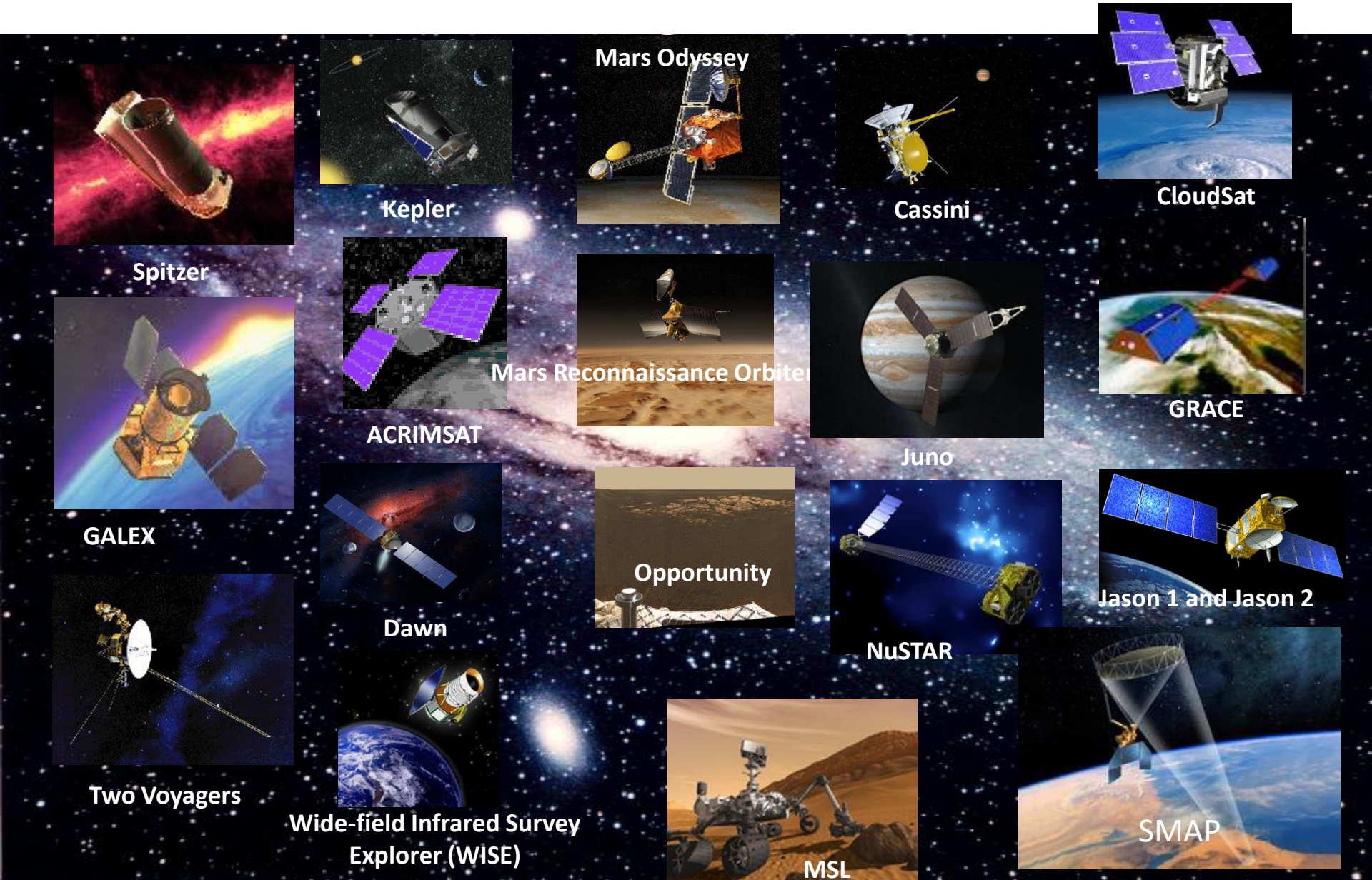
A Very Special Place.

Thirty-two spacecraft and instruments across the solar system (and beyond) – as of 2015



As of June 2016

	Projects	Launch Date	7120.X (5,8)	Classification (A,B,C,D,U)	Category	SMA TA (Y/N/*)	Project Type (I,II,III)
Development	COSMIC-2 (Air Force)	Aug 2015	N/A	B		Y	I
	Euclid	3/1/2020	5	B	1	Y	I
	Europa	5/1/2022	5	B	1	Y	I
	Grace Follow On	12/1/2017	5	C	2	Y	I
	InSight	5/1/2018	5	B	2	Y	I
	Interferometric SAR (NI-SAR) [Formally DESDyni (Deformation, Ecosystem Structure and Dynamics of Ice)]	9/29/2020	5	C	2	Y	I
	JUICE RIME	June 2022	5	B	1	Y	I
	Mars 2020	7/16/2020	5	B	1	Y	I
	MIRI (on JWST)	11/1/2018	5	B	2	Y	I
	OCO 3 (Space Station)	7/6/2016	5	C		Y	I
	RBI (Radiation Budget Instrument)	Nov. 2021	5	B	1	Y	I
	SWOT	4/1/2021	5	C	2	Y	I
	WFirst	8/1/2024	5	B	2	Y	I
	Sentinel-6 (Jason-CS)		5	B	2	Y	I
	CAL (Space Station)	4/1/2017	5	D	3	Y	II
	COWVR (Air Force)	2/17/2016	N/A	D		Y	II
	Deep Space Atomic Clock (DSAC)	3/1/2017	8	D	3	Y	II
	ECOSTRESS (Space Station)	8/4/2017	5	D	3	Y	II
	SAM		8	D			III
	AOSP Blue	N/A	N/A	-	-	Y	N/A
	AOSP Brown	N/A	N/A	-	-	Y	N/A
	ARRM	12/1/2021				Y	

As of June 2016

Operations	Jason-3	1/17/2016	5	B	2	Y	I
	OCO 2 Orbiting Carbon Observatory Reflight	7/2/2014	5	C		Y	I
	SMAP (Soil Moisture Active Passive)	11/5/2014	5	C		Y	I
	ST7-DRS	12/2/2015		B	3	Y	I
	TGO Electra (Heritage with MSL, MRO, MTO and Maven)	1/16/2016	5	B	2	Y	I
	AIRS on Aqua	5/4/2002	5	B		Y	I
	Cassini-Huygens	10/15/1997	5	A		Y	I
	CloudSat	4/28/2006	5	C		Y	I
	Dawn	9/27/2007	5	B		Y	I
	GRACE (Gravity Recovery and Climate Experiment Project)	3/17/2002	5	C		Y	I
	Juno MOAM (New Frontiers 1)	8/5/2011	5	B		Y	I
	Mars Exploration Rover	6/10/2003	5	B		Y	I
	Mars Odyssey MOAM (2001)	4/7/2001	5	B		Y	I
	Mars Reconnaissance Orbiter	8/12/2005	5	B		Y	I
	MISR on Terra	12/18/1999	5	B		Y	I
	MLS instrument on Aura	7/15/2004	5	B		Y	I
	MSL	11/26/2011	5	B		Y	I
	Near Earth Object Widefield Infrared Survery Explorer (NEOWISE)	12/9/2009	5	C		Y	I
	Nuclear Spectroscopic Telescope Array (NuSTAR)	6/13/2012	5	D		Y	I
	OSTM/Jason-2	6/20/2008	5	B		Y	I
	Spitzer Space Telescope	8/25/2003	5	B		Y	I
	TES on Aura	7/15/2004	5	B		Y	I
	US Rosetta	3/2/2004	5	B		Y	I
	Voyager	8/20/1977	5	A		Y	I
	RapidScat (7120.8)	6/6/2014	8	U		N*	II

JPL's Natural Space Environment Group

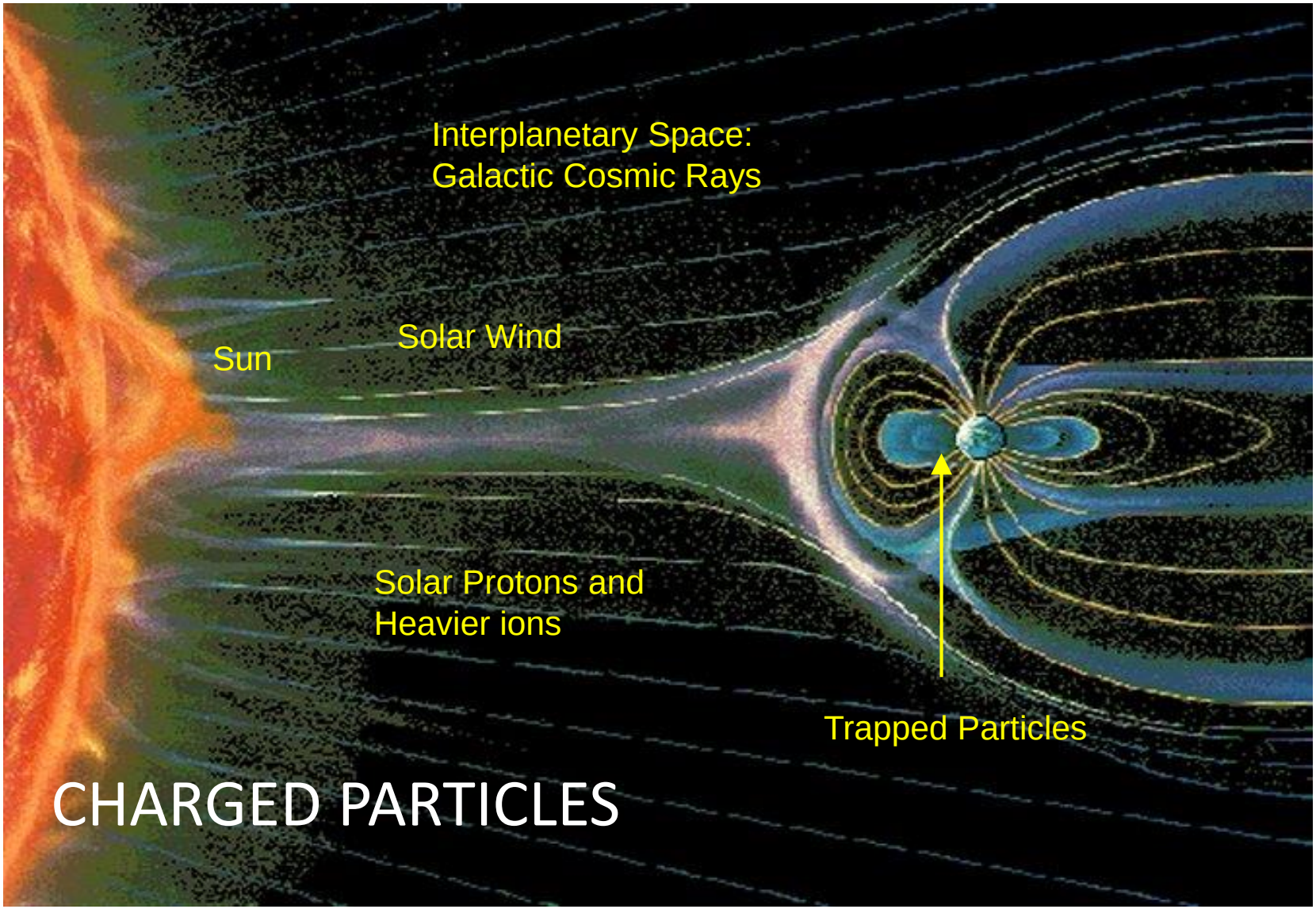
- Supports all JPL flight missions for the space environments and effects area
  - Radiation (environment, shielding, charging, ….),
  - MMOD
  - Space weather
  - Atomic Oxygen, etc.

- Is responsible for developing and maintaining the radiation environment models for planetary missions (Mars, Jupiter, Saturn, etc.)

- Is responsible for evaluating other radiation environment models available in the community (e.g., AP9/AE9, Solar proton models) and adopting for JPL missions

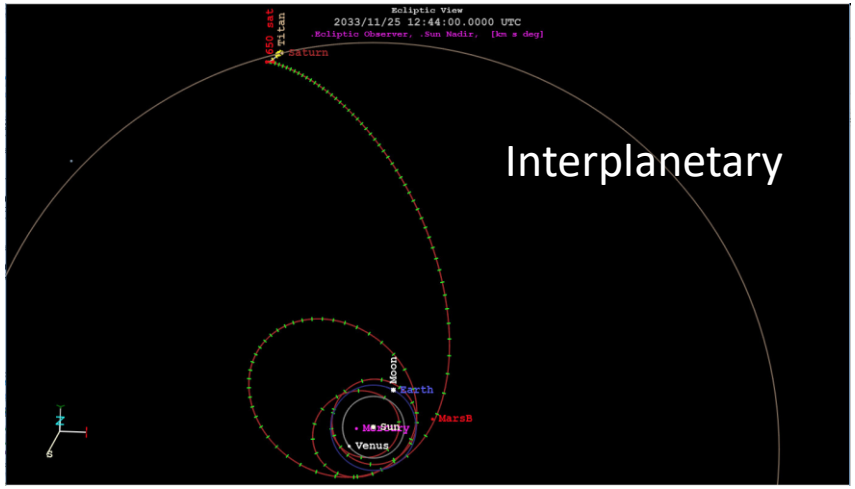
- Is the JPL lead for nuclear planetology
  - Gamma ray and neutron spectroscopy

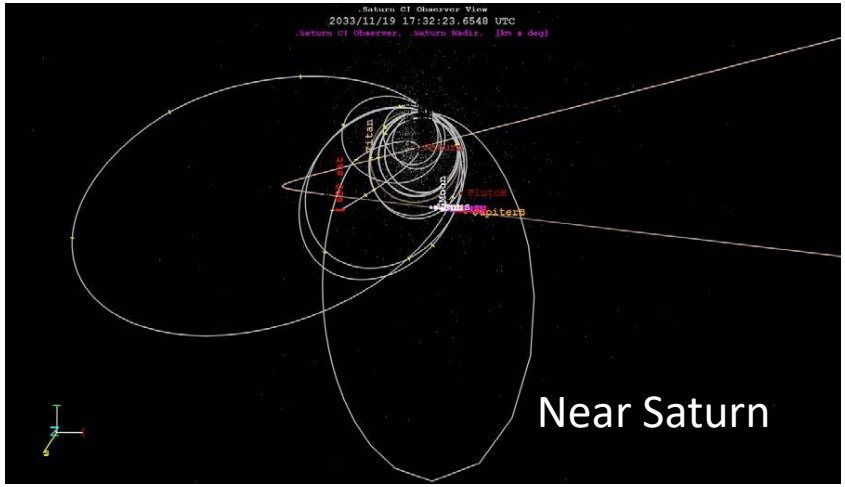
The Space Radiation Environment



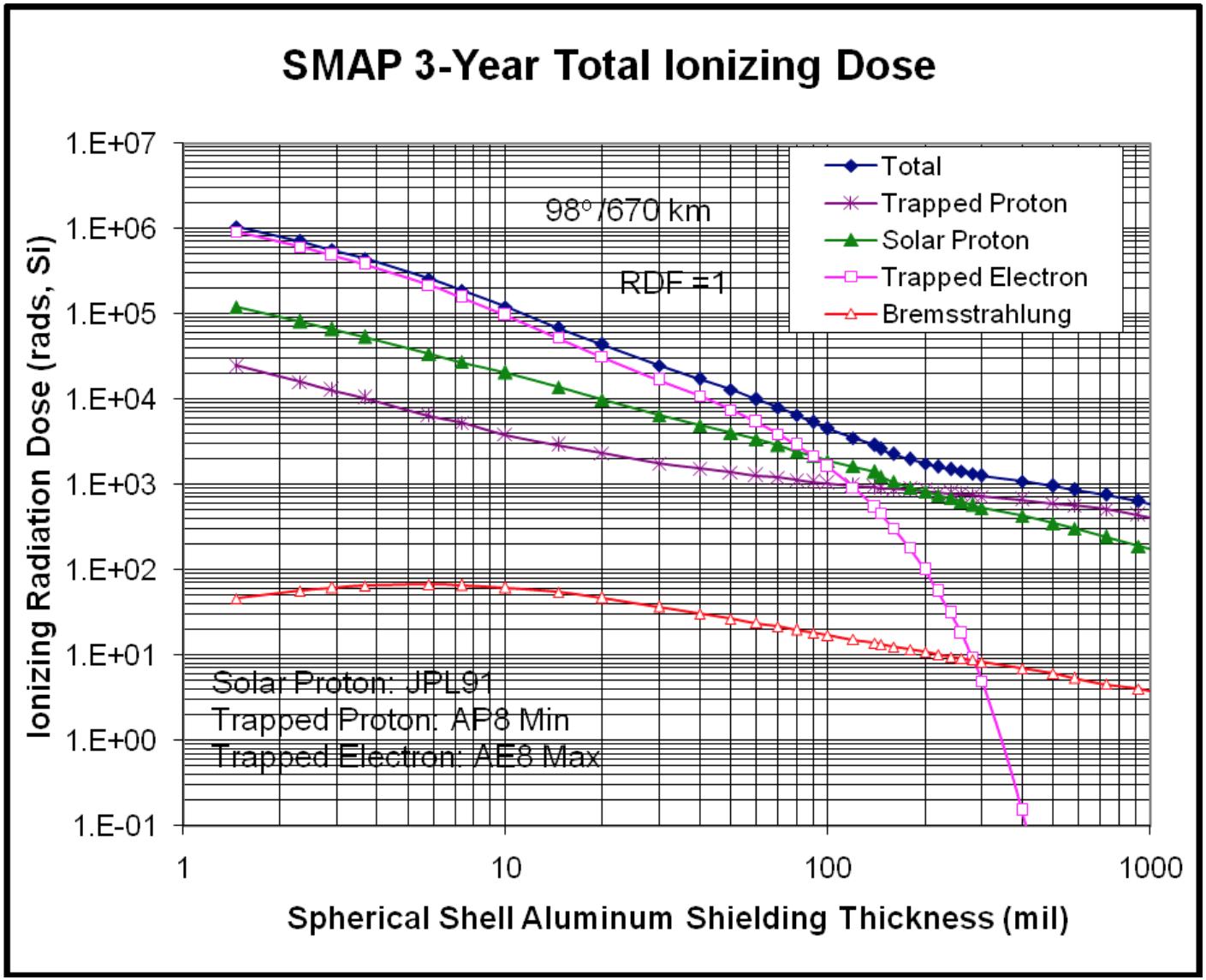
Radiation Environment Specifications at JPL

- Mission Targets
- Trajectory. For example,
  - Earth escape
  - At the target
  - Interplanetary
- On-board nuclear power source??
- Radiation Environment Model(s)
- Dose-depth curve





Example Dose-Depth Curve: Earth



Example Dose-Depth Curve: Moon

Aluminum Shielding Thickness			Solar Proton Ionizing Dose, rad(Si)	
g/cm²	mm	mils	(RDF = 1)	(RDF = 2)
1.00E-02	3.70E-02	1.46E+00	1.60E+05	3.20E+05
1.26E-02	4.67E-02	1.84E+00	1.30E+05	2.60E+05
1.59E-02	5.89E-02	2.32E+00	1.06E+05	2.12E+05
2.00E-02	7.41E-02	2.92E+00	8.89E+04	1.78E+05
2.51E-02	9.30E-02	3.66E+00	7.33E+04	1.47E+05
3.16E-02	1.17E-01	4.61E+00	6.23E+04	1.25E+05
3.98E-02	1.47E-01	5.80E+00	5.21E+04	1.04E+05
5.01E-02	1.86E-01	7.31E+00	4.14E+04	8.28E+04
6.31E-02	2.34E-01	9.20E+00	3.36E+04	6.72E+04
6.86E-02	2.54E-01	1.00E+01	2.97E+04	5.94E+04
7.94E-02	2.94E-01	1.16E+01	2.55E+04	5.10E+04
1.00E-01	3.70E-01	1.46E+01	2.07E+04	4.14E+04
1.26E-01	4.67E-01	1.84E+01	1.68E+04	3.36E+04
1.37E-01	5.07E-01	2.00E+01	1.51E+04	3.02E+04
1.59E-01	5.89E-01	2.32E+01	1.32E+04	2.64E+04
2.00E-01	7.41E-01	2.92E+01	1.08E+04	2.16E+04
2.06E-01	7.63E-01	3.00E+01	9.97E+03	1.99E+04
2.51E-01	9.30E-01	3.66E+01	8.11E+03	1.62E+04
2.74E-01	1.01E+00	4.00E+01	7.32E+03	1.46E+04
3.16E-01	1.17E+00	4.61E+01	6.50E+03	1.30E+04
3.43E-01	1.27E+00	5.00E+01	5.75E+03	1.15E+04
3.98E-01	1.47E+00	5.80E+01	5.00E+03	1.00E+04
4.12E-01	1.53E+00	6.01E+01	4.62E+03	9.24E+03
4.80E-01	1.78E+00	7.00E+01	4.11E+03	8.22E+03
5.01E-01	1.86E+00	7.31E+01	3.79E+03	7.58E+03
5.49E-01	2.03E+00	8.01E+01	3.43E+03	6.86E+03
6.17E-01	2.29E+00	9.00E+01	3.11E+03	6.22E+03
6.31E-01	2.34E+00	9.20E+01	2.92E+03	5.84E+03
6.86E-01	2.54E+00	1.00E+02	2.68E+03	5.36E+03
7.94E-01	2.94E+00	1.16E+02	2.36E+03	4.72E+03
8.23E-01	3.05E+00	1.20E+02	2.16E+03	4.32E+03
9.60E-01	3.56E+00	1.40E+02	1.91E+03	3.82E+03
1.00E+00	3.70E+00	1.46E+02	1.77E+03	3.54E+03
1.10E+00	4.07E+00	1.60E+02	1.62E+03	3.24E+03
1.23E+00	4.56E+00	1.79E+02	1.45E+03	2.90E+03
1.26E+00	4.67E+00	1.84E+02	1.35E+03	2.70E+03
1.37E+00	5.07E+00	2.00E+02	1.24E+03	2.48E+03

Example Dose-Depth Curve: Mars

Table 4.15.1.7-1 - MSL Mission TID
(1 Earth year for the cruise period + 2 earth years for the Surface Operation Period)
for a Spherical Shell Geometry

Aluminum spherical Shield Thickness (mil)	1 Earth Year Cruise (rad(Si)), RDF=1			Surface segment (2 Earth Years), (rad(Si)),RDF=1			Mission TID (rad(Si))	Mission TID (rad(Si))
	SEP	GCR	MMRTG*	SEP	GCR	MMRTG*	RDF=1	RDF=2
1.46E+00	8.88E+04	2.10E+01	641	8.72	15.11	1282	9.08E+04	1.82E+05
1.84E+00	7.22E+04	1.89E+01	641	8.71	15.11	1282	7.42E+04	1.48E+05
2.32E+00	5.88E+04	1.74E+01	641	8.71	15.11	1282	6.08E+04	1.22E+05
2.92E+00	4.91E+04	1.63E+01	641	8.71	15.11	1282	5.11E+04	1.02E+05
3.66E+00	4.12E+04	1.55E+01	641	8.71	15.11	1282	4.32E+04	8.63E+04
4.61E+00	3.46E+04	1.49E+01	641	8.71	15.11	1282	3.66E+04	7.31E+04
5.80E+00	2.89E+04	1.45E+01	641	8.70	15.11	1282	3.09E+04	6.17E+04
7.31E+00	2.25E+04	1.41E+01	641	8.70	15.11	1282	2.45E+04	4.89E+04
9.20E+00	1.84E+04	1.38E+01	641	8.69	15.11	1282	2.04E+04	4.07E+04
1.00E+01	1.63E+04	1.37E+01	641	8.69	15.11	1282	1.83E+04	3.65E+04
1.16E+01	1.42E+04	1.36E+01	641	8.68	15.11	1282	1.62E+04	3.23E+04
1.46E+01	1.12E+04	1.34E+01	641	8.67	15.10	1282	1.32E+04	2.63E+04
1.84E+01	9.13E+03	1.32E+01	641	8.66	15.10	1282	1.11E+04	2.22E+04
2.00E+01	8.21E+03	1.32E+01	641	8.66	15.10	1282	1.02E+04	2.03E+04
2.32E+01	7.23E+03	1.31E+01	641	8.65	15.10	1282	9.19E+03	1.84E+04
2.92E+01	5.90E+03	1.30E+01	641	8.63	15.10	1282	7.86E+03	1.57E+04
3.00E+01	5.43E+03	1.30E+01	641	8.62	15.10	1282	7.39E+03	1.48E+04
3.66E+01	4.51E+03	1.30E+01	641	8.60	15.10	1282	6.47E+03	1.29E+04
4.00E+01	4.03E+03	1.30E+01	641	8.59	15.10	1282	5.99E+03	1.20E+04
4.61E+01	3.52E+03	1.27E+01	641	8.57	15.10	1282	5.48E+03	1.10E+04
5.00E+01	3.11E+03	1.27E+01	641	8.56	15.10	1282	5.07E+03	1.01E+04
5.80E+01	2.76E+03	1.27E+01	641	8.53	15.10	1282	4.72E+03	9.44E+03
6.01E+01	2.54E+03	1.27E+01	641	8.53	15.10	1282	4.50E+03	9.00E+03
7.00E+01	2.23E+03	1.27E+01	641	8.49	15.10	1282	4.19E+03	8.38E+03
7.31E+01	2.03E+03	1.25E+01	641	8.48	15.10	1282	3.99E+03	7.98E+03
8.01E+01	1.85E+03	1.25E+01	641	8.46	15.10	1282	3.81E+03	7.62E+03
9.00E+01	1.69E+03	1.25E+01	641	8.43	15.09	1282	3.65E+03	7.30E+03
9.20E+01	1.59E+03	1.25E+01	641	8.42	15.09	1282	3.55E+03	7.10E+03
1.00E+02	1.45E+03	1.25E+01	641	8.40	15.09	1282	3.41E+03	6.82E+03
1.16E+02	1.27E+03	1.24E+01	641	8.34	15.09	1282	3.23E+03	6.46E+03
1.20E+02	1.16E+03	1.24E+01	641	8.33	15.09	1282	3.12E+03	6.24E+03
1.40E+02	1.03E+03	1.22E+01	641	8.26	15.09	1282	2.99E+03	5.98E+03
1.46E+02	9.50E+02	1.22E+01	641	8.24	15.09	1282	2.91E+03	5.82E+03
1.60E+02	8.58E+02	1.22E+01	641	8.19	15.08	1282	2.82E+03	5.63E+03
1.70E+02	7.78E+02	1.21E+01	641	8.13	15.08	1282	2.74E+03	5.47E+03

Example Dose-Depth Curve: Jupiter

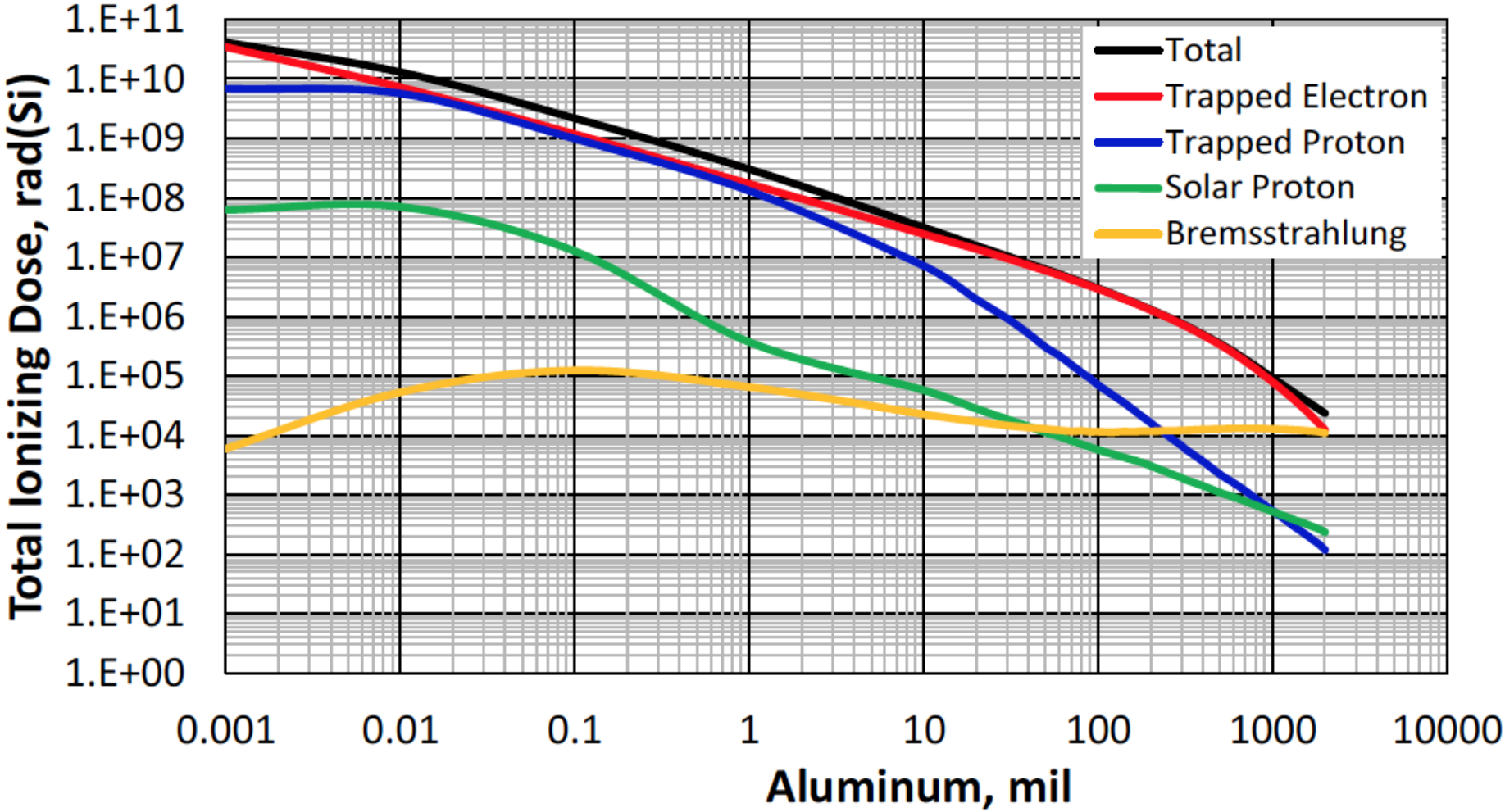


Figure 4.9-3a. Aluminum Spherical Shell TID Dose-Depth Curve for the Design Reference Mission, RDF=1.

Example Dose-Depth Curve: Saturn

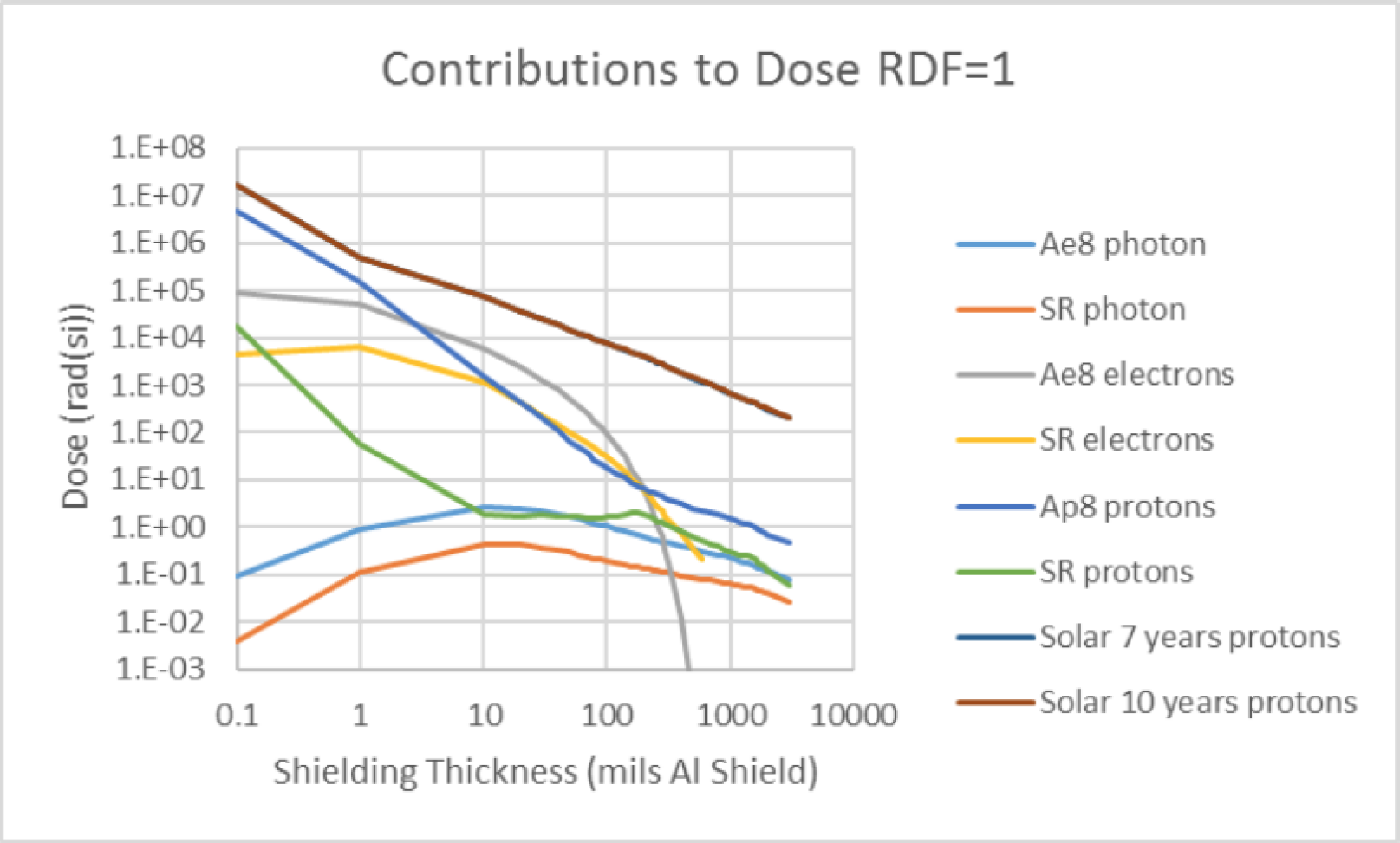


Figure 6. Radiation Models Contribution to Dose (RDF=1).

Summary

- **With 100-mil (~2.5 mm) aluminum shielding**
- **RDF=1**

Mission	Total (krad(Si))	SPE (krad(Si)	% of SPE
SMAP	4.57	1.90	**42**
Moon	2.68	2.68	**100**
Mars (MSL)	3.41	1.46	**43**
Jupiter (Europa)	3000	5.69	0.2
Satrurn	7.5	7.34	**98**

JPL Solar Proton Model

- Also called the Feynman Model (Joan Feynman)
  - Feynman et al., JGR, 1993 (where it is called the JPL 1991 model)
  - Feynman et al., Journal of Atmospheric and Solar-Terrestrial Physics, 2002

- The JPL Solar Proton Model is one of a class of fluence models which follow the lead set by King (1974).

JPL Solar Proton Model (cont'd)

- Dataset:
  - IMP 1, 2, 3, 5, 6, 7, and 8 (APL instrument)
  - OGO 1
- Event Definition:

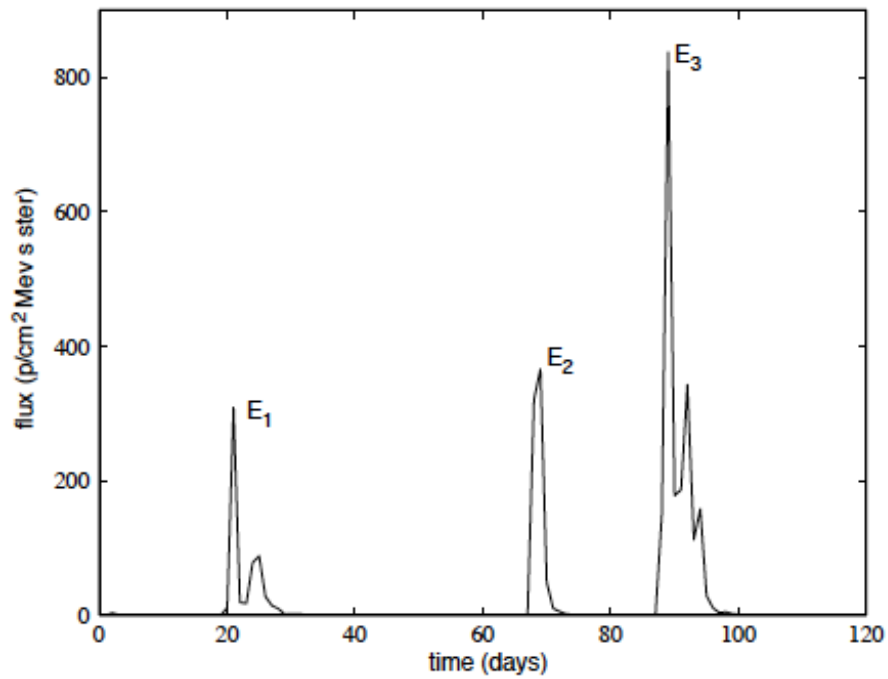
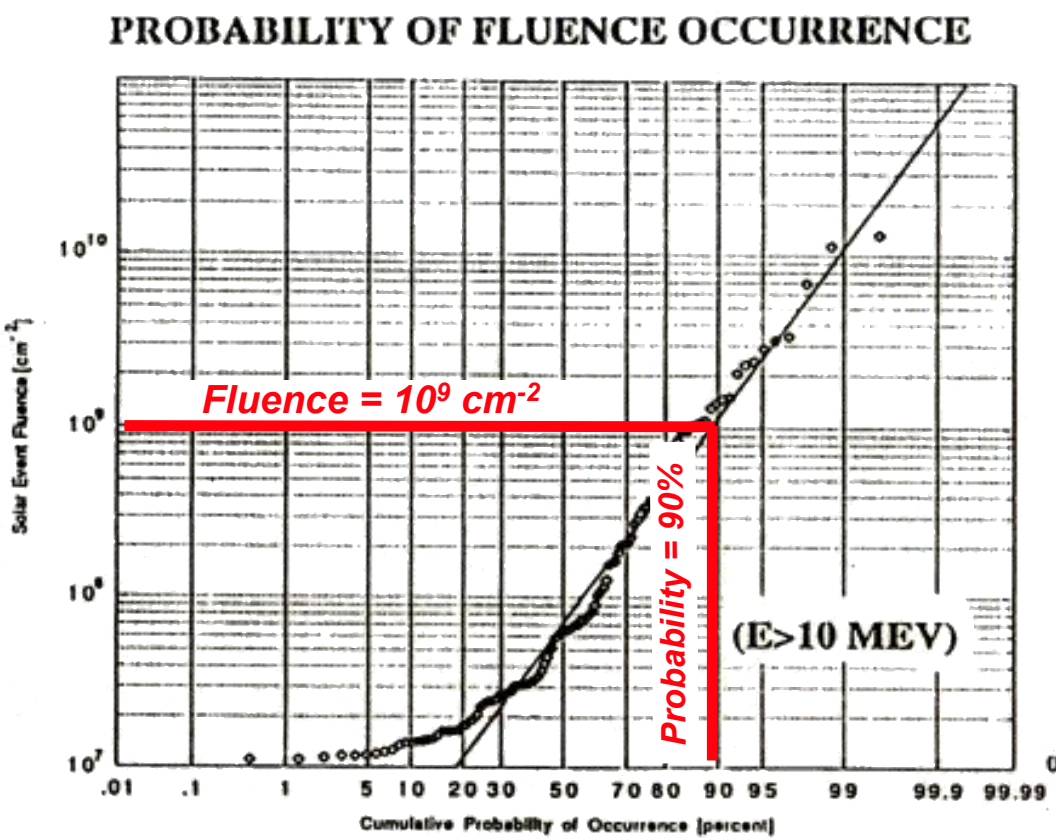
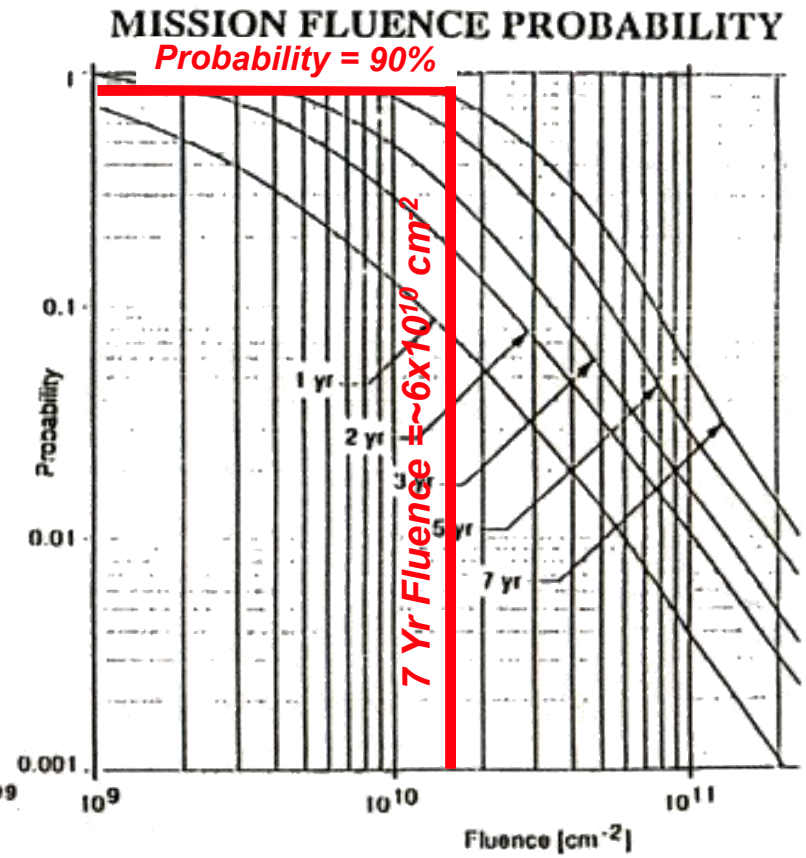


Fig. 1. The definition of "an event". Events, denoted by E_1, also E_2, E_3, are sums of fluences from successive CMEs. The time intervals between events are defined as the difference between the beginning times of two sequential events. For example, τ_1 is the difference between the beginning of event E_1 and event E_2.

JPL Solar Proton Model (cont'd)

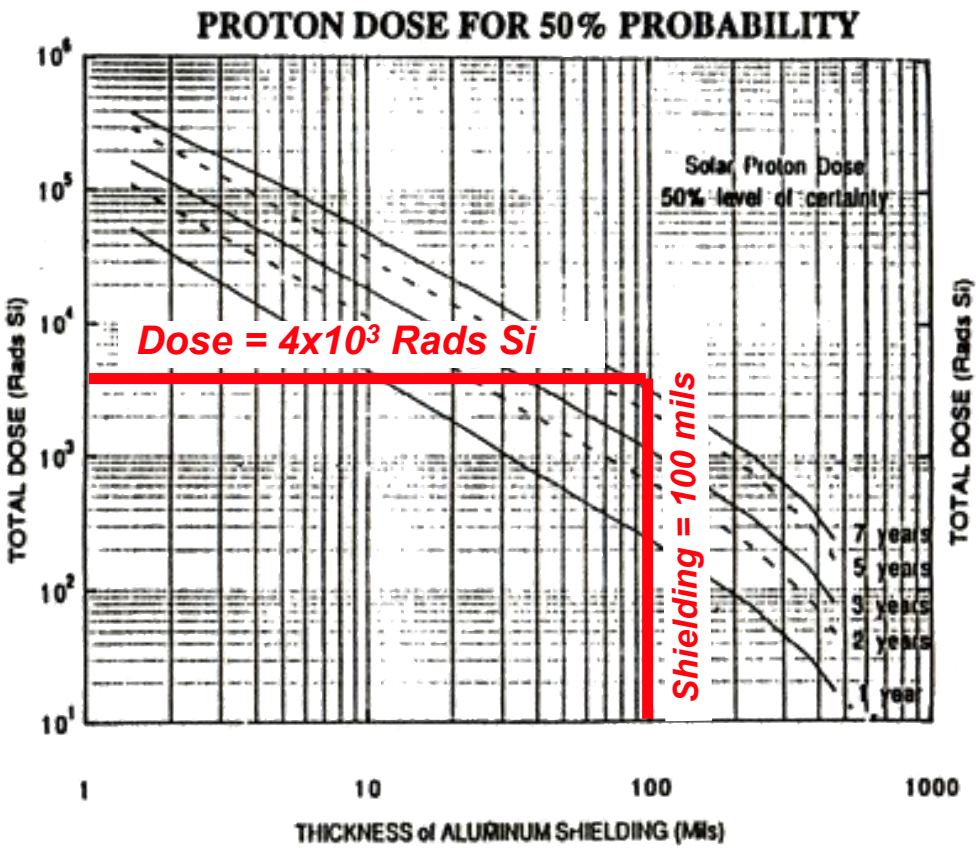
- Log-Normal Distribution

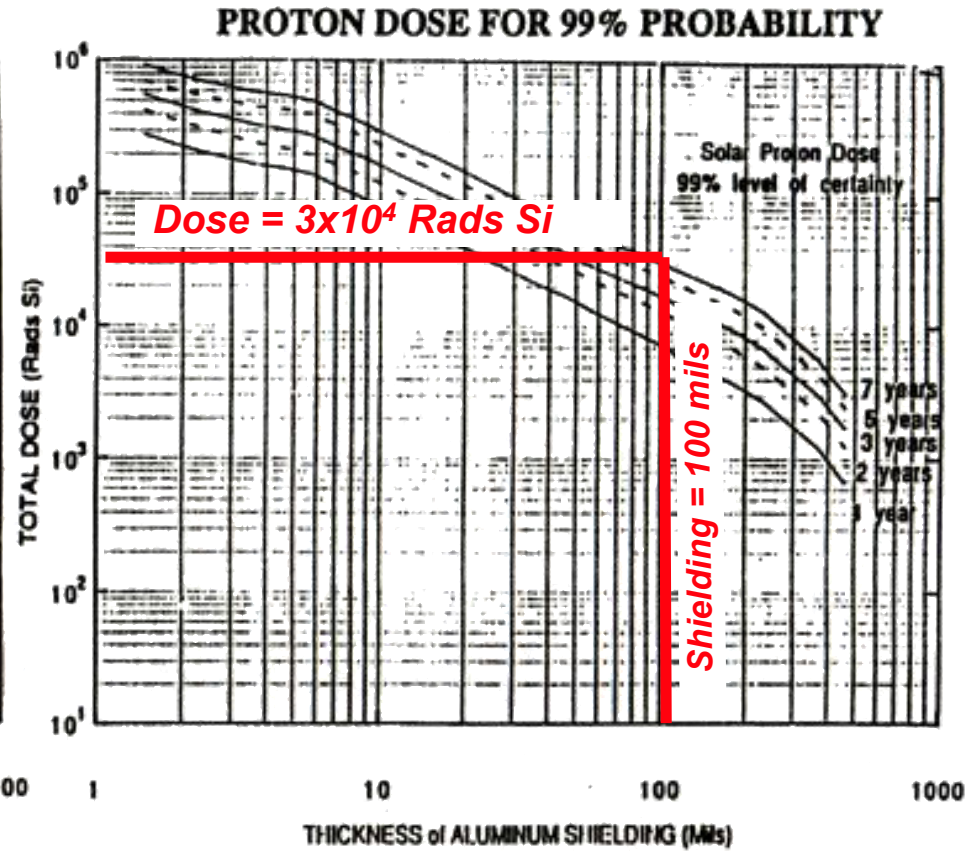




Courtesy of Henry Garrett, JPL

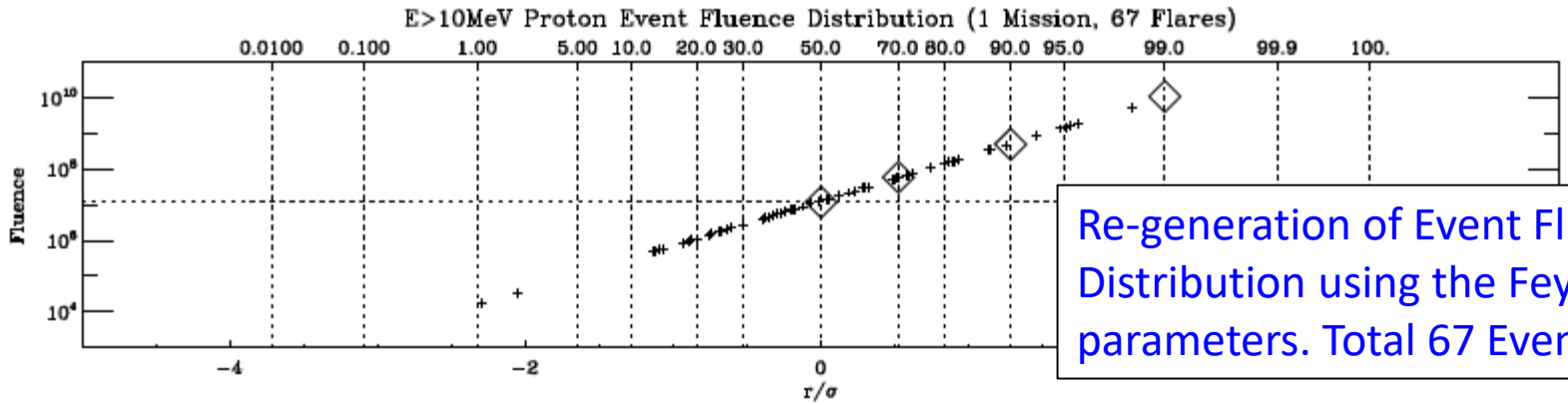
The JPL Proton Model 1 AU Dose Prediction



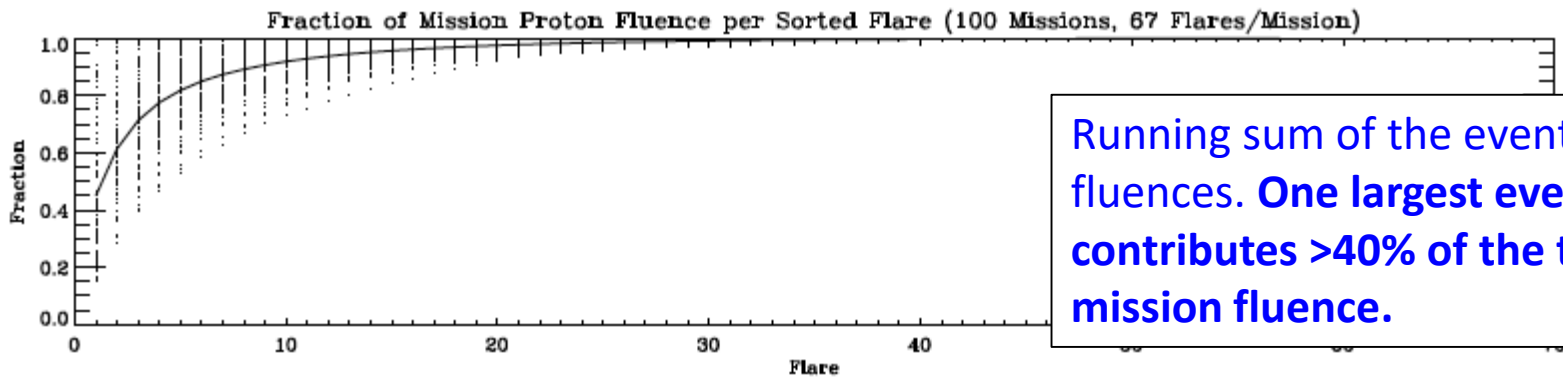


Courtesy of Henry Garrett, JPL

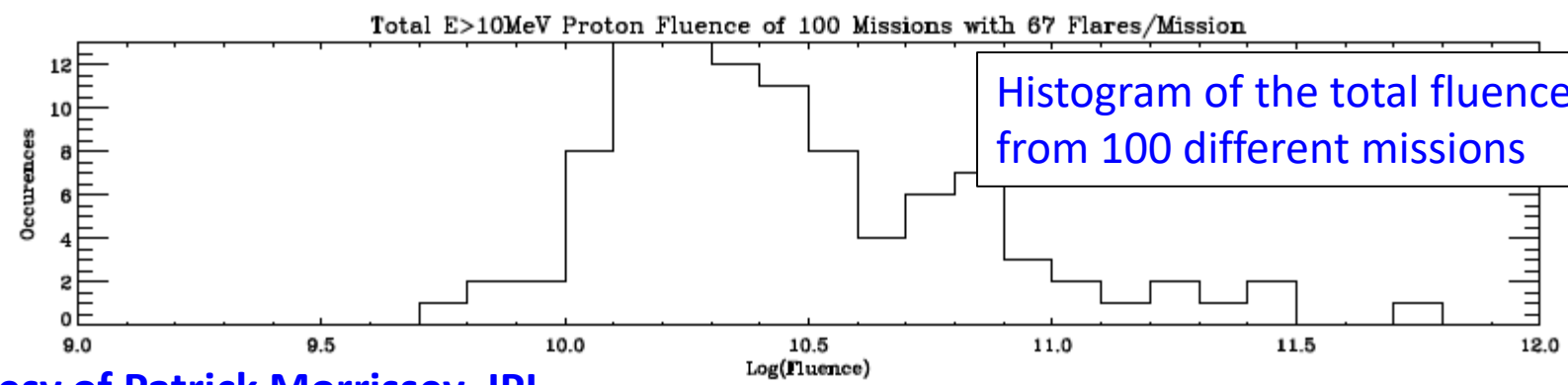
Some Notes on the Model



Re-generation of Event Fluence Distribution using the Feynman's parameters. Total 67 Events



Running sum of the event fluences. **One largest event contributes >40% of the total mission fluence.**



Histogram of the total fluence from 100 different missions

Courtesy of Patrick Morrissey, JPL

Other Considerations

- JPL uses the 95% confidence level.
- JPL applies a Radiation Design Factor (RDF) of 2.
- For missions other than at 1 AU, JPL scales the mission <u>fluence</u> by the time average of $1/r^2$.
- For the peak flux environment, we use CREME96 (i.e., Oct 1989 Event)

Comparison among Different Solar Proton Models

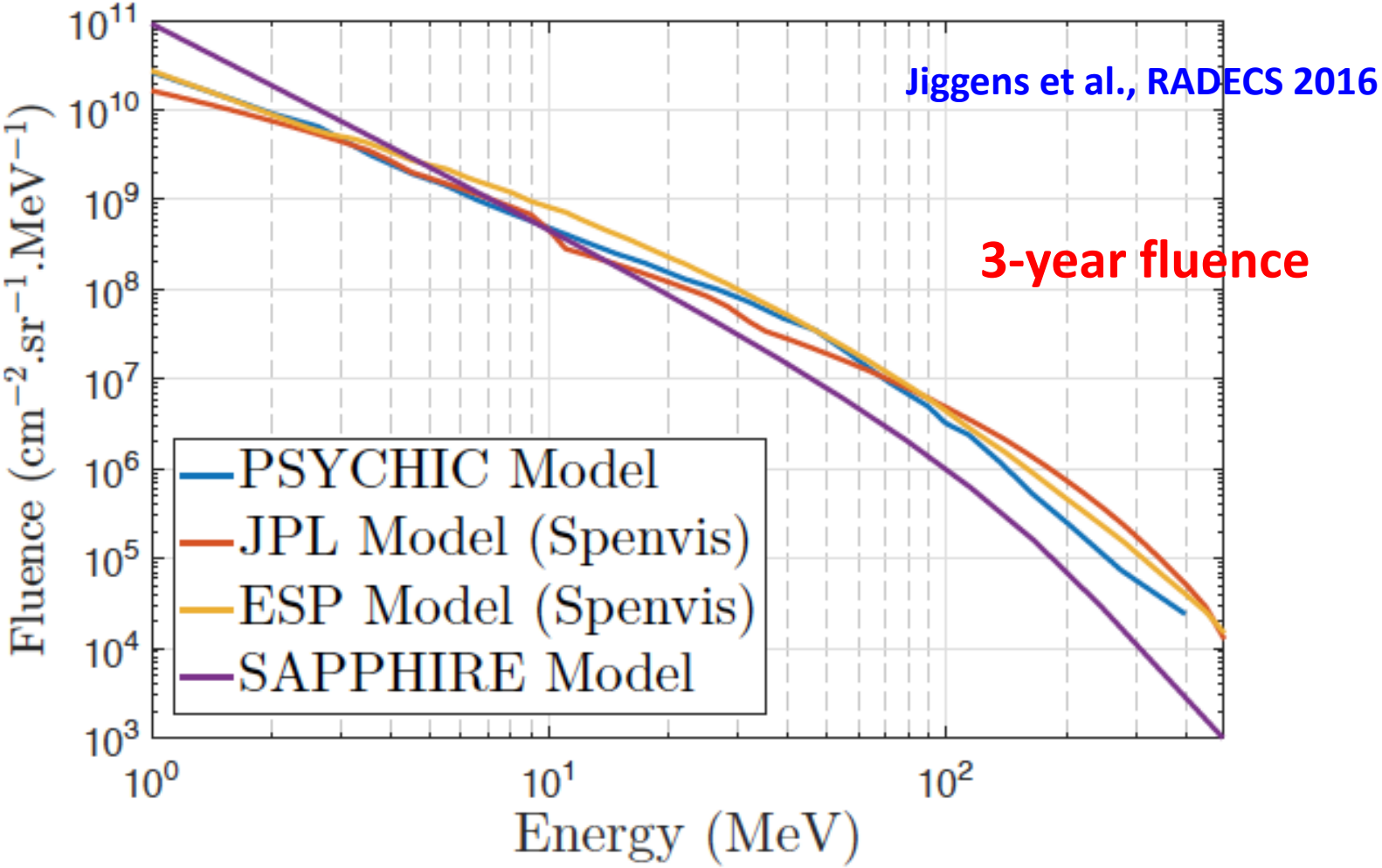


Fig. 5. Comaprison of cumulative fluence model outputs for protons at 95% confidence.

THANK YOU!
QUESTIONS?