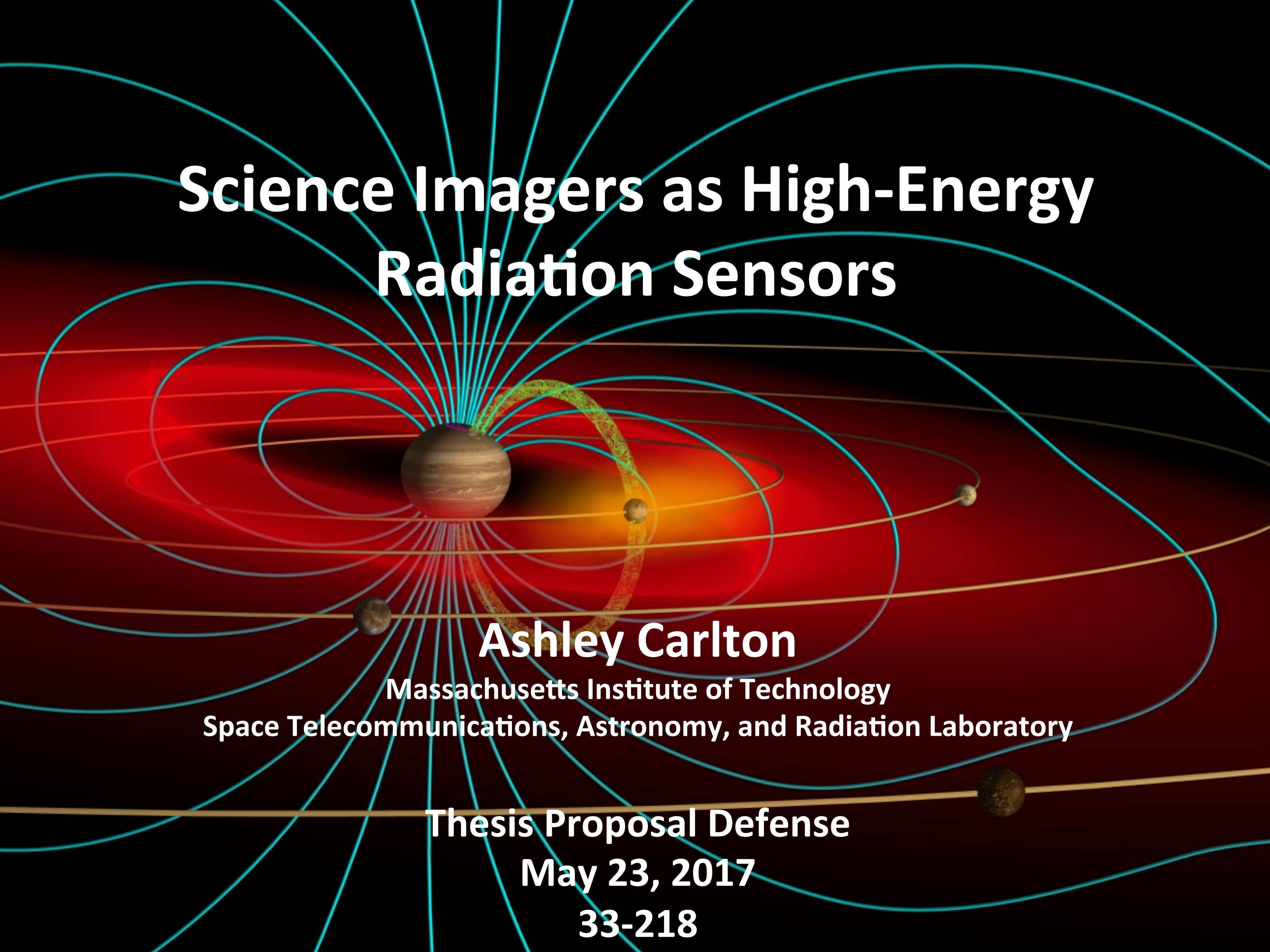

Science Imagers as High-Energy Radiation Sensors

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Massachusetts Institute of Technology

Space Telecommunications, Astronomy, and Radiation Laboratory

Thesis Proposal Defense

May 23, 2017

33-218

Outline

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  - Research, academic, degree

Jovian Magnetosphere

MIT STAR Lab
Space Telecommunications, Astronomy, and Radiation

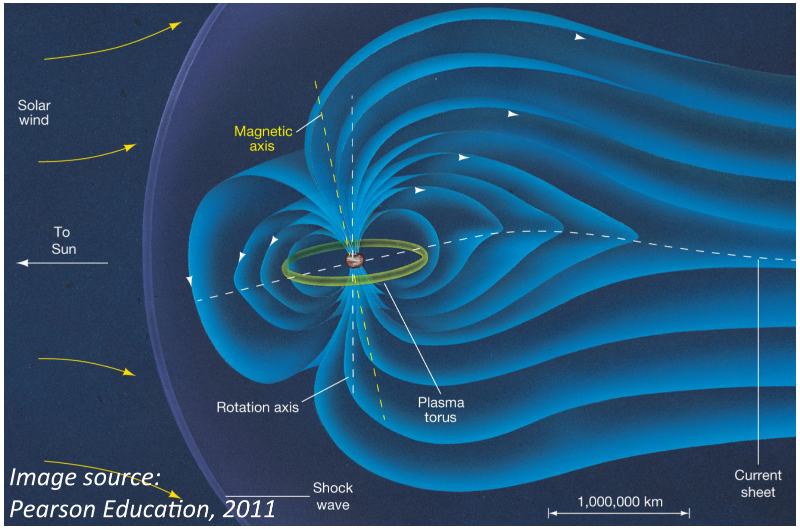
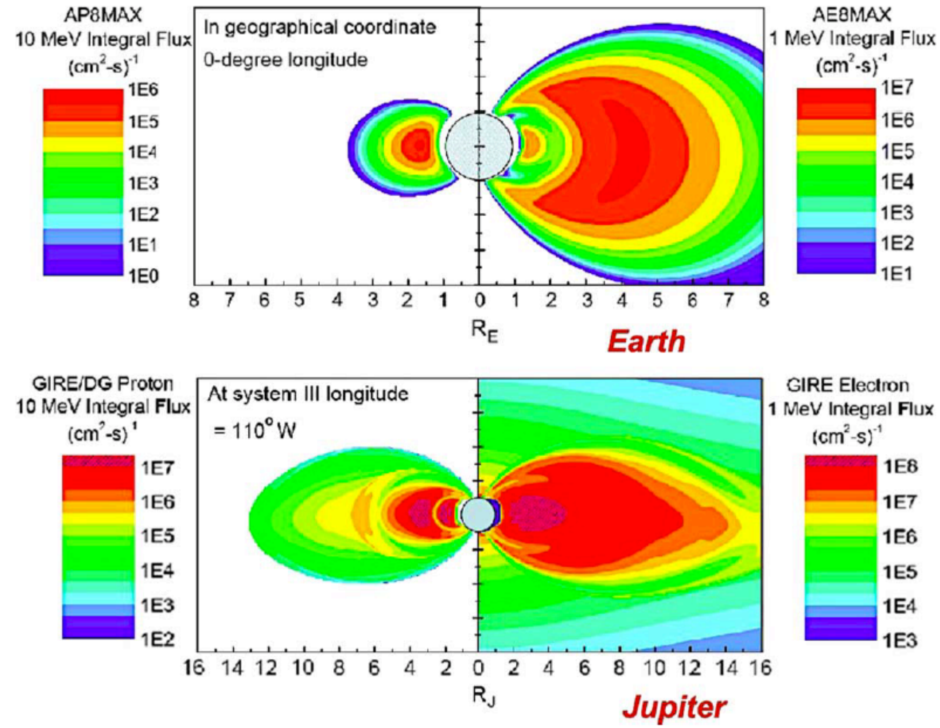


Image source: Pearson Education, 2011

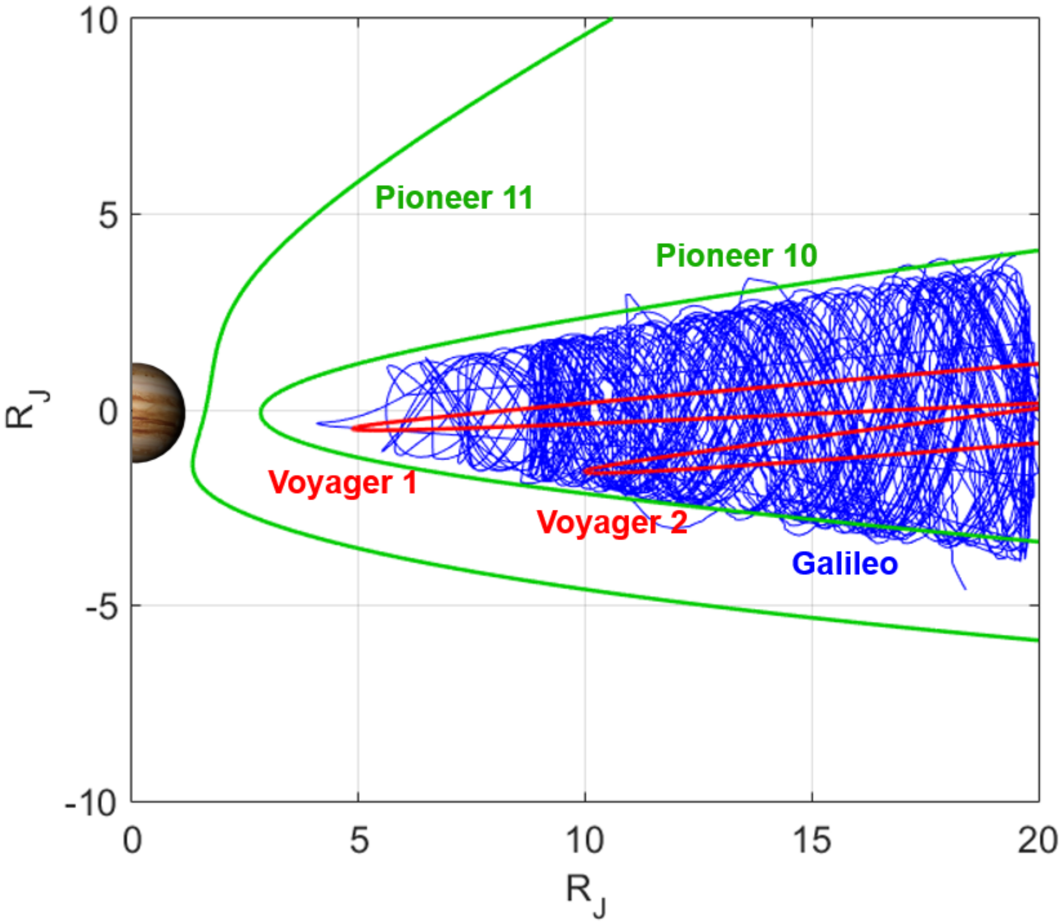
	Earth	Jupiter
Equatorial radius [km]	6.38 x 10^3	7.15 x 10^4
Magnetic moment [G-cm^3]	8.10 x 10^{25}	1.59 x 10^{30}
Dipole tilt [^{o}]	11.5	11
Rotation period [hr]	24.0	9.925
Aphelion / perihelion [AU]	1.01 / 0.98	5.45 / 4.95



Contours of the integral electron and proton fluxes at the Earth and Jupiter. Image courtesy of I. Jun.

<u>Jovian environment is dominated by electrons.</u> [1,2]

Limited High-Energy Measurements



Spacecraft	Orbit	Date
Pioneer 10	flyby	December 1973
Pioneer 11	flyby	December 1974
Voyager 1	flyby	March 1979
Voyager 2	flyby	July 1979
Galileo	35 orbits	Dec. 1995 – Sept. 2003

Trajectories of spacecraft that have made high-energy particle measurements with respect to Jupiter. R_J = 71,492 km.
Image source: M. de Soria-Santacruz Pich et al., 2016.

R_J = 71,492 km

Missions to Jupiter

Current and planned missions to Jupiter do not have instruments dedicated to measuring >1 MeV electrons.

- Juno:
  - In orbit at Jupiter (JOI: July 2016)
  - Highly elliptical orbit over the poles [4]
- Europa Clipper concept:
  - In phase B of design, launch date ~2024
  - Consists of an orbiter (flying by Europa on each of ~40-45 highly elliptical orbits) and lander [5,6]

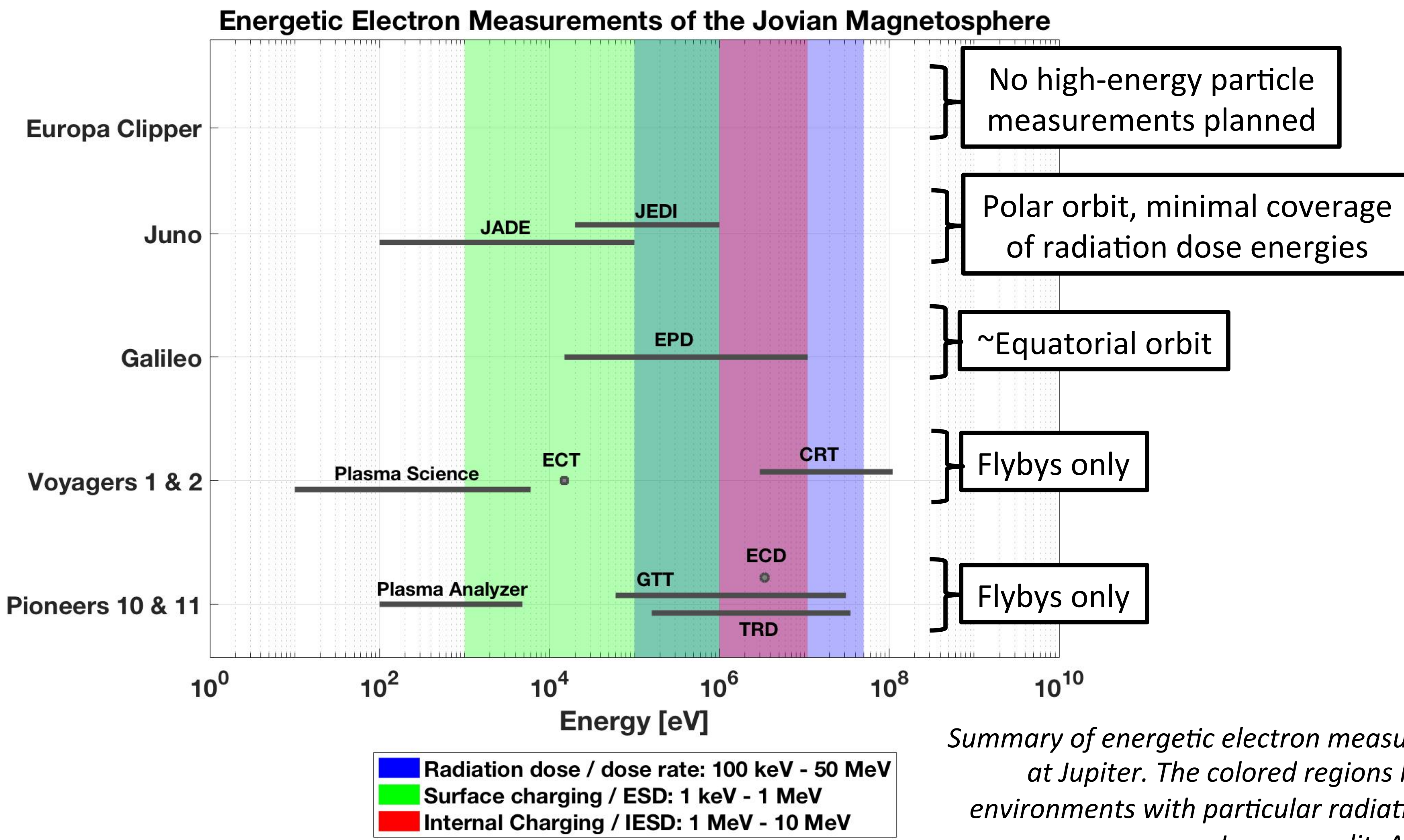
Video showing the planned Juno orbit with respect to Jupiter and the Galilean moons. Video created using NASA's Eyes: https://eyes.nasa.gov/

Why do we care about >1 MeV e-?

- **Science** Motivation:
  - Magnetospheric science
  - MeV electrons affect surfaces of Jovian moons [7,8]
- **Engineering** Motivation:
  - Mission operations
  - Anomaly investigation and mitigation [9,10]
  - Improvement of models for future mission design

Effect	Environment Source
1. Radiation dose / dose rate	100 keV − 50 MeV electrons 1 MeV − 100 MeV protons
2. Surface Charging / ESD	1 keV − 1 MeV electrons
3. Single Event Effects	1 − 100 MeV protons >1 MeV/Nuc. heavy ions
4. Internal Charging / IESD	1 − 10+ MeV electrons

Limited High-Energy Measurements



Summary of energetic electron measurements at Jupiter. The colored regions highlight environments with particular radiation risks. Image credit: A. Carlton

Thesis Research Statement

Develop a method to extract quantitative information about the high-energy (>1 MeV) electron environment at Jupiter using existing technologies on-board.

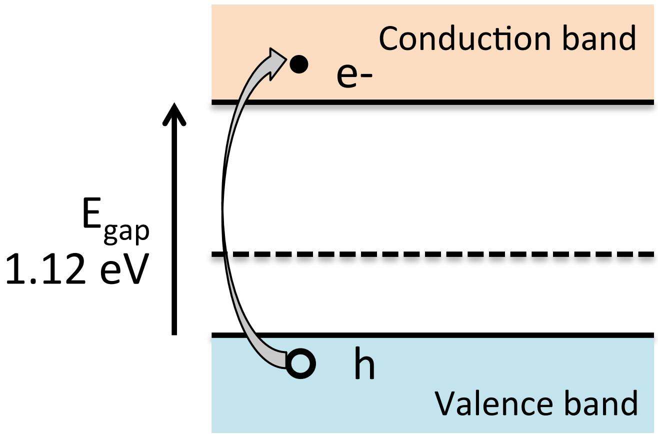
- Science imagers as sensors of the MeV electrons.
- Develop the technique using imagers on the Galileo spacecraft and compare results to Galileo Energetic Particle Detector.

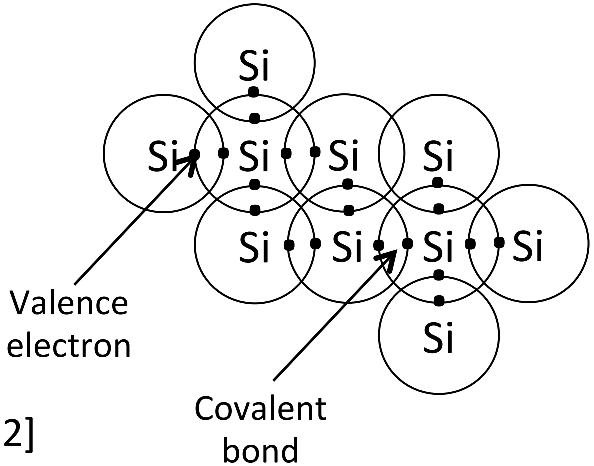
Imagers as Radiation Sensors

- Impact ionization
- Energetic charged particles lose kinetic energy predominately through inelastic collisions with the orbital silicon electrons
- Electrons promoted from valence to conduction band

$$Q \propto \Delta E$$

Average energy needed for e-h pair generation in Silicon: 3.6 eV

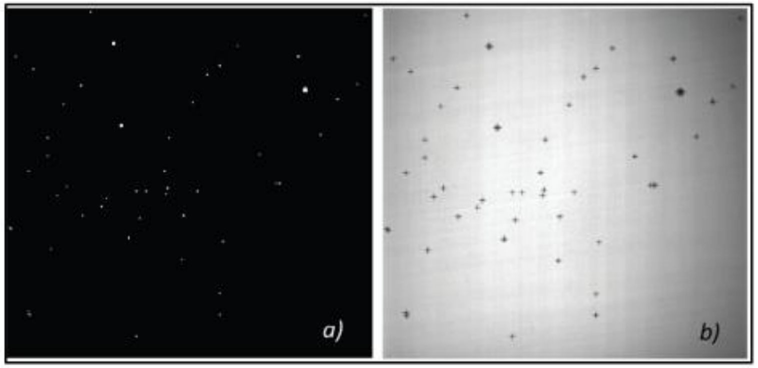




[11,12]

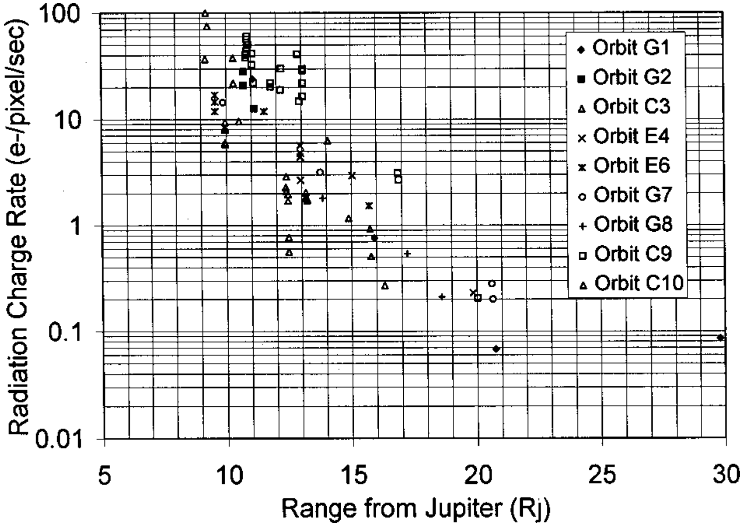
Literature Review

- Radiation "hits"/noise extracted from imagers
  - Radiation hit removal algorithms [12,13,14,15]
  - Comparing radiation hit rate to simulations [16]
  - Comparing radiation hit rate to pre-flight testing and to different locations on orbit [17,18,19]



Original CCD image. Right: Image with crosses indicating a noise pixel. Image source: Girón and Correa, 2010.

- Imagers as radiation detectors
  - Diagnostics of inertial confinement fusion implosions [20,21]
  - Threshold-crossing rates [22,23]



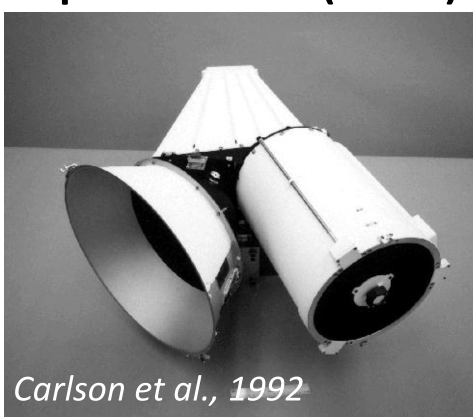
Radiation-induced signal rates in SSI images as a function of R_J. Image source: Klaasen et al., 1999.

Approach and Methodology (1/2)

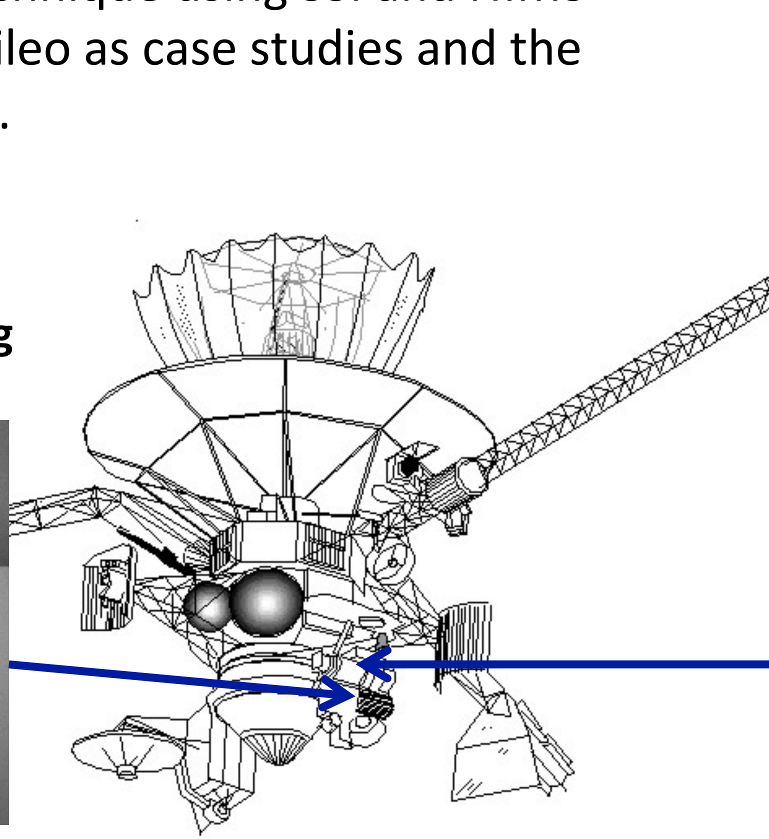
- The Galileo spacecraft orbited Jupiter from December 1995 to September 2003, completing 35 orbits.
- Develop the technique using SSI and NIMS imagers on Galileo as case studies and the EPD to validate.

[24,25,26]

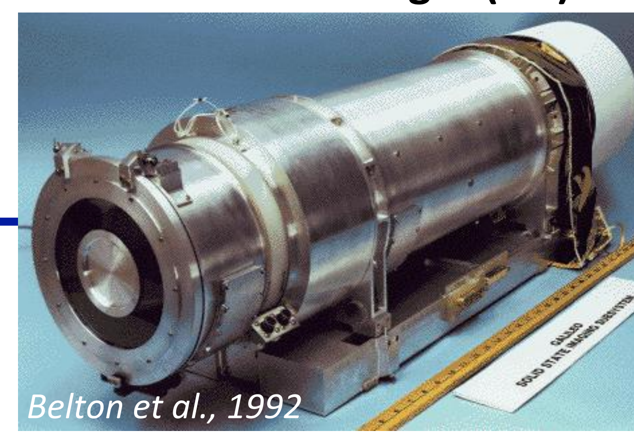
Near-Infrared Mapping Spectrometer (NIMS)



Carlson et al., 1992



Solid-State Imager (SSI)



Belton et al., 1992

Image source: NASA https://solarsystem.nasa.gov/images/galleries/Galileo_Diagram_No_Labels.jpg

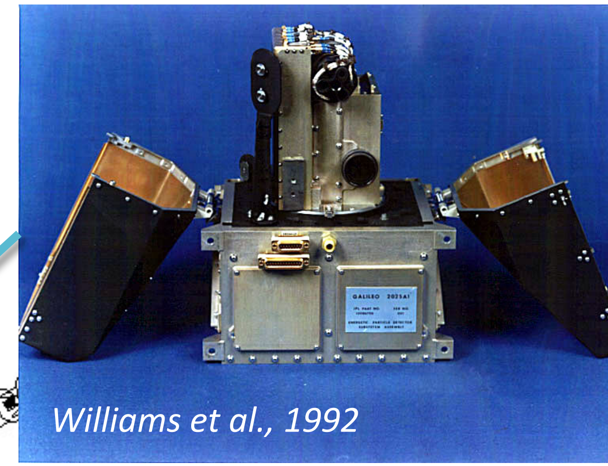
Approach and Methodology (2/2)

For Galileo SSI and NIMS, we will:

- Determine the energy (or energies) the imager is sensitive to
- Calculate the flux at a given energy
- Compare results to the Galileo EPD

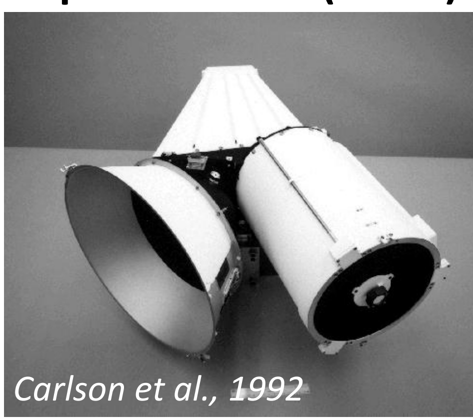
[24,25,26]

Energetic Particle Detector (EPD)

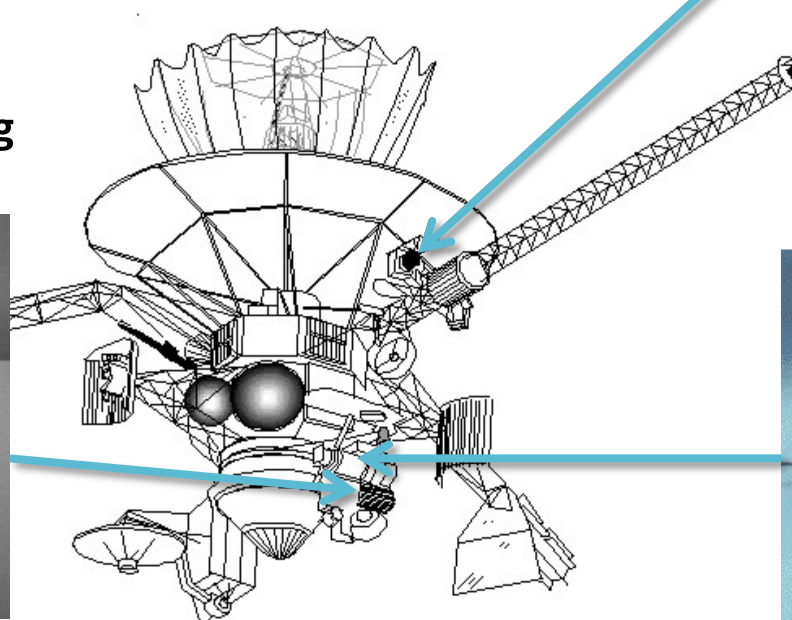


Williams et al., 1992

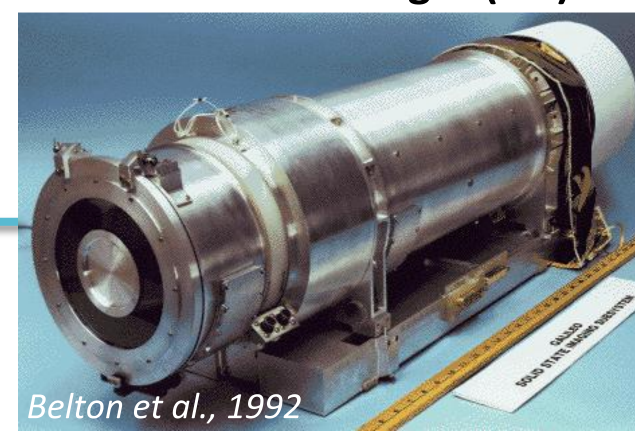
Near-Infrared Mapping Spectrometer (NIMS)



Carlson et al., 1992



Solid-State Imager (SSI)

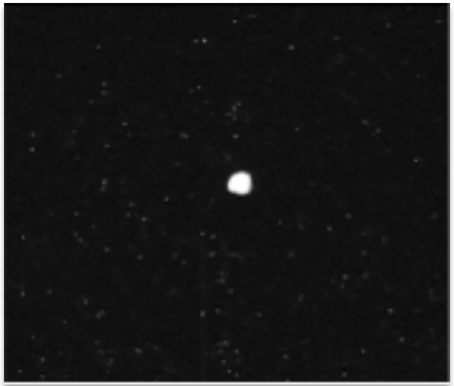


Belton et al., 1992

Image source: NASA https://solarsystem.nasa.gov/images/galleries/Galileo_Diagram_No_Labels.jpg

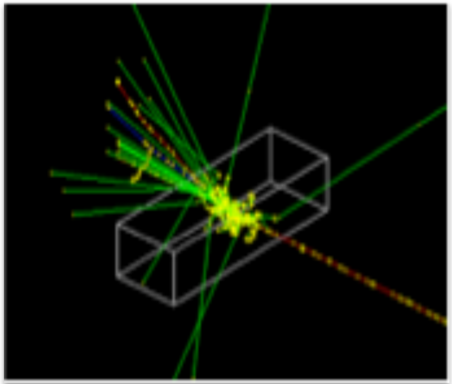
Approach

Data Analysis: Radiation Noise in SSI Images



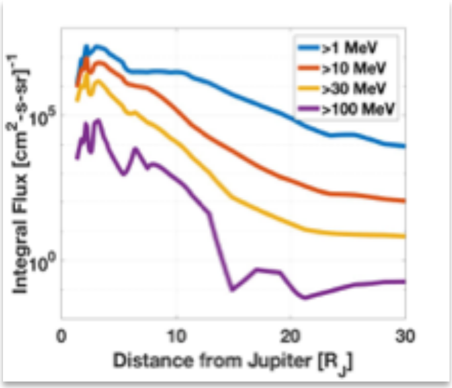
- Collect raw instrument frames with radiation noise
- Process frames to remove target and dark current
- Use calibrated instrument gain to determine energy deposited

Simulations: Instrument Response to MeV e-



- Model instrument in Geant4
- Perform mono-energetic simulations

Extract Environment Information

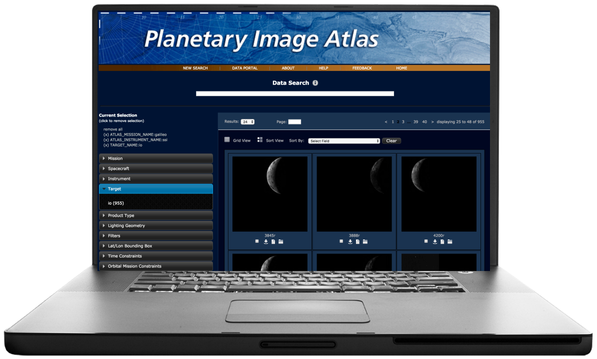


- Determine instrument response to mono-energetic beams
- Determine flux at a given energy

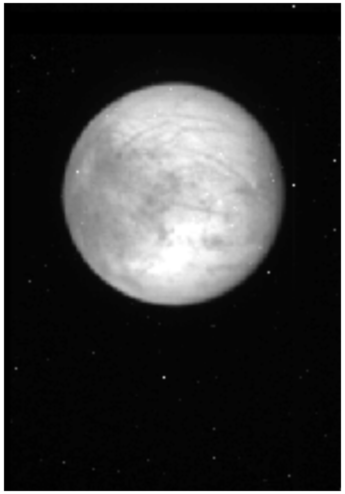
Compare to EPD for validation.

Approach: Data Analysis (1/2)

1. Collect raw instrument frames (pictures) with radiation noise.



Screenshot of the image atlas from the Planetary Data System (PDS), which can be accessed here: https://pds-imaging.jpl.nasa.gov/

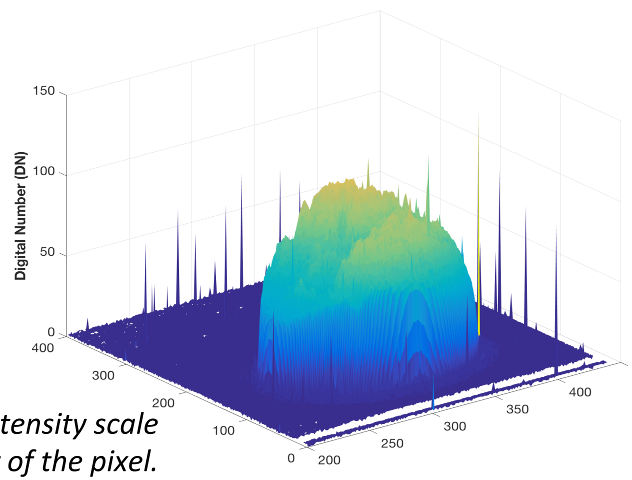


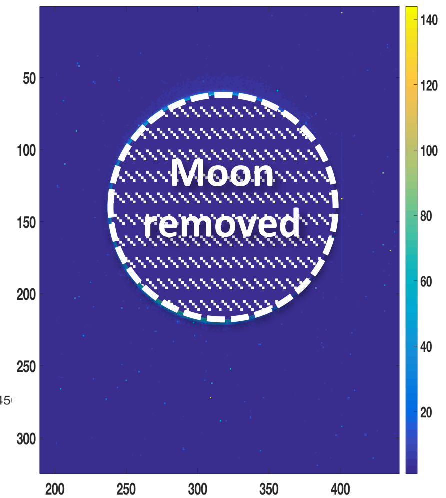
Galileo SSI image of Europa, downloaded from the PDS.

Example SSI Observation:

- Orbit 33, 18 Jan 2002
- Integration Time: 195.83 ms (exposure) + 8.667 s (read-out)
- Image taken at R_J = 17.1

2. Process frames to remove target object and dark current, leaving only radiation hits.





Right: Contrasted image with the intensity scale representing the digital number of the pixel.

Approach: Data Analysis (2/2)

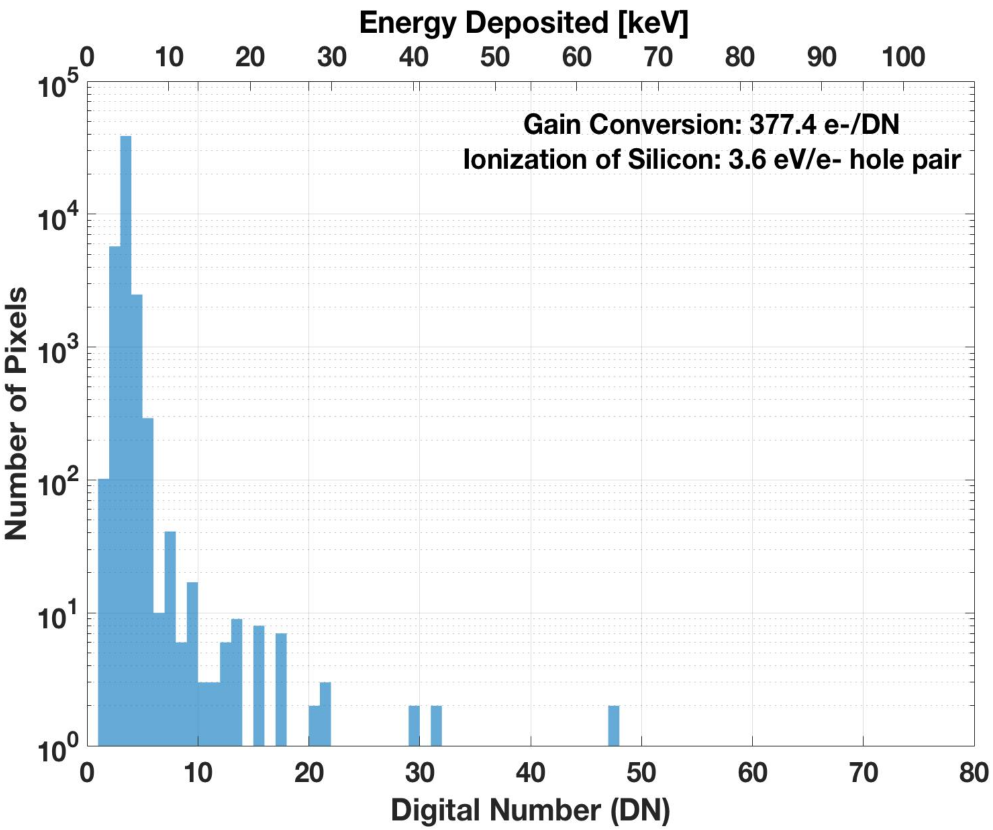
3. Use calibrated instrument gain to determine energy deposited per pixel per frame from noise. Make histogram of deposited energy.

1 bin = 1 DN = 377.4 e- = 1.36 keV

Commanded Gain	Gain State Ratio Factors	Conversion [e-/DN]	Notes
0 = Gain 1	1.00	1822	Summation mode only, ~400 K full scale
1 = Gain 2	4.824	377.4	Low gain, ~100 K full scale
2 = Gain 3	9.771	186.5	~40 K full scale
3 = Gain 4	47.135	38.66	High gain, ~10 K full 255 DN scale

Gain states for converting to digital number to electrons [19].

Histogram of the energy deposited by pixel, after the dark current and moon have been removed.



Approach: Simulations (1/2)

1. Model full instrument (including shielding) in a charged particle transport simulation code, Geant4.

Red orange: tantalum
Brown: printed wiring board
Yellow: silicon
Dark blue: aluminum
Cyan: titanium
Green: invar
Pink: silica

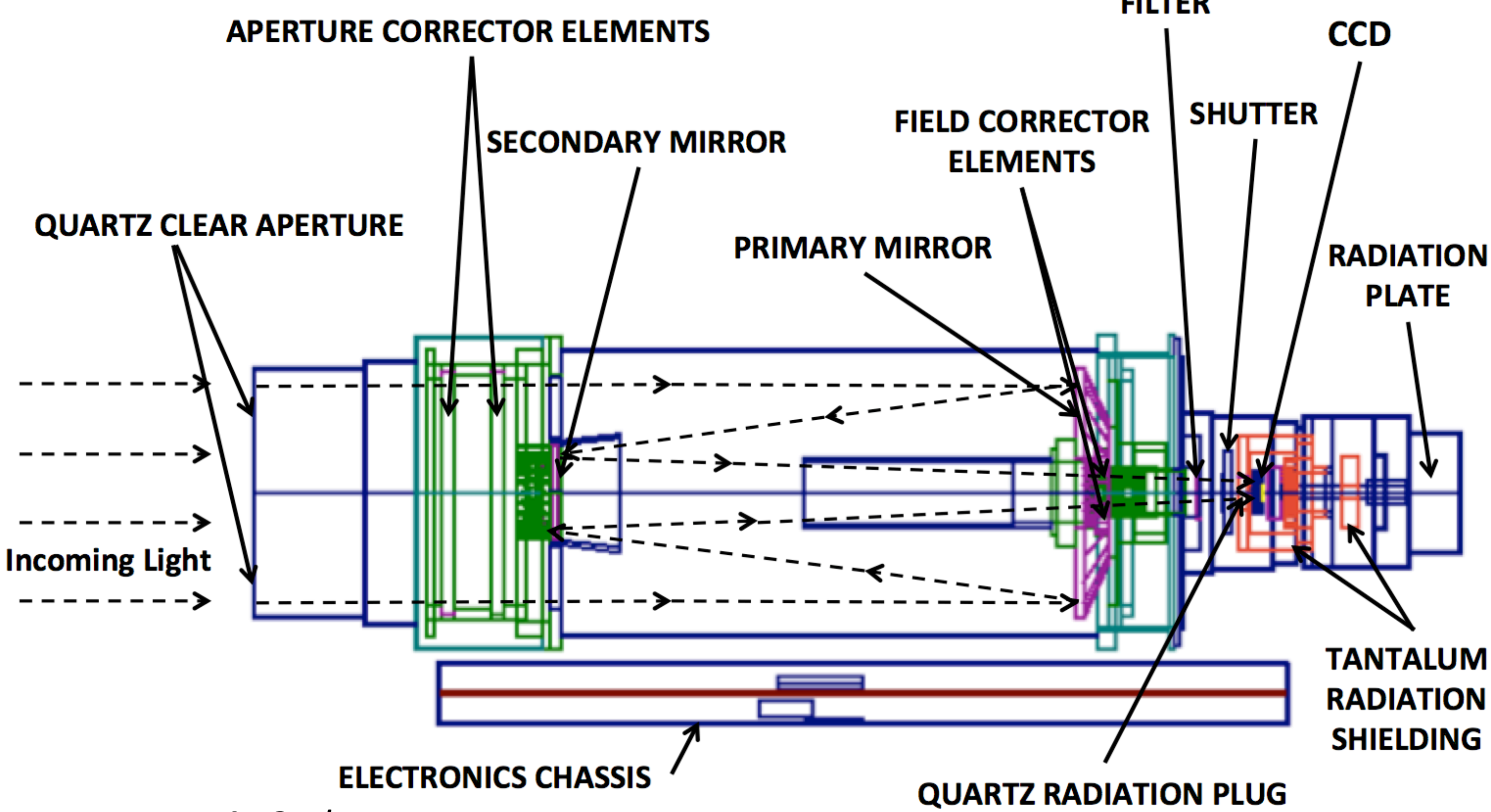


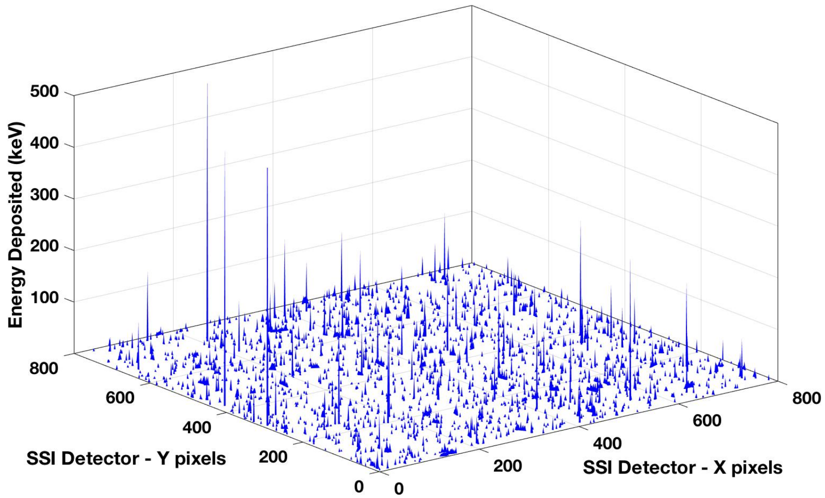
Image source: A. Carlton

Approach: Simulations (2/2)

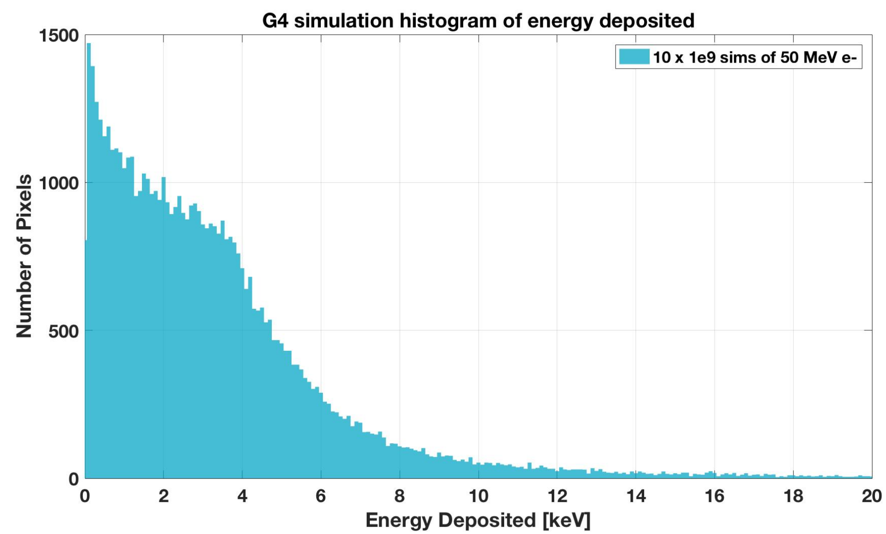
2. Perform simulations of SSI under mono-energetic environments.

Source environment	Sphere radiating inwards
Radius of source sphere	150 cm
Number of source particles	1E9 electrons
Energies simulated	1, 3, 5, 10, 30, 50, 100, and 200 MeV

Simulation parameters used. The input is essentially a fluence, since the time component is negligibly small for these high-energy electrons.

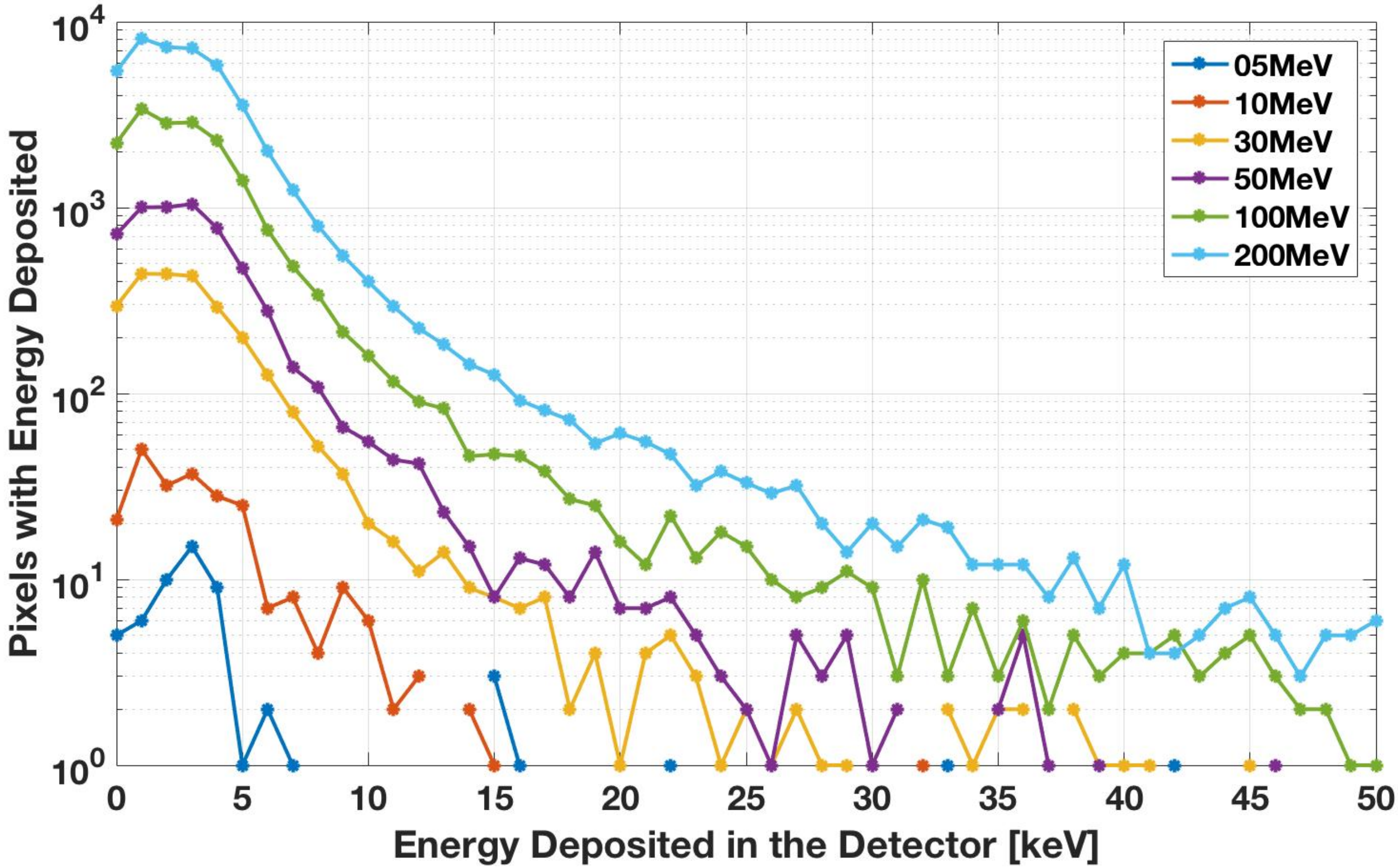


Resulting image from simulating 1 billion 100 MeV electrons on the SSI. Images are in 800 by 800 pixels with the intensity scale representing energy deposited in a pixel.

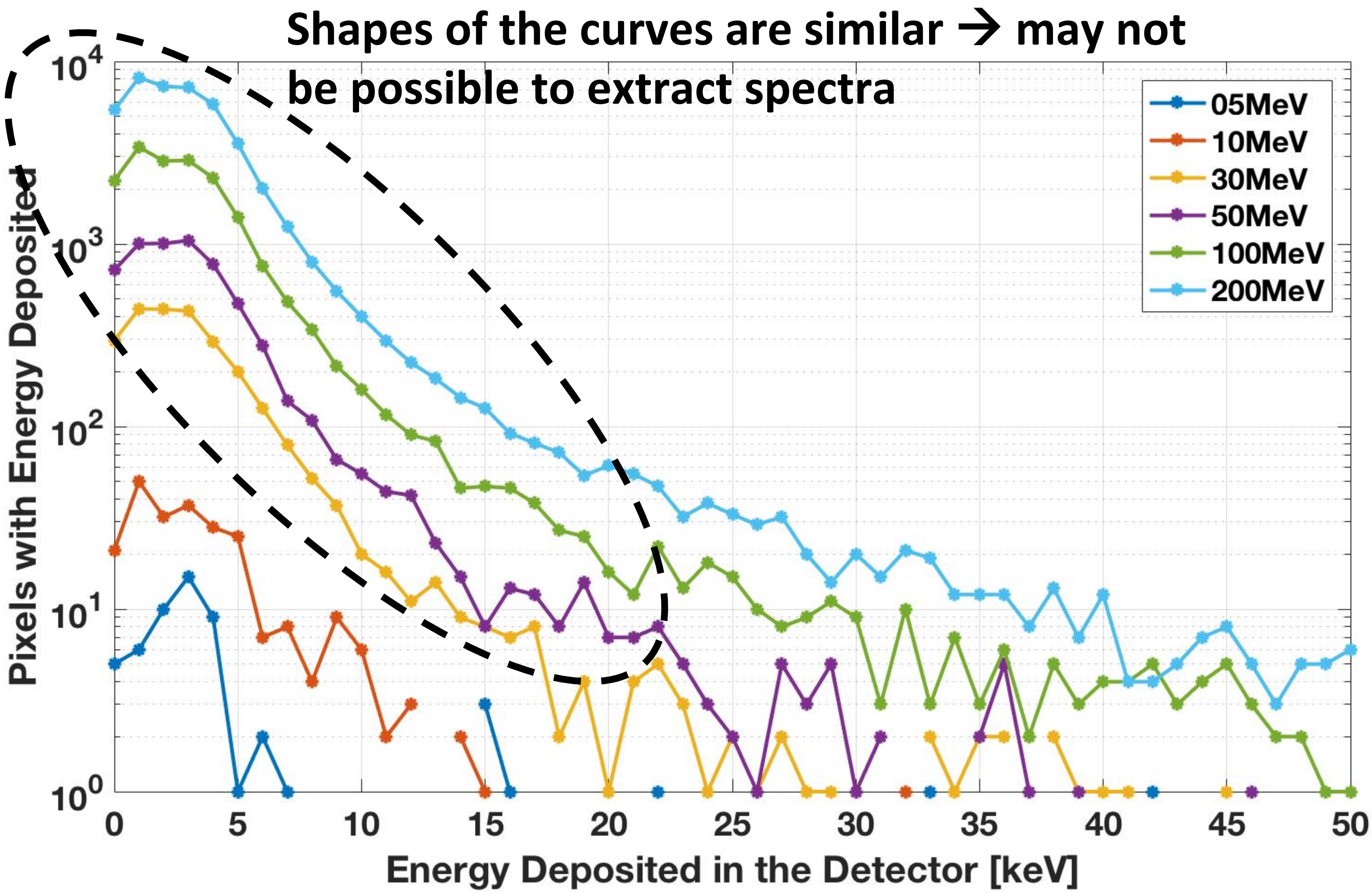


Histogram of results from simulation of 10 billion 50 MeV e-.

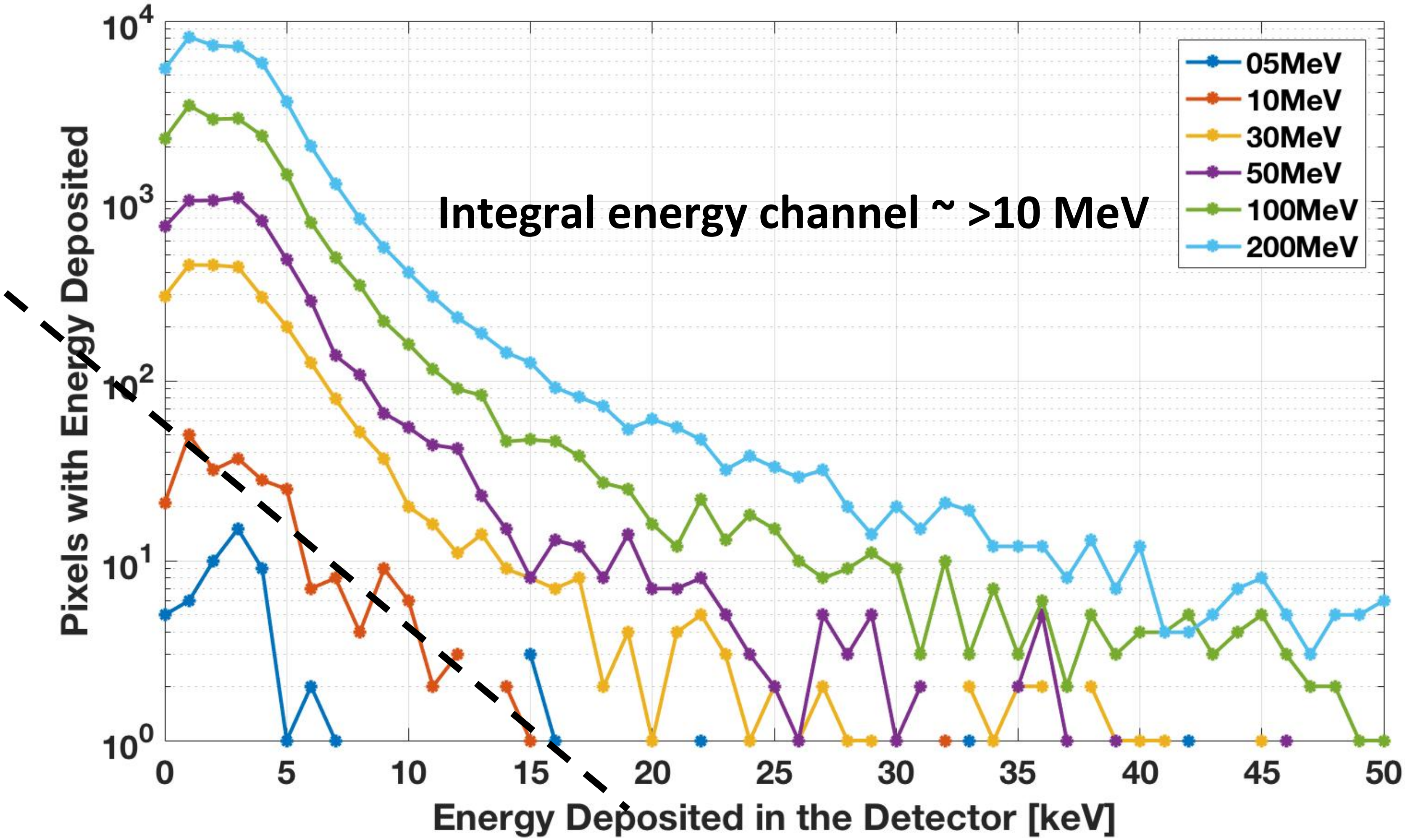
Mono-energetic Sims: Energy Deposited



Mono-energetic Sims: Energy Deposited



Mono-energetic Sims: Energy Deposited



Geant4 Results

- Source environment simulated:
  - One billion mono-energetic electrons
  - Sphere radiating inward with a cosine distribution and radius *r = 150 cm*

A	B	C	D	E	F
Energy [MeV]	# Unique Hits			# Pixels with Hits	Particle to Pixel Hits (D/E)
	Primaries	Secondaries	Total (B+C)		
1	0	0	0	0	n/a
3	0	6	6	11	0.53
5	1	19	20	57	0.35
10	37	91	128	241	0.53
30	329	1063	1392	2529	0.53
50	626	2544	3170	5910	0.54
100	1197	8063	9260	17742	0.52
200	1975	20573	22548	44281	0.51

Ratio of the number of particles reaching the detector and the number of pixels with hits, G_1

Number of particles that reach the detector

Number of pixels with energy deposited

Geant4 Results

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200	1975	20573	22548	44281	0.51

Ratio of the number of particles reaching the detector and the number of pixels with hits, G_1

We find $G_1=0.53 \pm 0.014$ (95% conf.) particles/pixel

Number of particles that reach the detector

Number of pixels with energy deposited

Geometric Scaling Factors

Determining the flux from pixels with hits on the SSI observation requires scaling factors that can be calculated with the Geant4 simulations.

1. Calculate the ratio of pixels with hits to particles that deposit energy on the detector
   - R_0: pixel hits / total pixels
   - R_1: particles / total pixels

$$R_1 = R_0 G_1$$

G_1=0.53 particles/pixel

2. To find the number of particles per unit area, divide by the pixel size
   - Pixel size: 15 µm x 15 µm

[particles/cm^2]

3. Using the known fluence from the simulation f_0, compute the geometric view factor, G_2

Simulation fluence:
$f_0 = 1.258 \times 10^3$ #/cm^2-sr

$$f_0 = \frac{N}{4\pi(4\pi r^2)}$$

$$R_1 = f_0 G_2$$

Energy [MeV]	*Geometric scale factor, G_2 [sr]*
5	0.0036
10	0.0186
30	0.827
50	1.93
100	5.80
200	14.5

Example: SSI Observation 5101r, Orbit 22

- SSI image of Amalthea, taken at 9.4 R_J
- 295 pixels with hits out of 4161 pixels (7.09%)
- Integration time: 62.5 ms, Readout time: 8.667 s
- Pixel size: 15 µm x 15 µm

Image 5101r, from NASA PDS.

1. Calculate the pixel hit rate:

$$R_0 = \frac{295\ px}{4161\ px} \times \frac{1\ px}{(15 \mu m)^2} = 31510\ \frac{px}{cm^2}$$

2. Particle rate (from particles in the environment from all energies):

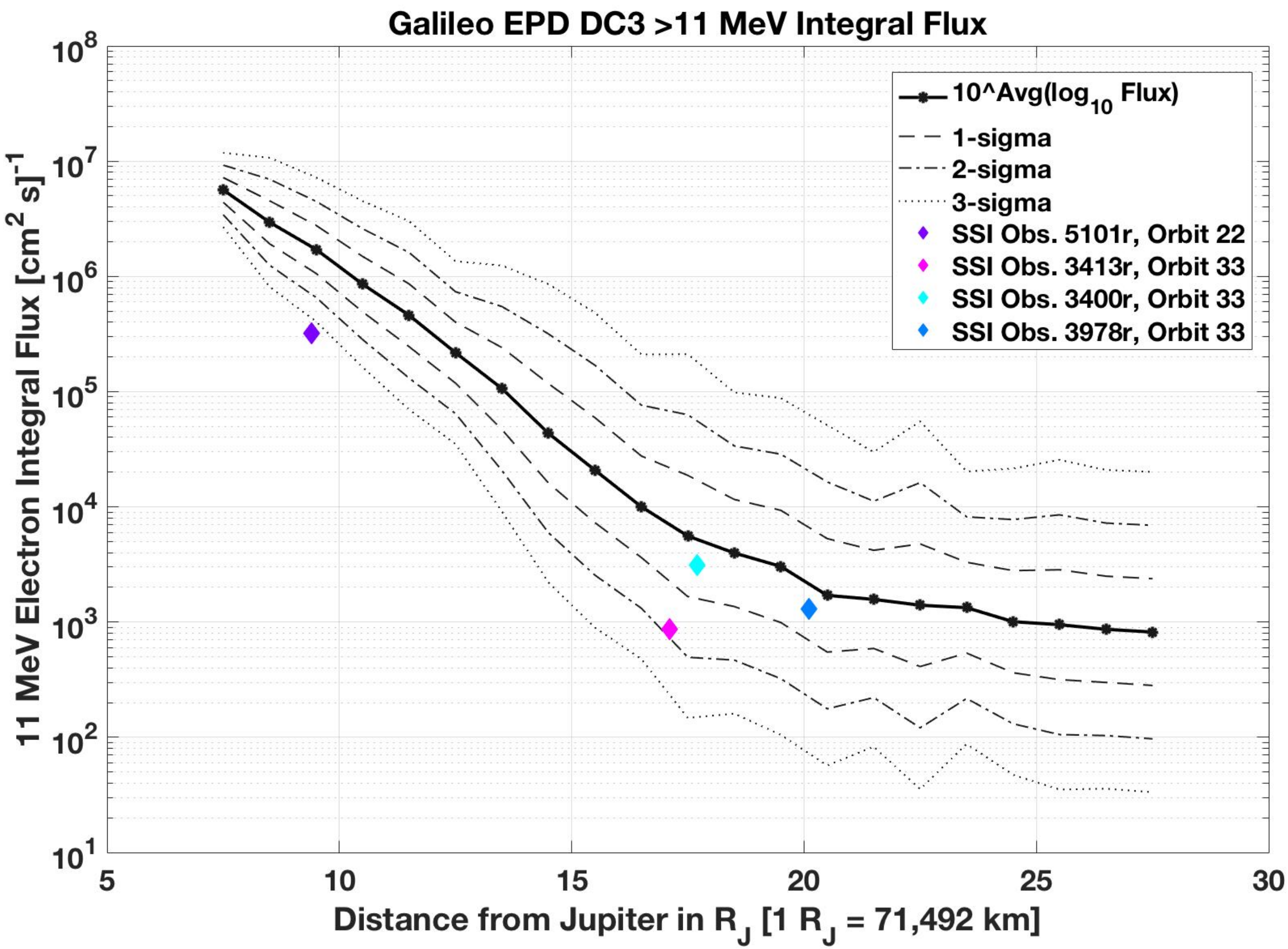
$$R_1 = R_0 G_1 = \left(31510\ \frac{px}{cm^2}\right)\left(0.53\ \frac{particles}{px}\right) = 16700\ \frac{particles}{cm^2}$$

$$R_1 = \frac{16700\ \frac{particles}{cm^2}}{0.0625\ s + 8.667\ s} = 1913\ \frac{particles}{cm^2 s}$$

3. Apply the scale factor G_2 for 10 MeV and calculate the flux:

$$f = \frac{R_1}{G_2(E = 10\ MeV)} = \frac{1913\ \frac{particles}{cm^2 s}}{4 \times 0.0186\ sr} = 2.57 \times 10^4\ \frac{particles}{cm^2\ s\ sr}$$

Comparison to Galileo EPD



Log-normal fitting and EPD uncertainties can be found in Jun et al., 2005.

Next Steps

- Galileo SSI
  - Build confidence in ~10 MeV integral channel by performing more Geant4 simulations
  - Process all remaining SSI images and extract energy deposition curves and >10 MeV flux
  - Compare curves to EPD

- Galileo NIMS analysis to demonstrate technique can be applied to other imagers

- Testing with electron beam for validation of Geant4 modeling physics
  - Test solid-state detector response to energetic electron beams under different amounts of shielding

Expected Contributions

- Invent a technique and design a generalized procedure to extract high-energy (>1 MeV) electron environment information from solid-state detectors.
  - Demonstrate how to find at least one integral energy channel from the Galileo Solid-State Imaging instrument.
  - Demonstrate how to find at least one integral energy channel from the Galileo Near-Infrared Mapping Spectrometer (NIMS).
  - Demonstrate agreement with the Galileo Energetic Particle Detector (EPD).
  - Analyze results compared to current Jovian radiation models (GIRE-2, supplied by JPL).

- Test solid-state detector in electron beams to validate Geant4 modeling physics.

- Compose recommendations and requirements for testing, calibration, and operational procedures for an instrument on the Europa Clipper mission in order to use the technique developed in this thesis.

Research Schedule

Summer 2017	Fall 2017	Spring 2018	Summer 2018	Fall 2018
Galileo SSI: Complete additional mono-energetic simulations of the SSI in Geant4 to define confidence interval on energy and flux scaling factors. **Testing:** Support test plan and part procurement; Model test set-up; Perform tests in lab **Writing:** Submit paper on masters research	**Galileo SSI:** Complete extraction of radiation info and processing of all SSI images; Comparison to EPD and GIRE-2. **Galileo NIMS:** Begin analysis of data; Determine how to extract the energy and hit rate info from the images. **Testing:** Post-process results	**Galileo NIMS:** Modeling of NIMS in Geant4; Perform simulations **Writing:** Write and submit paper on SSI work Conference presentation (TBD)	**Galileo NIMS:** NIMS scaling factors; Comparison of NIMS results to EPD and GIRE-2, and to SSI. Assessment of generalizability, recommendations for Europa Clipper instrument **Writing:** Write thesis	**Writing:** Write thesis, defend, and graduate Conference presentation (TBD)

Academic Requirements

Req.	Course Number	Course Title	Semester Taken	Grade/ Status
Major	16.413	Intro. to Autonomy & Decision-Making	Fall 2013	A
Major	16.851	Satellite Engineering	Fall 2014	A
Major	16.363	Communication Systems	Spring 2015	A
Major	16.89	Space Systems Engineering	Spring 2015	A
Major	16.899	Systems Engineering of FLARE project	Fall 2016	A
Major	22.16	Nuclear Technology and Society	Spring 2015	A
Minor	16.910	Intro. to Numerical Simulation	Fall2014	A
Minor	16.343	Sensors and Instrumentation	Spring 2017	In progress
Minor	8.613 OR 8.701	Plasma Physics OR Nuclear and Particle Physics	Fall 2017	Planned

On track to meet PhD requirements.

Degree Milestones

Degree Requirement	Date Complete
Qualifying Exams	January 2016
Masters Degree	May 2016
Thesis Proposal Defense	May 23, 2017
Thesis Defense	Summer 2018 (TBR)

References (1/2)

[1] F. Bagenal, T. Dowling, and W. McKinnon, eds. *Jupiter: The Planet, Satellites and Magnetosphere*. Cambridge University Press, 2004.

[2] H. Garrett et al. "The Jovian Charging Environment and Its Effects – A Review". In: *IEEE Transactions on Plasma Science* 40.2 (Feb. 2012), pp. 144–154.

[3] M. de Soria-Santacruz Pich, et al., "An empirical model of the high-energy electron environment at Jupiter". In *J. Geophys. Res. Space Physics*, 121.10 (2016). Pp. 9732-9743.

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[6] C. Phillips and R. Pappalardo. "Europa Clipper Mission Concept: Exploring Jupiter's Ocean Moon". In: *EOS, Trans. Am. Geophys. Union* 95.20 (2014), pp. 165-167).

[7] C. Chyba and C. Phillips, "Surface-Subsurface Exchange and the Prospects for Life on Europa," In: *Proc. of Lunar and Planetary Sci. Conf*, Vol. 32, 2001.

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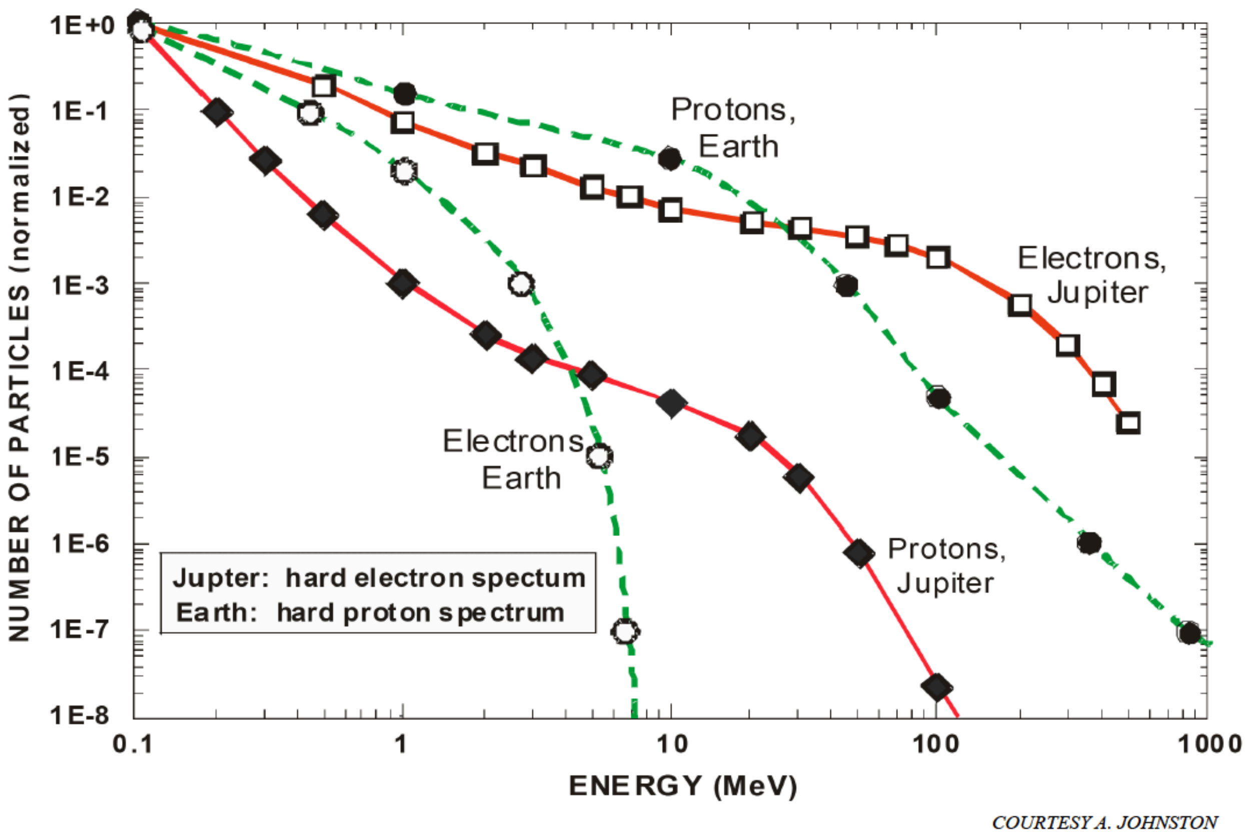
Hard Electron Spectrum at Jupiter

- Comparison between Jovian and Terrestrial radiation spectra



Missions to the Outer Solar System

Spacecraft	Jupiter	Cost	Mass (wet)
Pioneer 10	**Jupiter**: 1973, flyby	$350 M (FY2001)	258 kg
Pioneer 11	**Jupiter**: 1974, flyby; **Saturn**: 1979, flyby		259 kg
Voyager 1	**Jupiter**: 1979, flyby; **Saturn**:1980, flyby	$900 M	2080 kg
Voyager 2	**Jupiter**: 1979, flyby; **Saturn**:1981, flyby; **Uranus**: 1986, flyby; **Neptune**: 1989, flyby		2080 kg
Galileo	**Jupiter**: 1995-2003, orbiter; 1995, 2003 atmospheric	$1.41 B	2223 kg
Ulysses	**Jupiter**: 1992, 2004, gravity assist	$318 M (FY1989)	371 kg
Cassini-Huygens	**Jupiter**: 2000, gravity assist; **Saturn**: 2004-present, orbiter; 2005, Titan lander	$3.27 B	5712 kg
New Horizons	**Jupiter**: 2007, gravity assist; **Pluto**: 2015, flyby	$700 M	478 kg
Juno	**Jupiter**: 2016-present, orbiter	$1.1 B	3625 kg

Current Models and Limitations

Model Name	Reference	Description and Comments
Divine and Garrett (D&G)	Divine and Garrett, 1983	First comprehensive model of the radiation and plasma environment around Jupiter Empirical, from Geiger tube telescope (GTT) on Pioneer 10 and 11, and from the cosmic ray telescope on Voyager 1 and 2.
Divine and Garrett (D&G), updated	Garrett et al., 2005	Included data from Earth-based observations of the Jupiter synchrotron emissions
Jovian Specific Environment (JOSE)	ONERA, France Sicard-Piet et al., 2011	Based on Salammbô theoretical code in combination with data from the Energetic Particle Detector (EPD) on the Galileo spacecraft
Galileo Interim Radiation Environment (GIRE) and GIRE2	Garrett et al., 2002; Garrett et al., 2012; de Soria-Santacruz et al., 2016	Empirical model, uses 10-min averages from the Energetic Particle Detector (EPD) on Galileo V2 addresses discontinuities at the boundary between GIRE and the D&G models and extends from ~16 R_J to up to ~50 R_J

Current models are limited by lack of data, both spatially and temporally.

Key Environmental Interactions

TABLE 1. Key environmental interactions for Juno while in jovian orbit. Interactions are listed in approximate order of concern (1 being the highest).

EFFECT	*ENVIRONMENTAL SOURCE*
1. Radiation dose/dose rate	100 KeV—50 MeV Electrons 1 MeV—100 MeV Protons
2. Surface Charging/ESD	1-1000 KeV Electrons
3. Single Event Effects	1-100 MeV Protons Greater than 1 MeV/Nuc Heavy Ions
4. Internal Charging/IESD	1-10 MeV Electrons
5. Contamination	Outgassing of Spacecraft Materials, Thrusters
6. Solar Array Power Loss/Arcing	Plasma
7. Hypervelocity Impact	10^{-6}—10^{-3} g Meteoroids
8. Induced E-Field	VxB Effect
9. Drag	Neutral Atmosphere
10. Surface Damage (Sputtering)	Positive Ions
11. Spacecraft Glow	Neutral Atmosphere

Table credit: H. Garrett

High-Energy Particle Measurements

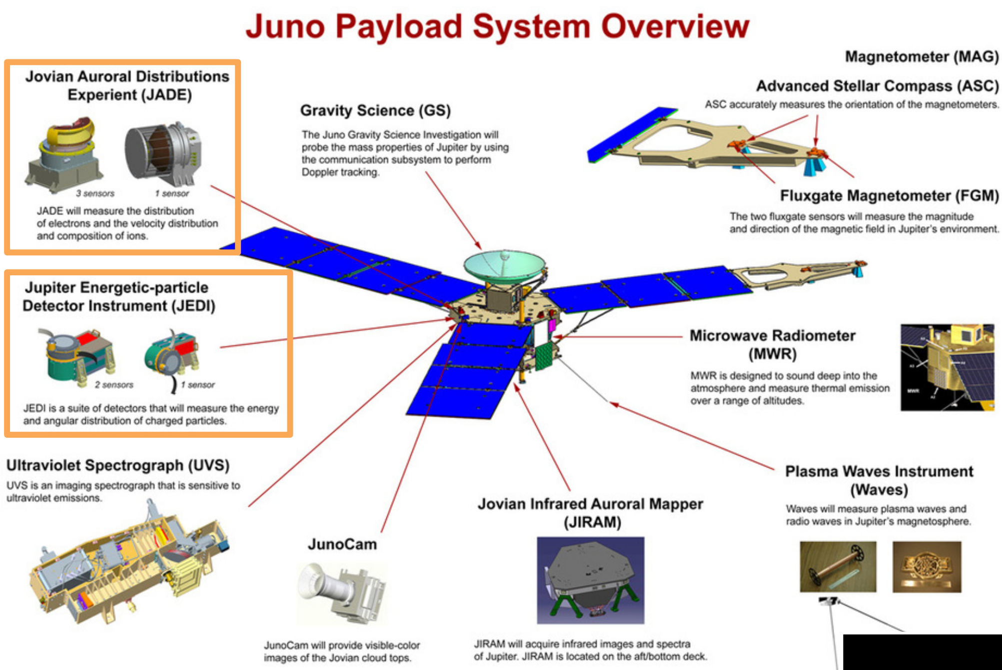


Image source: NASA/JPL-Caltech

- Juno: high-energy particle measurement instruments
  - Jovian Auroral Distribution Experiment (JADE):
    - Electrons: 100 eV – 100 keV
    - Ions (1-50 amu): 10 eV – 40 keV
  - Jupiter Energetic-particle Detector Instrument (JEDI):
    - Electrons: 20 keV – 1 MeV
    - Protons: 15 keV to 3 MeV

- Europa Clipper: no instruments currently dedicated to MeV particle detection

- ***Why do we care? Why is this not enough?***

Effect	Environment Source
1. Radiation dose / dose rate	100 keV – 50 MeV electrons 1 MeV – 100 MeV protons
2. Surface Charging / ESD	1 keV – 1 MeV electrons
2. Single Event Effects	1 – 100 MeV protons >1 MeV/Nuc. heavy ions
3. Internal Charging / IESD	1 – 10 MeV electrons

Extract Information from Existing Hardware

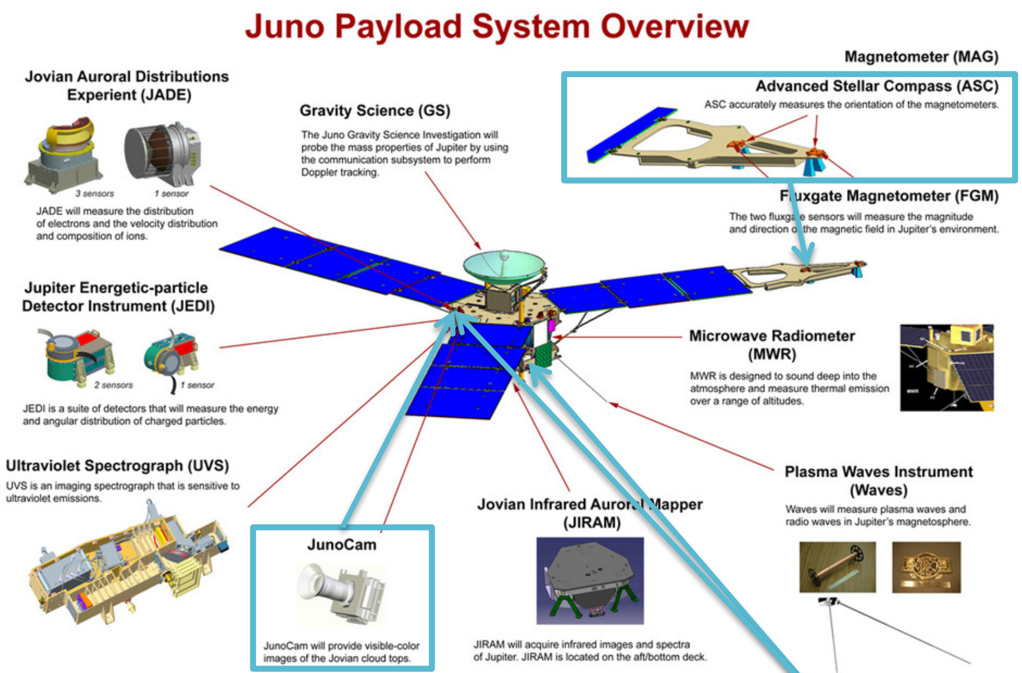
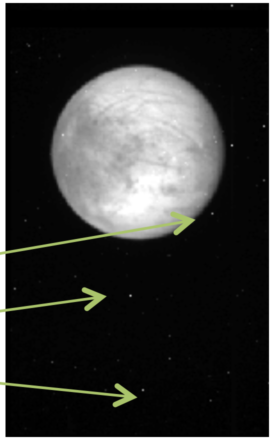


Image source: NASA/JPL-Caltech

Stellar Reference Units (SRUs)

- **Science imagers** are
  1. Common to exploration missions, such as those to Jupiter
  2. Affected by MeV particles
- Three instruments on Juno are CCDs
- Europa Clipper: UVS, MISE, EIS, and MASPEX are sensitive to MeV electrons

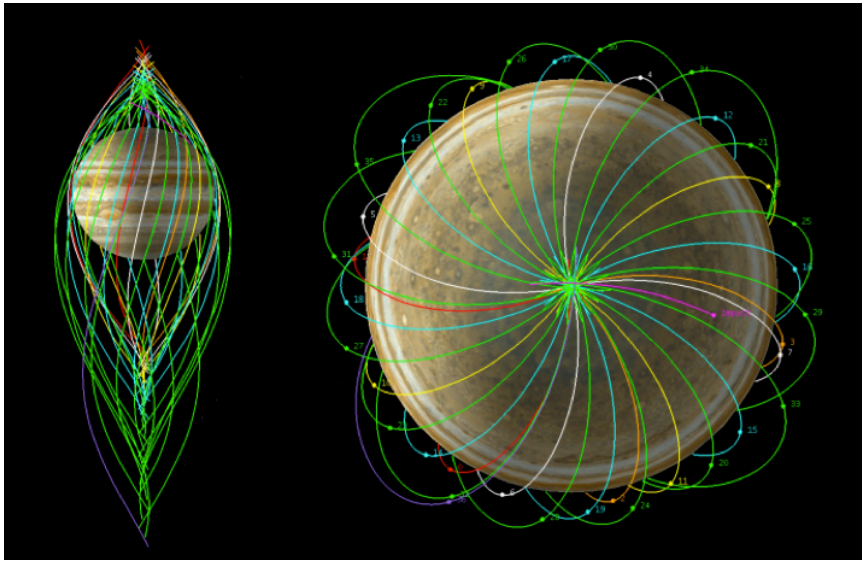
Goal: Use science imagers to measure the high-energy radiation environment.



~~Trash?~~
Treasure!

Opportunities: Juno

- Mission Overview: Juno
  - JOI: July 2016, nominal science to start Dec. 2016
  - Science phase: 37 orbits, 20 months
  - Polar measurements → greater orbit diversity
  - Juno equipped with detectors for 1 MeV e- and 3 MeV p+
- Three instruments are CCDs
  - Juno Color Camera (JunoCAM)
  - Advanced Stellar Compass (ASC)
  - Stellar Reference Unit (SRU)



Juno orbit plan, resulting in 24° spacing over 15 orbits. Image source: NASA/JPL-Caltech (Note: Image made prior to JOI.)

Juno Instruments and Systems

TABLE 2. Juno scientific and engineering systems considered to be of possible value to a study of environmental effects.

Name of Systems	Measurement Capability
Jovian Auroral Distribution Experiment (JADE)	Electrons: 100 eV-100 keV Ions (1-50 amu): 10 eV-40 keV
Energetic Particle Detector (EPD)	Ions: >5 keV H, >20 keV S/O Protons: 15 keV to 3.0 MeV Alphas: 25 keV-3.0 MeV CNO: 60 keV-20 MeV Sulfur: 80 keV-20 MeV Electrons: 20 keV-1 MeV
Waves Experiment (WAVES)	E-Field: 50 Hz-40 MHz B-Field: 50 Hz-20 kHz Periapsis survey temporal resolution: 1 spectrum/s Apoapsis survey temporal resolution: 1 spectrum/30s
Magnetometer (MAG)	Fluxgate (FGM): 0-16.384 G Scalar Helium (SHM): 0.1-16.0 G
Juno Color Camera (JunoCAM)	CCD
Advanced Stellar Compass (ASC)	CCD
Stellar Reference Unit (SRU)	CCD
Power Subsystem	Solar cells (Total Area = 36 m^2)

Opportunities: Europa

- Mission Overview:
  - Phase B of design, Launch date: ~2022
  - Orbiter and lander to study Europa
  - Highly elliptical orbit design

- No detectors with dedicated MeV capabilities at all…
- UVS, MISE, EIS, and MASPEX are sensitive to MeV electrons
- Measured electron energy range determined by instrument shielding and sensitivity
- Beam tests and transport simulations should be performed to calibrate the instrument response to radiation

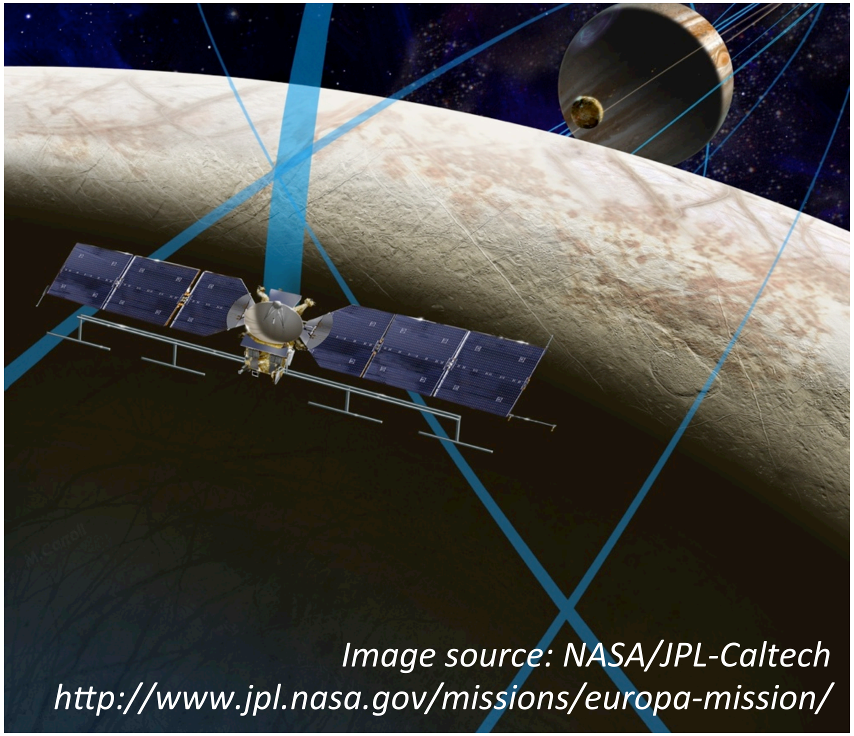


Image source: NASA/JPL-Caltech
http://www.jpl.nasa.gov/missions/europa-mission/

Approach and Methodology

- The Galileo spacecraft orbited Jupiter from December 1995 to September 2003, completing 35 orbits.

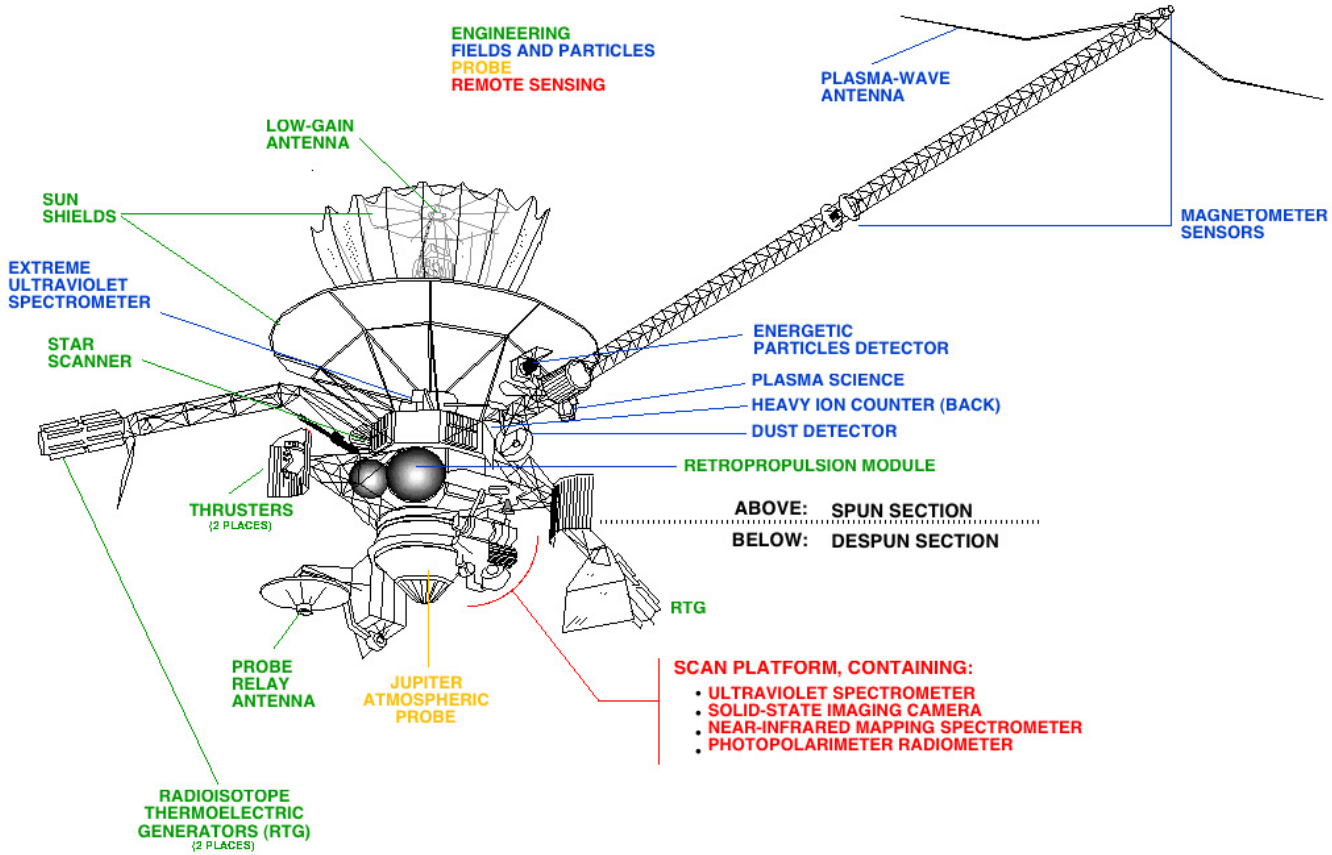
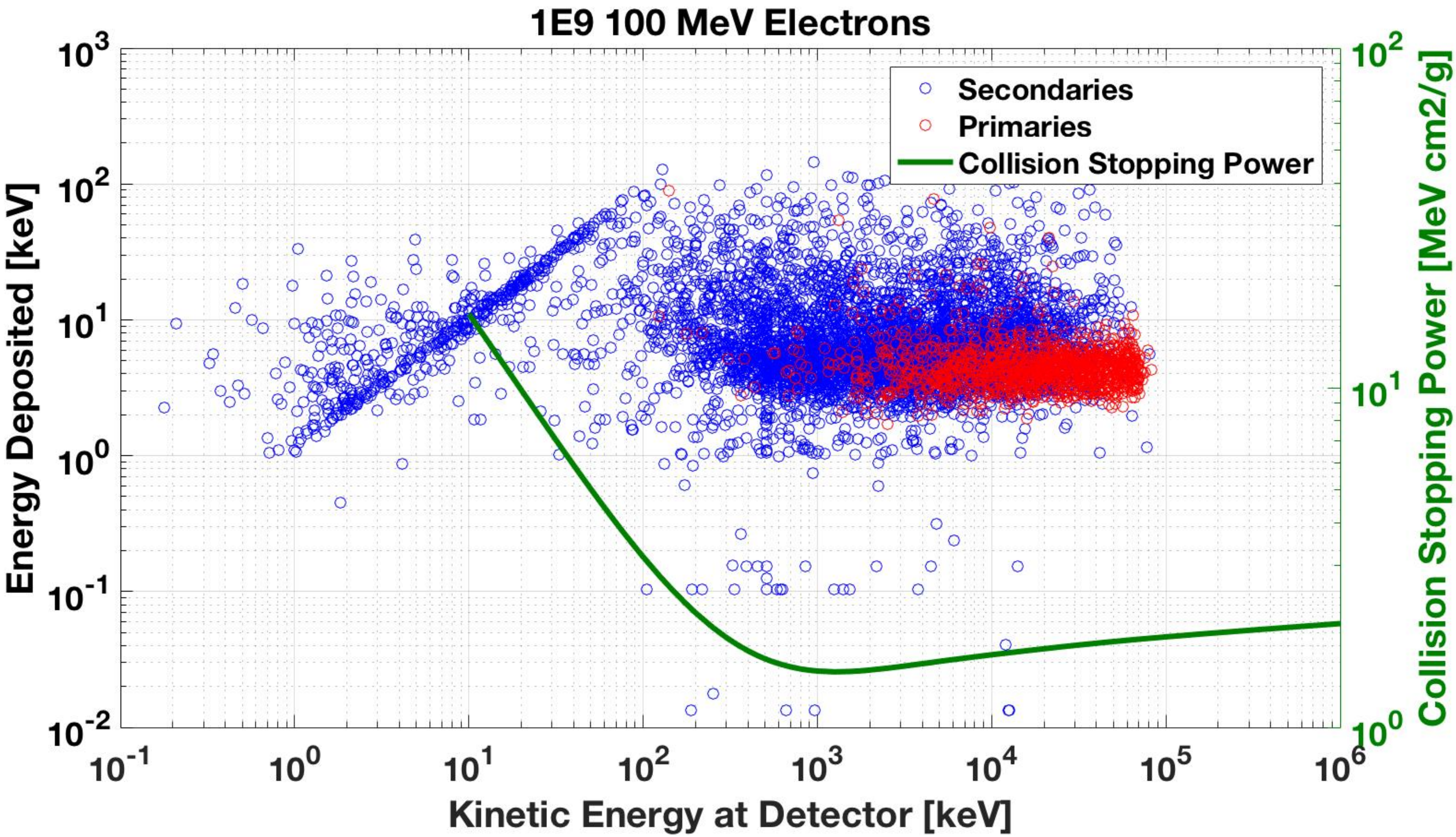


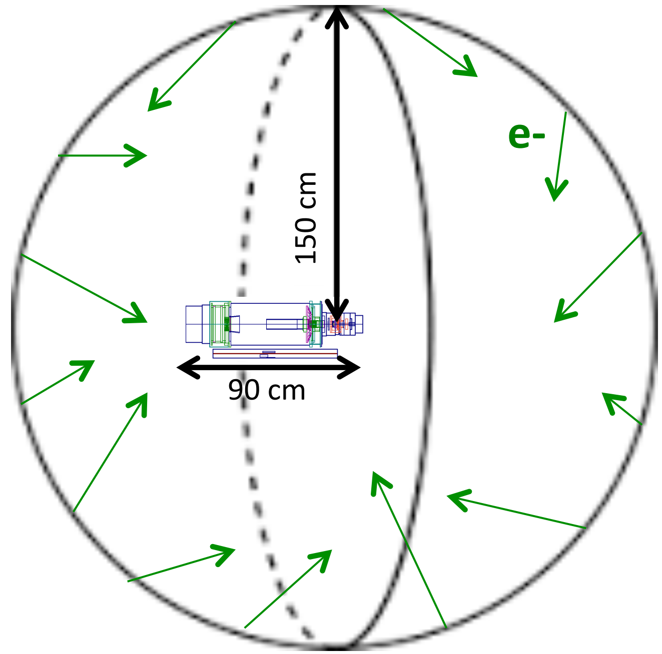
Image source: NASA https://solarsystem.nasa.gov/galleries/galileo-diagram-labeled

Mono-energetic Sims: Energy Deposited



Simulation Fluence

- 1E9 electrons simulated
- Sphere with radius r = 150 cm
- Angular distribution: cosine-law (uniform 2π flux from a plane)



$$f_0 = \frac{N}{4\pi(4\pi r^2)} = \frac{1\times 10^9}{4\pi(4\pi(150)^2)} = 1.258\times 10^3$$

Units: particles/sr-cm^2

- Need to multiply by a factor of 4 for the real environment:
  - Particles radiate inwards *and outwards*
  - Angular distribution is isotropic (what would be seen from a uniform 4π flux)

Simulation Run 2

A	B	C	D	E	F
	#Unique Hits				Hits to Pixels
Energy [MeV]	Primaries	Secondaries	Total (B+C)	# Pixels with Hits	Particle to Pixel Hits (D/E)
1	0	0	0	0	0
3	0	3	11	3	0.27
5	0	16	26	16	0.62
10	48	99	225	147	0.65
30	296	1001	2489	1297	0.52
50	622	2661	6151	3283	0.53
100	1144	7989	18263	9133	0.50
200	1999	20496	44650	22495	0.50

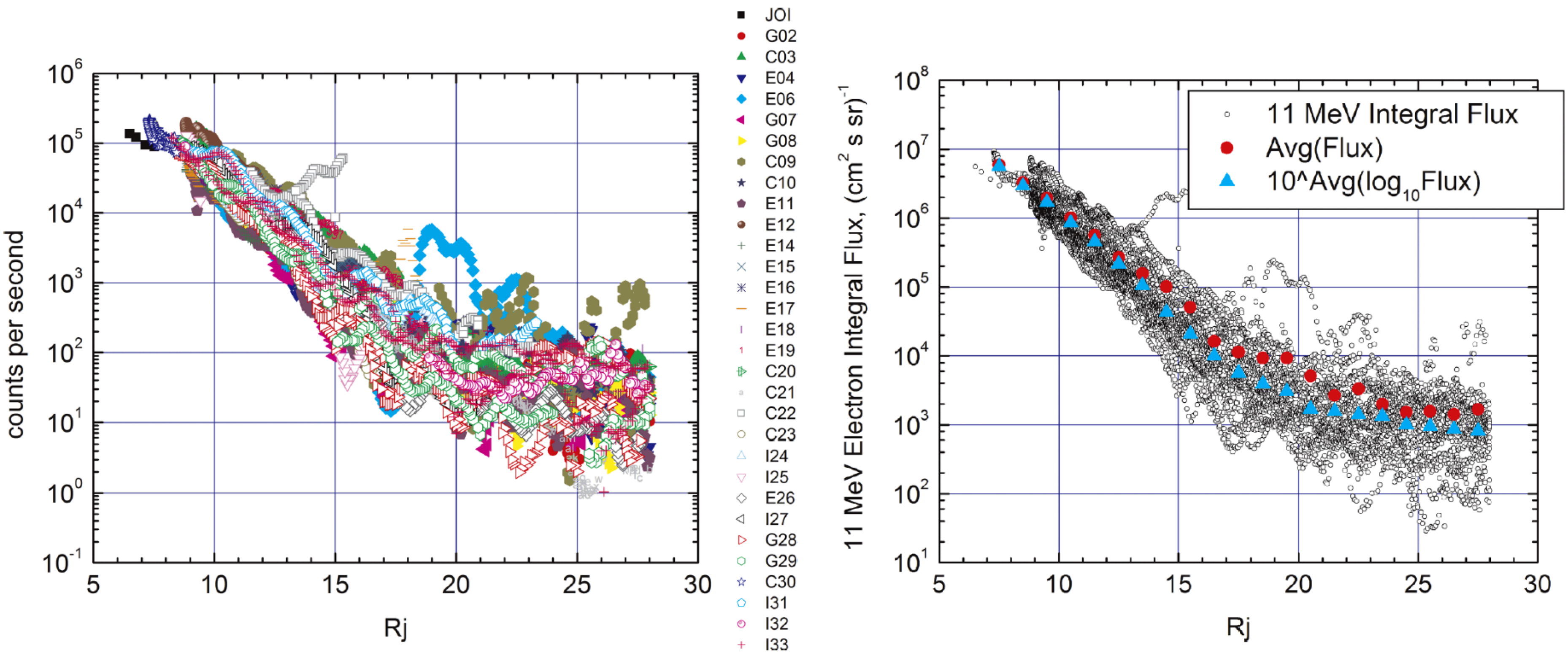
Ratio of the number of particles reaching the detector and the number of pixels with hits, G_1

We find G_1=0.54 ± 0.056 (95% conf.) particles/pixel

Number of particles that reach the detector

Number of pixels with energy deposited

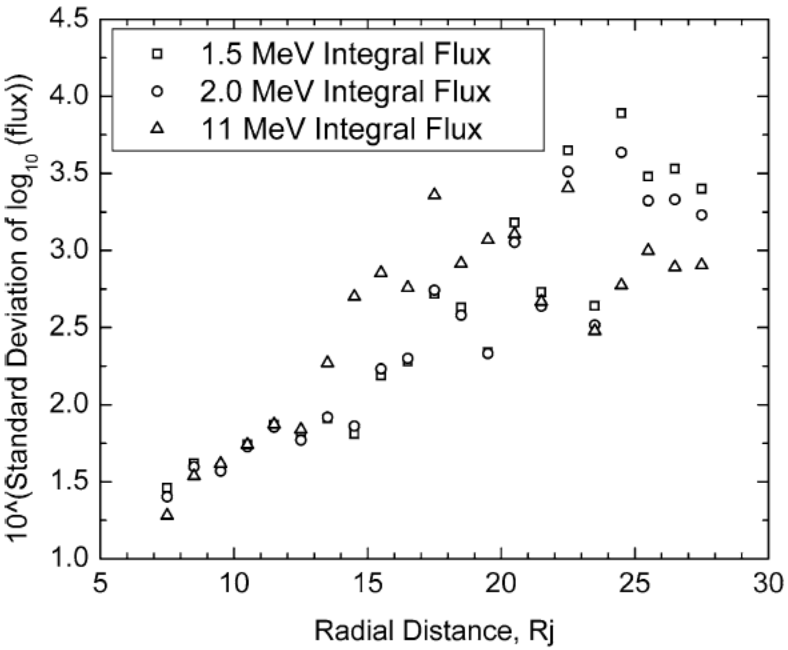
Galileo Energetic Particle Detector



10-minute EPD integral count rate (left) and omnidirectional flux (right) for the DC3 (>11 MeV) channel as a function of distance from Jupiter. On the right, the data are fit with a linear (in red) and a log-normal distribution (in blue). The log-normal average are a better fit to the data. Image source: I. Jun et al., 2005

Galileo EPD Uncertainties

$$x = \sigma^n \bar{x}$$

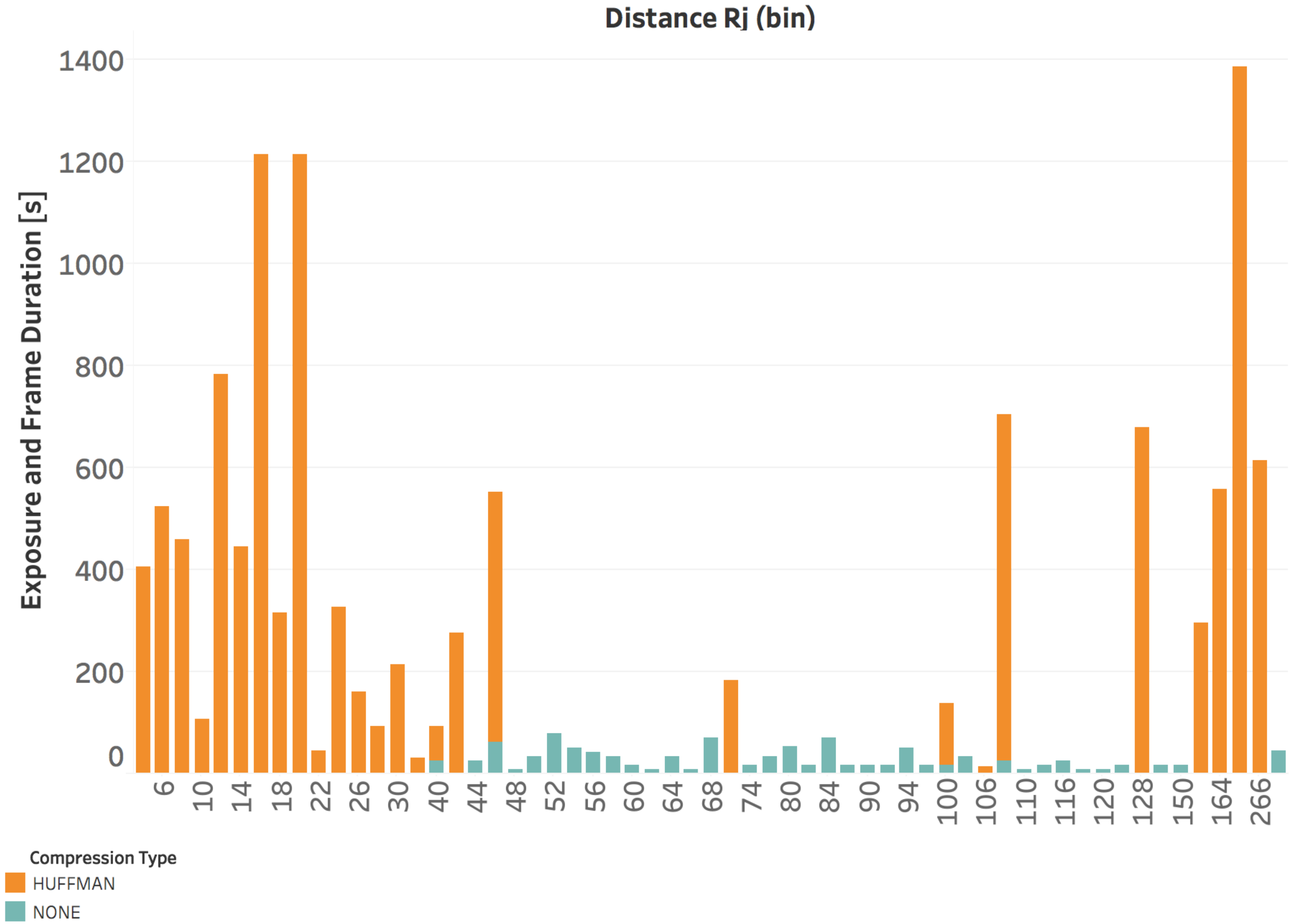


Plot of the uncertainty (standard deviation) of the ratio of the observed flux to the predicted flux as a function of distance (binned by 1 R_J). Image source: I. Jun et al., 2005.

For 11 MeV integral flux:

Distance from Jupiter, $R_{J,avg}$	10^STD(11 MeV)
7.5	1.280
8.5	1.537
9.5	1.616
10.5	1.740
11.5	1.872
12.5	1.839
13.5	2.270
14.5	2.700
15.5	2.854
16.5	2.758
17.5	3.359
18.5	2.915
19.5	3.069
20.5	3.107
21.5	2.667
22.5	3.405
23.5	2.478
24.5	2.774
25.5	2.998
26.5	2.891
27.5	2.906

Galileo SSI Images for Analysis



Backup Plans

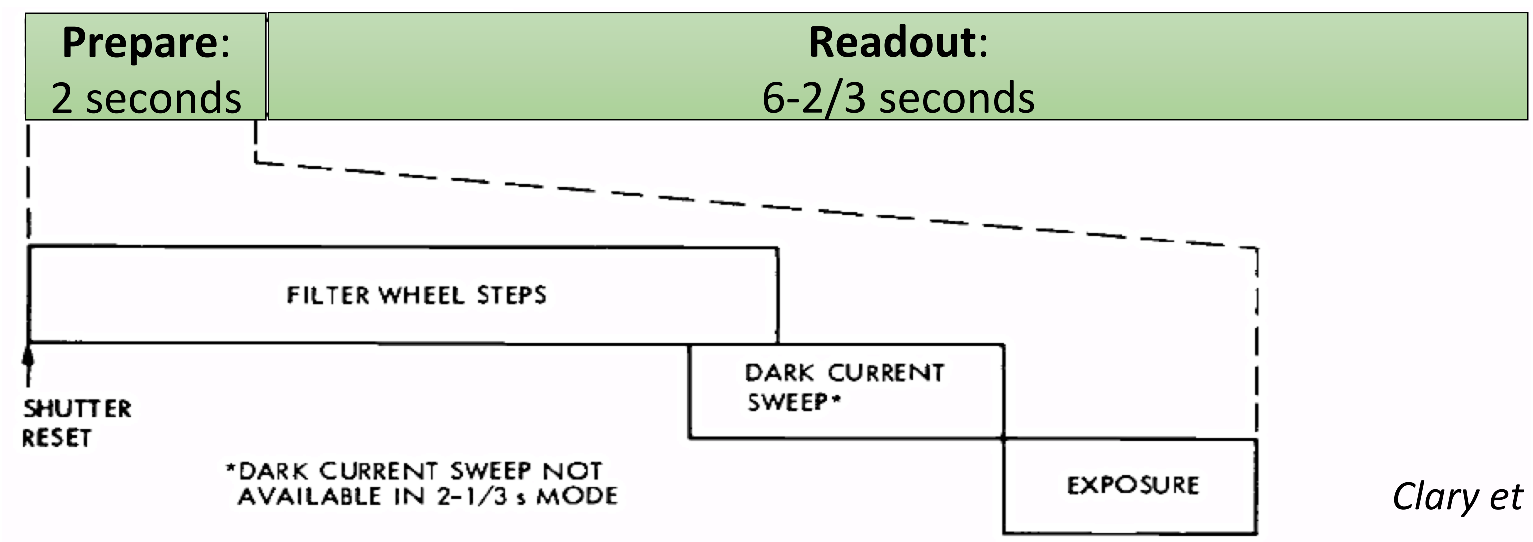
- If it is not possible to extract an integral energy channel from either the SSI or NIMS instruments (*e.g.*, the information extracted does not agree with the EPD), we will augment the null result with additional analyses of non-traditional sources of radiation information.
  - Analysis of Galileo star tracker data (not images, but hits)
  - Analysis of housekeeping telemetry from Galileo
  - Analysis of Galileo's Ultra-Stable Oscillators (USOs). USO frequency shifts correspond to radiation dose.

Galileo SSI Operation and Modes

- Four imaging modes:

Imaging Modes	2-1/3 s	8-2/3 s	30-1/3 s	60-2/3 s
Prepare Time	2/3 s	2 s	3-2/3 s	7-1/3 s
Readout Time	1-2/3 s	6-2/3 s	26-2/3 s	53-1/3 s
Filter Steps Allowed	1	2	3	7

- Each frame has a "prepare" and "readout" operation.
- Example of 8-2/3 s mode:



Clary et al., 1979