Radiation Effects
in Outer Solar System Exploration

Challenges, State of the Art, Future Directions

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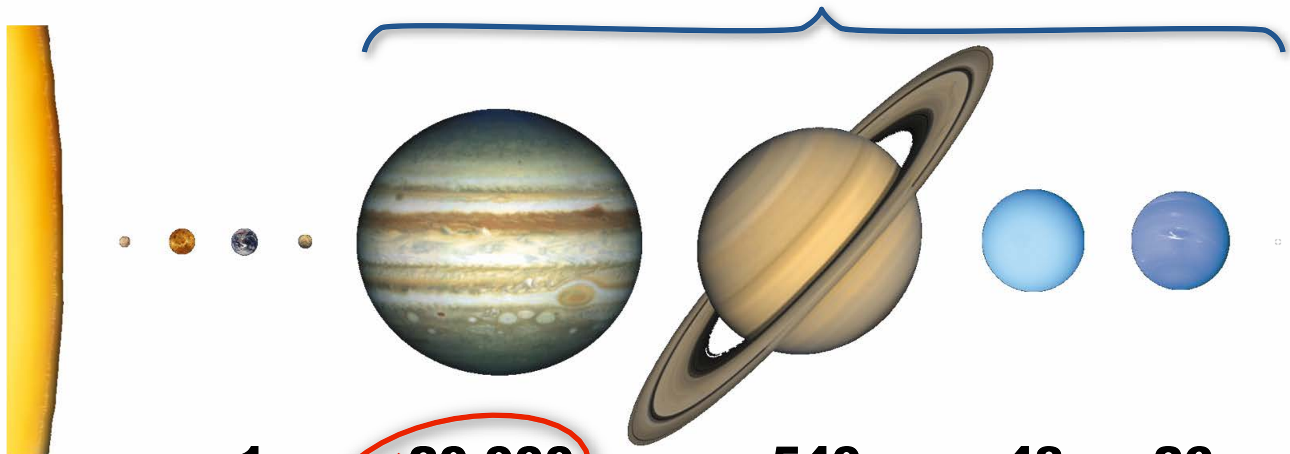
Radiation Troubles All Space Missions

- Total Ionizing Dose is a prime consideration
- But *also* important are…
  - Displacement damage effects
  - Sensor noise (damage and flux induced)
  - Single event effects (transient, upset, latch-up…)
  - Electrostatic discharge (internal and external)
  - Degradation of material properties
  - Local sources (radioisotope power and heating)
  - Diminishing returns from shielding (secondary particles)
- Outer solar system exploration presents a special challenge
  - Especially near planets and their satellites

Radiation in the Outer Solar System

Factors include solar distance & magnetic fields



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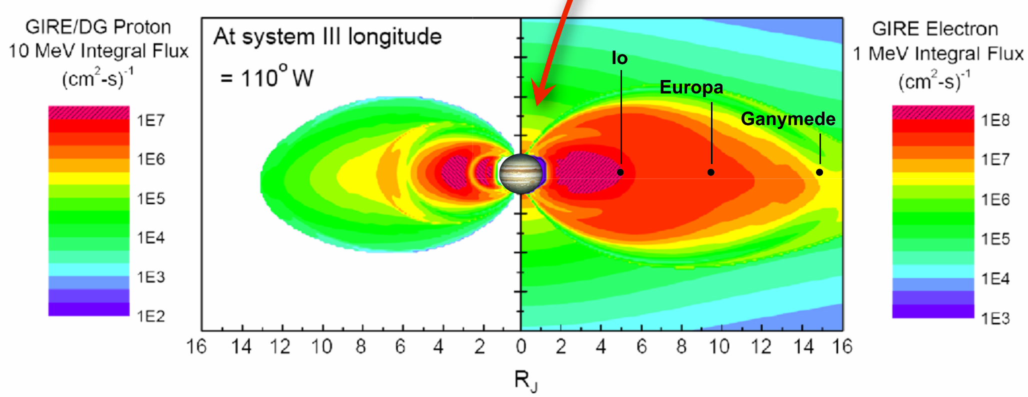
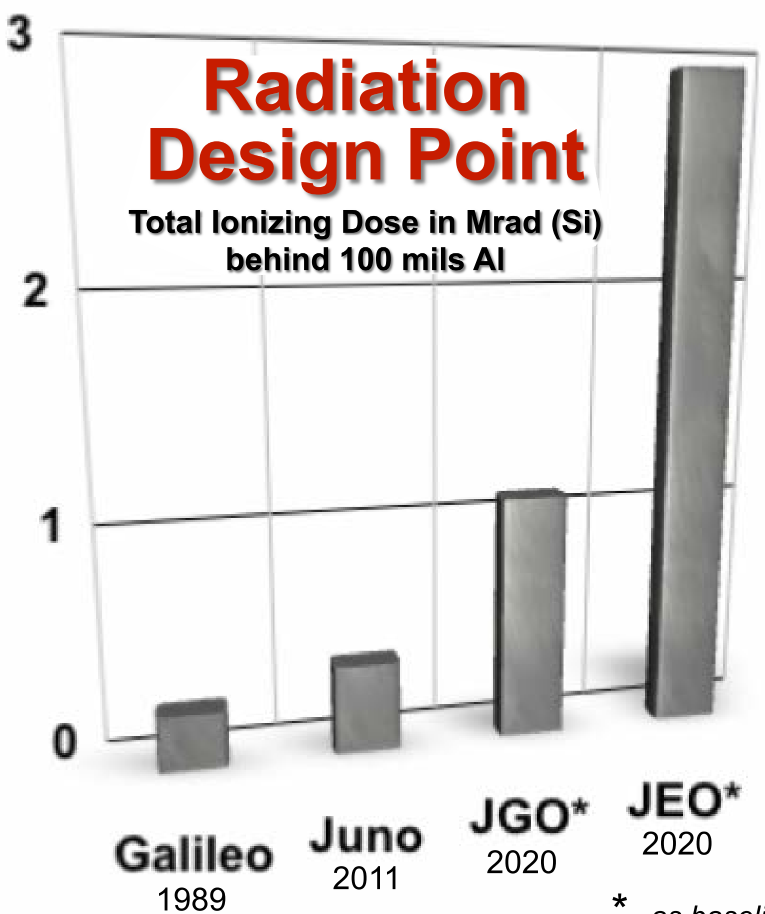
Magnetic Dipole Moment
in multiples of Earth's moment



- **Jupiter system radiation is the most intense**
- **But outer solar system planets, in general, are demanding**

Growing Mission Needs



* *as baselined in a recent study*

- Driven by great science
  - Get closer; stay longer; do more
- Enabled by progress in…
  - Understanding past experience
  - Bounding the environment
  - Availability of radiation-hard parts
  - Characterization of radiation effects
  - Design and analysis of shielding
  - Statistical assessment of lifetime

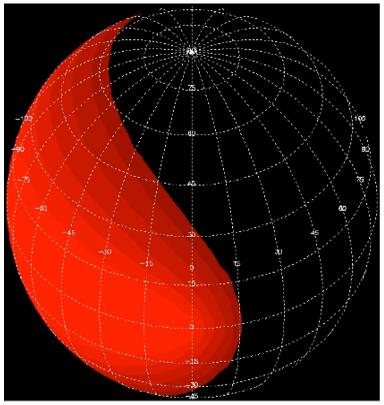
Progress in Understanding Past Experience

- Galileo still working at several times its design dose
  - Survived many radiation-related anomalies
- Factors in apparent conservatism:
  - Annealing
  - Circuit design margin
  - Operator interventions
  - Cautious hardness spec's
  - Passive redundancy
  - Fault masking autonomy
- However, surprising deficits also revealed
  - Weak parts
  - Uncharacterized degradations
- **Actual margins never well known**
- **Cross-system trades hampered**

Progress in Bounding the Environment

- Models refined using data of several missions
  - Orbiters: Jupiter (Galileo '96-'03), Saturn (Cassini '04-present)
  - Flybys: Jupiter (7), Saturn (3), Uranus (1), Neptune (1)

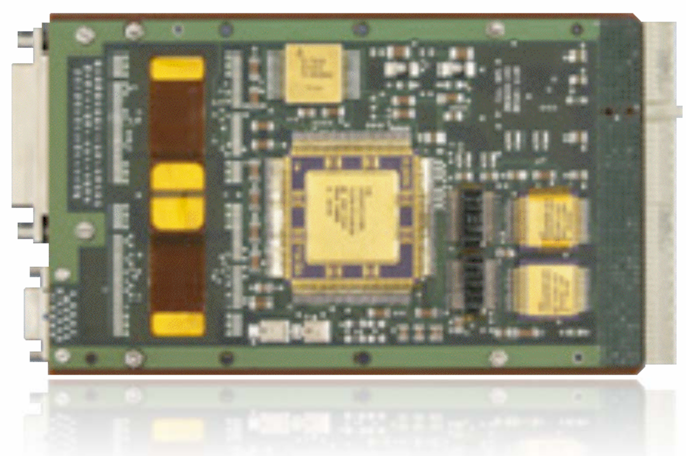
- Trapped radiation fluence found to be fairly stable, even given solar events
- Self-shielding effects of moons characterized



- Permits better trajectory tailoring to limit exposure

Progress in Availability of Radiation-Hard Parts

- Recent advances for military and nuclear applications
- Good choices in the 100 krad to 1 Mrad range
  - Key components (processors, memory, bus interface chips, ADCs…) available at 1 Mrad
  - Radiation-hardened ASICs qualified and flown
  - Many other parts tested and qualified to 300 krad
- Good range of detectors available, given appropriate mitigations
  - Adequate shielding and refined operational parameters
  - Data filtering to reduce noise
  - Test-as-you-fly characterization



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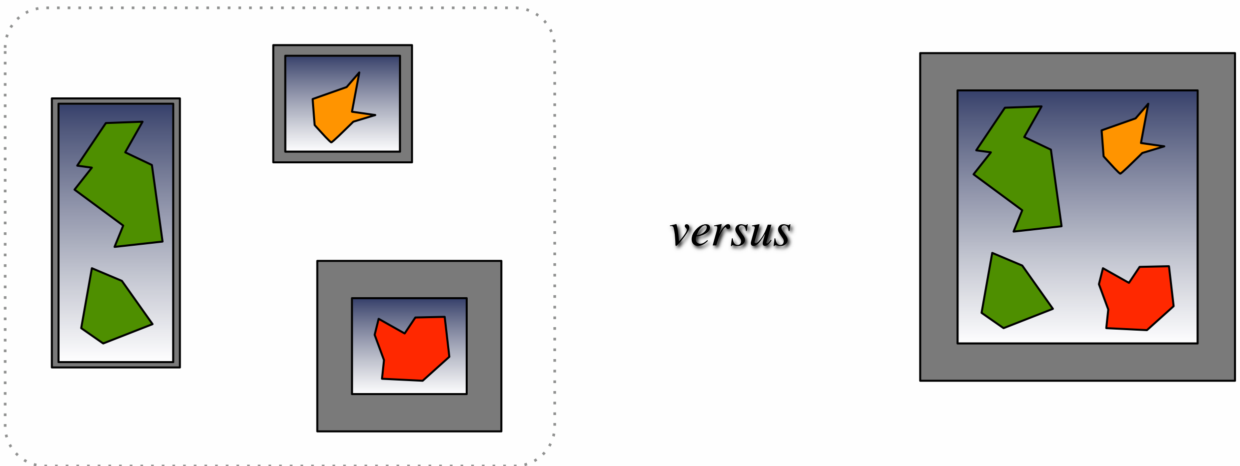
Progress in Characterization of Radiation Effects

- Broadened appreciation of…
  - Annealing (both passive *and* active)
  - Low dose rate effects (ELDRS)
  - Other phenomena
- Extended part testing past specification levels
  - Statistical insights into variation
  - Understanding of degraded behavior
- Improved circuit analysis
  - More realistic performance envelopes
  - Better understanding of sensitivities
  - Statistical characterization of degradation
- Commitment to on-board dosimetry

Understanding *the* **physics** *of radiation effects* **is important**, *if we are to take advantage of rapid technological advancement*

Progress in
Design and Analysis of Shielding

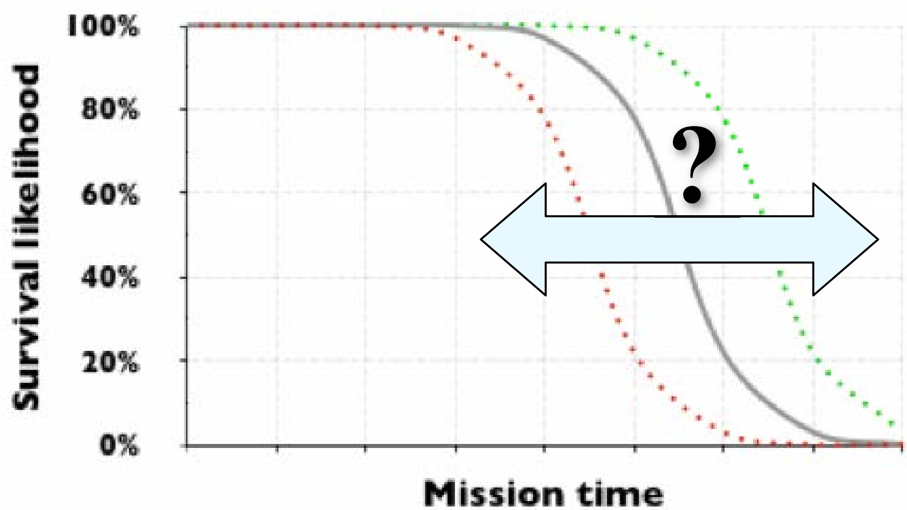
- Distributed shielding approaches
  - Local refinement instead of a common vault



- Improved radiation transport analysis tools
  - Faster; higher fidelity
  - Connection to CAD design
  - Accounting for secondary particles

Progress in Statistical Assessment of Lifetime

- Incorporates…
  - Environment spectrum and variation (temporal, spatial)
  - Part variation within lots and families (where available)
  - Screening to exclude outliers
  - Circuit, box, and system level mitigations
  - Operational usage (power, temperature, etc.)
  - Redundancy and graceful degradation modes



Where is This Headed?

- Modeling to link design features at all levels
  - Science value
  - Mission design
  - Operational flexibility and contingencies
  - Redundancy and fault management
  - Thermal and power configurations
  - Shielding and configuration
  - Circuit performance and robustness
  - Part and material degradation
- Better insight into margins, sensitivities, and dependencies, so…
  - Better cross-cutting system trades
  - Better exploitation of resources
  - Better risk management
  - Better exploitation of graceful degradation

Better Science!