National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Recent Radiation Research at JPL for University of Michigan Nuclear Engineering and Radiological Sciences Department Colloquium

April 15, 2005

Dr. Chuck Barnes (NE ’67 U of Mich.), Manager
Assurance Technology Program Office
Jet Propulsion Laboratory
California Institute of Technology

Outline

- Contributors
- JPL and the University of Michigan
  - A multi-faceted relationship
- JPL overview
  - Missions
  - Future Directions
    - Prometheus
  - Current work with U of M
- Radiation
  - Environments
    - Environmental modeling – Saturn
    - Environmental requirements for microelectronics
  - Examples of radiation effects work
    - Optocouplers
    - SOI microprocessors
    - Power MOSFETs
- Opportunities at JPL

Contributors

- Sammy Kayali
- Allan Johnston
- Richard Kemski
- Henry Garrett
- Chris Klatka
- Khori Dastoor

University of Michigan
Summary of Strategic Partnership Activity
2003-2004

- **Status of MOU**
  - **Modified MOU signed on February 16, 2004 by Dr. Marvin Parnes for U of M and Dr. Charles Elachi for JPL**
- **Summary of Research Activities**
  - **Funded Proposals**
    - Binary Near earth Asteroids
      - University PI: Daniel Scheeres
      - JPL PI: Steve Ostro
      - Description of Activity: Spacecraft Dynamics Using a Radar-Derived Model of the 1999 KW4 System
      - Funding: DRDF Competed ($82,251.00)
    - Tunable Comet Outgasing Models
      - University PI: Daniel Scheeres
      - JPL PI: Laureano Cangahuala
      - Description of Activity: Enabling Precisions S/C Navigation and Novel Scientific Measurement Opportunities at Comets
      - Funding: DRDF Competed ($144,000.00)
    - MACE
      - University PI: J. Hunter Waite
      - JPL PI: Isik Kanik
      - Description of Activity: Mars Analytical Chemistry Experiment
      - Funding: DRDF Off-Cycle ($499,966.60)

University of Michigan
Summary of Strategic Partnership Activity
2003-2004

- **Summary of Research Activities**
  - **Collaboration on Advanced Concepts for Interstellar Missions**
    - Description of Activity: U of M added JPL to their funded task
  - **Number of Joint Proposals to NASA/other agencies generated from Research: 13**
  - **Number of Participating Graduate/Undergraduate Students: 26**
  - **Seminars/Workshops**
    - Participated in 2 U of M hosted workshops (Mars and Earth Science)
    - 8 JPLers gave presentations to U of M students as part of Engineering 450 Course
  - **Internal R&D Coordination**
    - Began coordination on joint videoconferencing capabilities
    - Preliminary discussions held on coordination of Grid Computing investments
- **Summary of Educational Activities**
  - **Number of students in UAO Education Programs: 6**
  - **Number of students in HR Programs: 9**
  - **Other Educational Activities**
    - Engineering 450 Course Funded by MSL:
    - Bridging the Gap between Robotic and Human Exploration of Mars ($100K)
    - Participation in summer MIMIC student experiment

University of Michigan
Summary of Strategic Partnership Activity
2003-2004

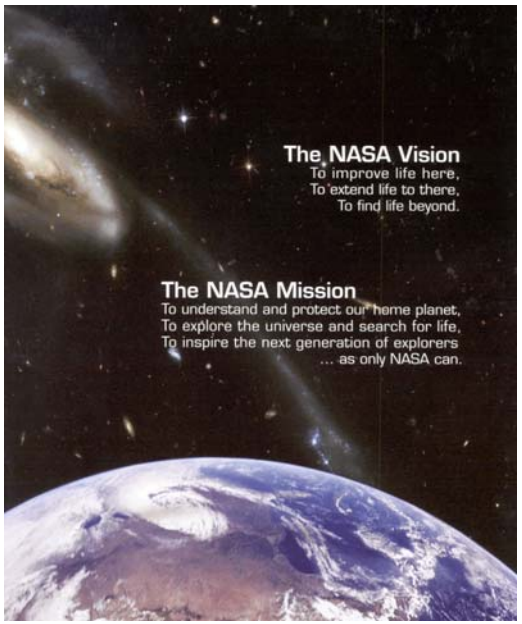
- **Summary of Pipeline Activities**
  - **Number of Recruiting Events: 4**
  - **Number of Students Hired: 7**
  - **Special Support Provided by SURP**
    - 39 Resumes personally collected from faculty and submitted to tech divisions
- **Additional FY 04 Developments**
  - **Program Office Representatives appointed: Claudia Alexander and Randy Friedl**
  - **Recruiting Technical Lead appointed: (not yet confirmed)**
- **Key New Initiatives planned for FY 05**
  - **Joint, Institutional-level research initiatives**
    - Planetary Research
      - Global Circulation Model for Mars that exploits synergies with Earth Science efforts (inclusion of aerosols)
      - Global “Circulation” Model appropriate to surface bound exospheres (regolith/atmosphere interactions with potential to test exobiology theories)
      - *Contingent upon a successful review*, possible 3rd year funding of MACE component(s)

JPL is part of NASA and Caltech

- Federally (NASA)-owned "Federally-Funded Research and Development Center" (FFRDC)
- University (Caltech)-operated
- $1.7 billion business base
- 5400 employees and contractors
- 177 acres
- 134 buildings and 57 trailers
- 670,000 net square feet of office space
- 860,000 net square feet of non-office space (e.g., labs)

Biggest Perk: Parking!!

JPL's Mission Flows from the NASA Mission



To understand and protect our home planet

To explore the Universe and search for life

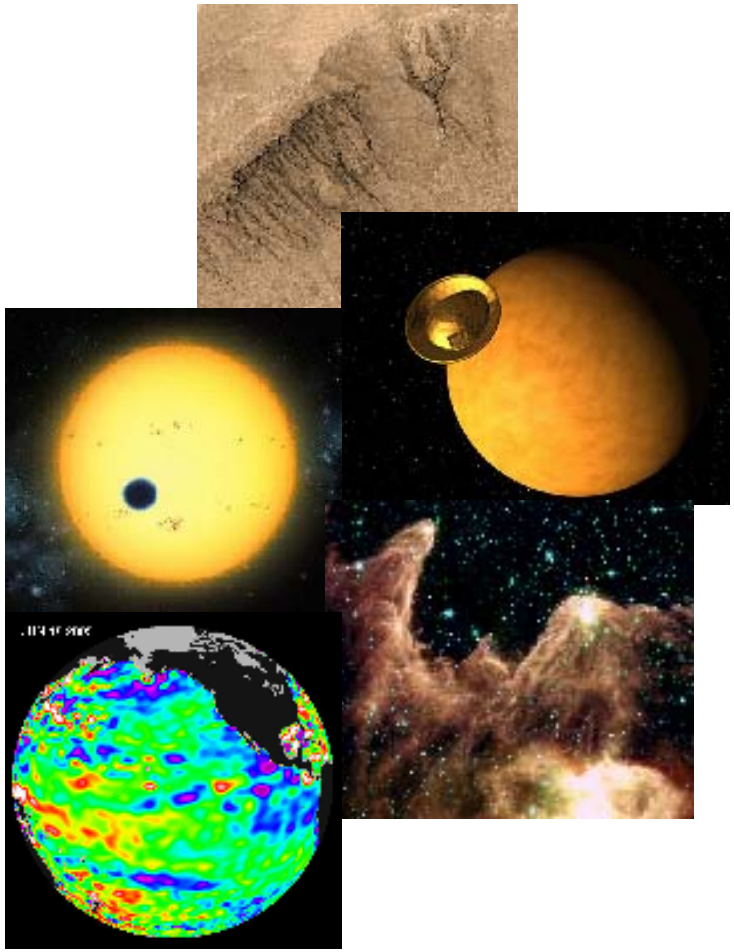
To inspire the next generation of explorers

.... as only NASA can

1. **To explore our own and neighboring planetary systems**
2. **To search for life outside the Earth's confine**
3. **To further our understanding of the origins and evolution of the Universe and the laws that govern it**
4. **To make critical measurements to understand our home planet and help protect its environment**
5. **To apply JPL's unique skills to address problems of national significance and security**
6. **To enable a virtual presence throughout the solar system by creating the Interplanetary Network**
7. **To inspire the next generation of explorers**

Realizing the potential of Space Science in five themes

1. **Mars exploration: Follow the water**
2. **Life-friendly sites in the solar system**
3. **Extra-solar planets**
4. **Origins of galaxies and the universe**
5. **Our home planet, Earth**



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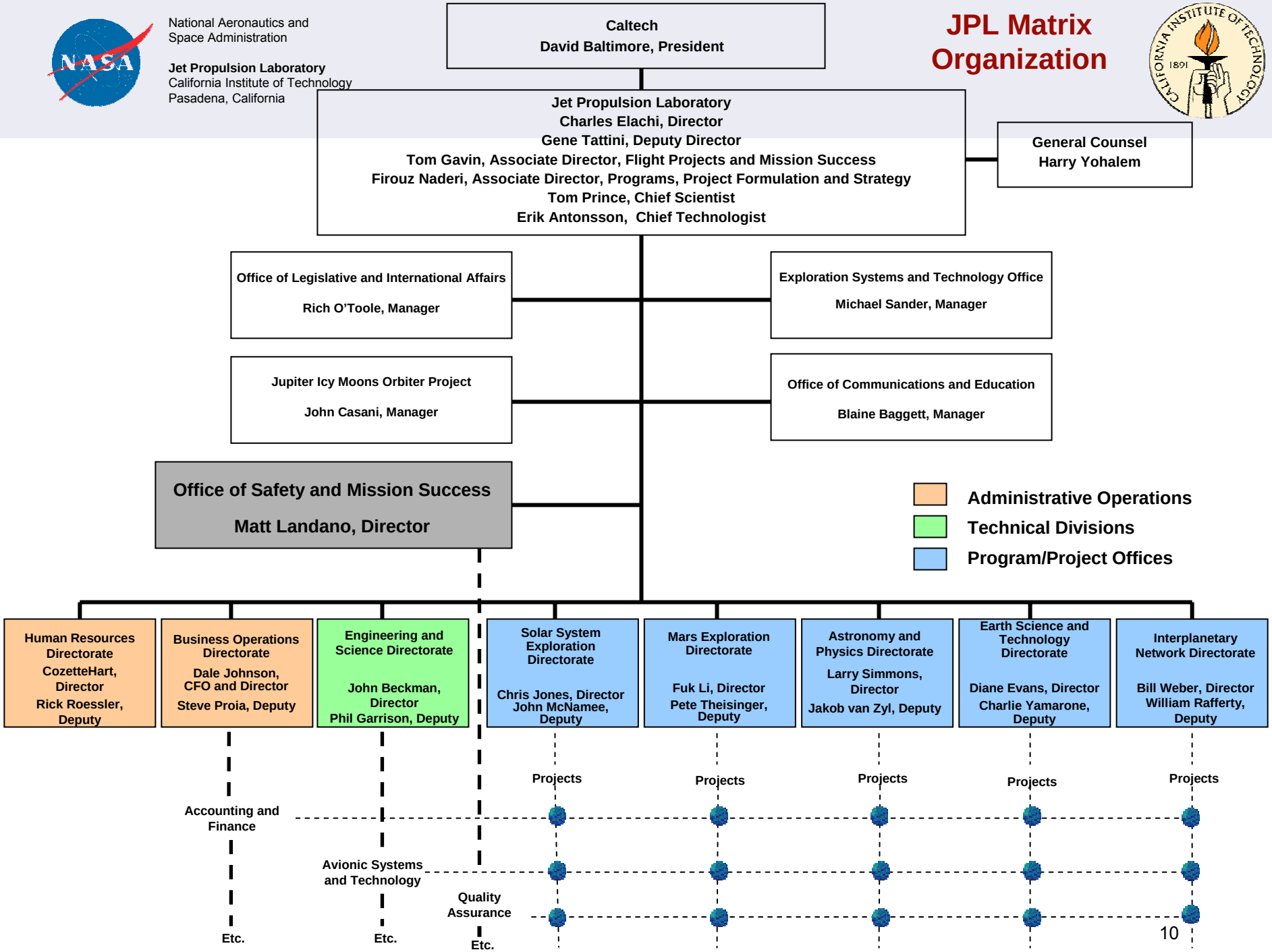
JPL Matrix Organization



Infrastructure for Robotic Missions

Major Facilities

- Spacecraft Assembly Facility
- Environmental Test Laboratory
- 7.6-m and 3.0-m Space Simulators
- Space Flight Operations Facility
- Deep Space Communications Complexes
- Project Design Center
- Architectural Platform
- Antenna Range
- Frequency Standards Laboratory
- Electric Propulsion Laboratory
- Battery Development and Test Laboratory
- Observational Instruments Laboratory
- Optical Interferometry Development Laboratory
- Telecommunications Development Laboratory
- Mars Yard

Laboratories

- Multi-mission Image Processing Laboratory
- Digital Image Analysis Laboratory
- Microdevices Laboratory
- Optical Interferometry Development Laboratory
- Space Telescope Cryogenic Test Facility
- Table Mountain Observatory Facility
- Physical Oceanography Data Analysis and Archive Center
- Supercomputer and Visualization Laboratory
- In-Situ Instruments Laboratory

Technical organizations

- Mars Program
- Project Support
- Planetary Flight Projects
- Safety and Mission Success
- Solar System Exploration
- Astronomy and Physics
- Earth Science and Technology
- Interplanetary Network
- Engineering and Science Systems
  - -Earth and Space Science
  - -Telecommunications
  - -Avionics Systems
  - -Mechanical Systems
  - -Information Technologies
  - -Observational Systems

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Mars Exploration Rovers' discoveries selected as "Breakthrough of the Year" by Science magazine

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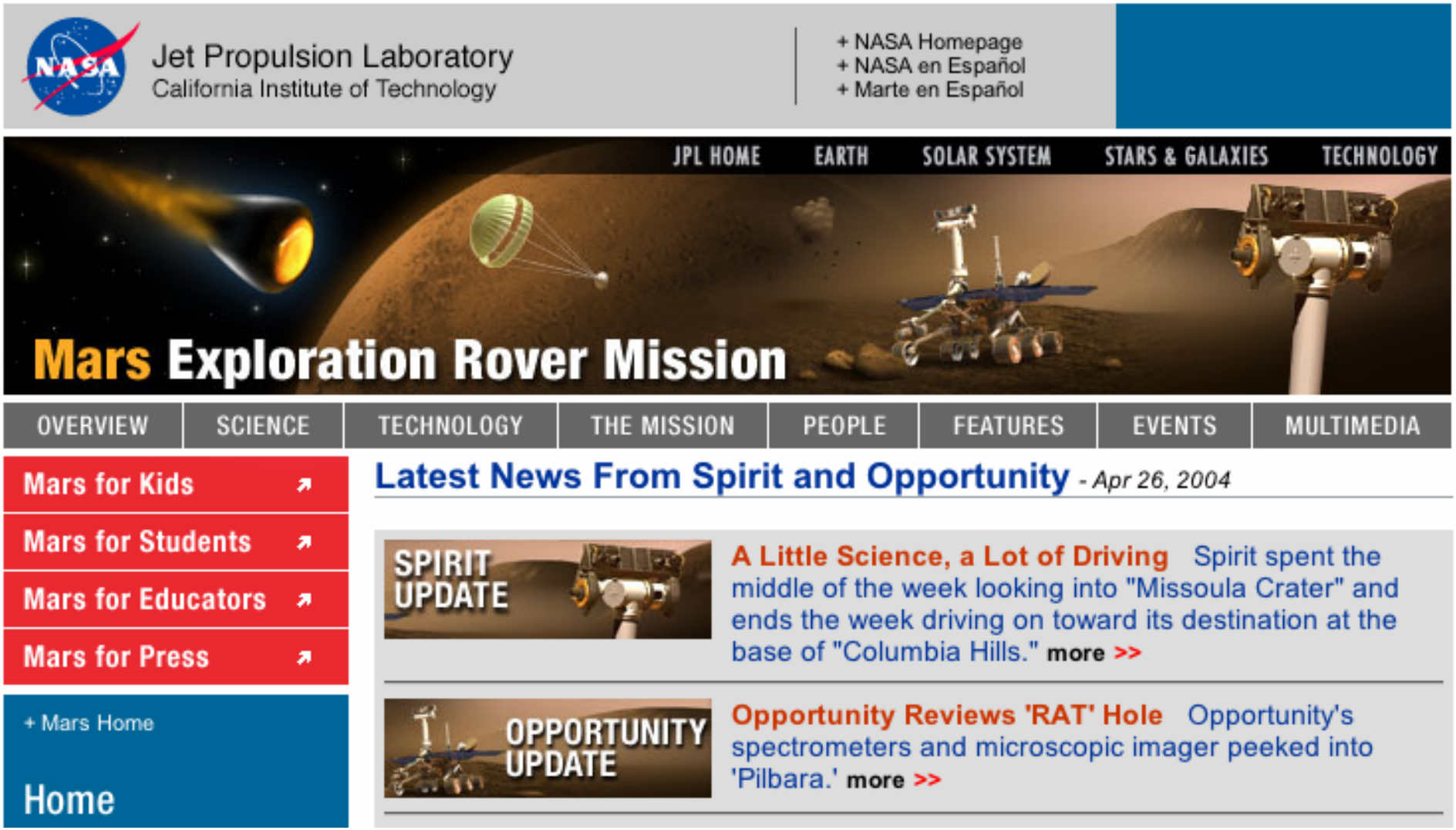
Over 18 billion hits to the NASA and Mars Rover web pages since January 3, 2004



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Earth and Mars are dramatically different.... but have many similar features.

Mars-Earth comparisons

Earth:

- 13,000 km diameter
- 150 million km from sun
- 365 days in year
- 24 hours in day
- -88 deg C to +58 deg C temp range
- 1000 mb surface pressure
- 78% nitrogen, 21% oxygen
- Grand Canyon is 800 km long by 1.6 km deep
- Mt Everest is 9 km high, and Mariana Trench is 11 km deep

Mars:

- 7000 km diameter
- 225 million km from sun
- 687 Earth-day year
- 24 hour, 37 minute sol (Mars day)
- -127 deg C to 17 deg C temp range
- 7 mb surface pressure
- 95% carbon dioxide atmosphere
- Valles Marineris is 4000 km long by 7 km deep
- Olympus Mons is 27 km high, and Hellas basin is 4 km deep
- One-way light (or radio) time from Earth to Mars varies from 4 minutes to 22 minutes

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Mars Exploration Rovers in test with 1997 Sojourner rover

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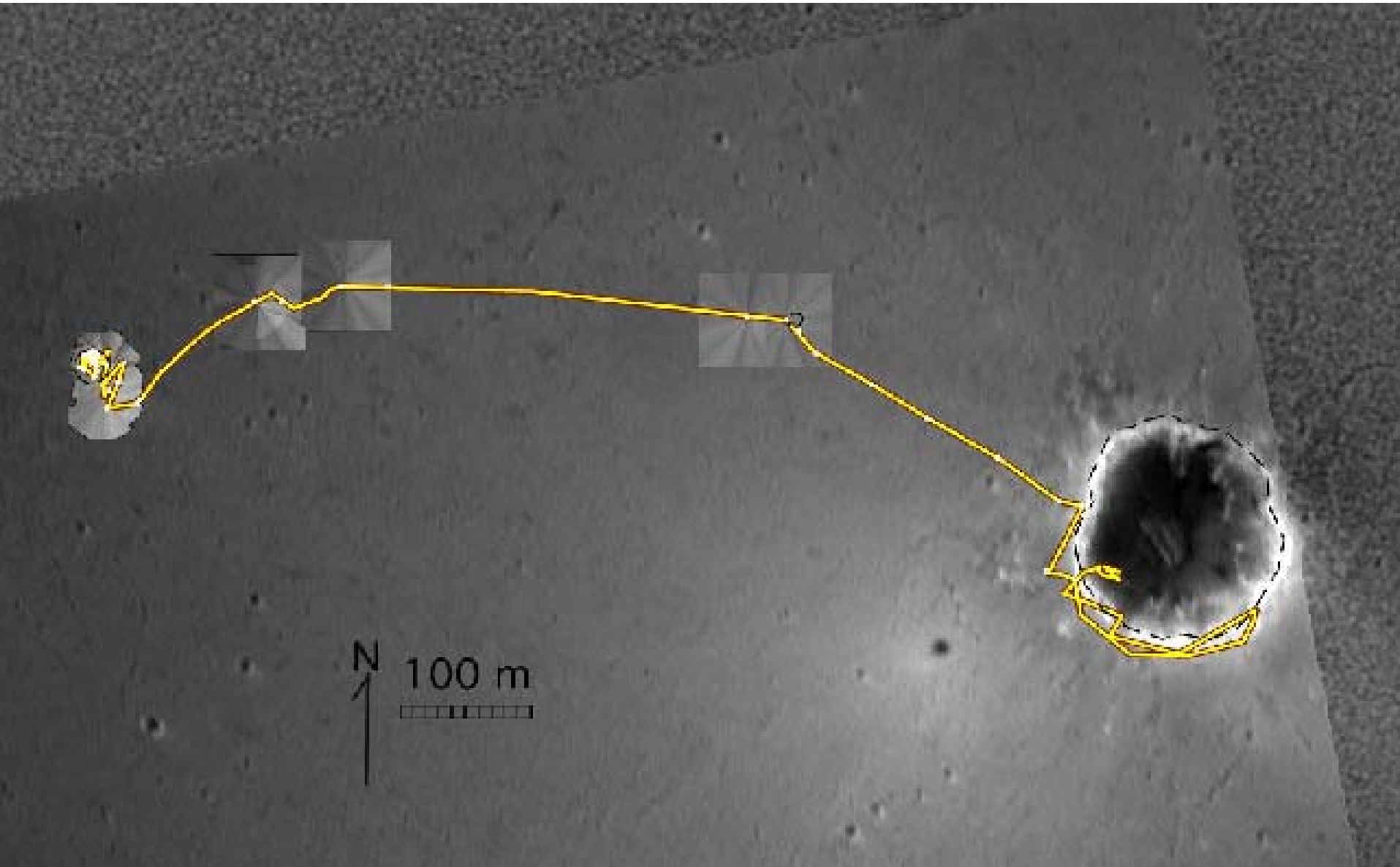
Opportunity's journey during its first 205 Martian days



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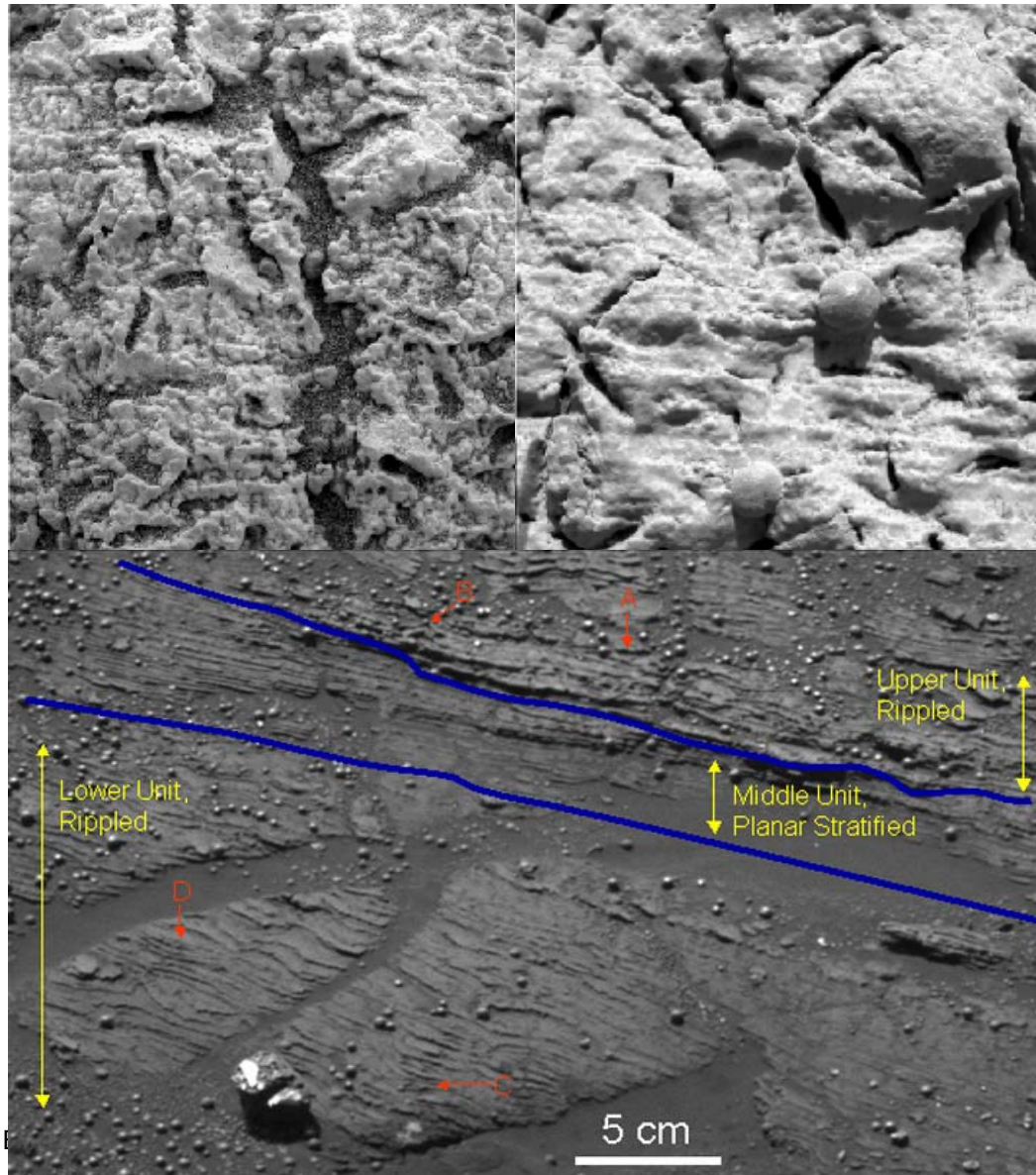
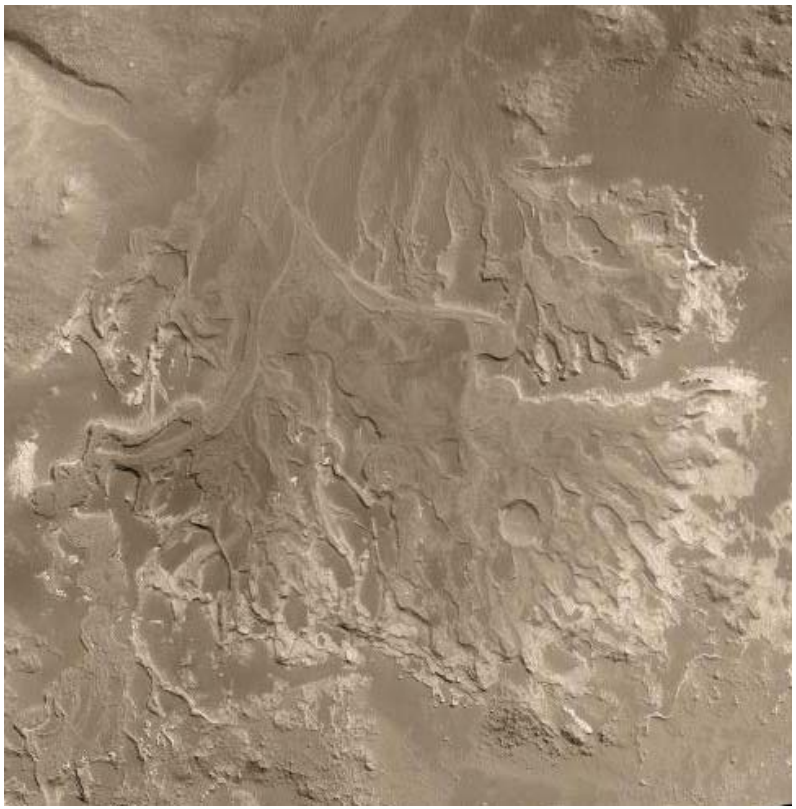
Voids, spherules, and distinct layers imply multiple water episodes at Opportunity's landing site

- **Voids suggest dissolved crystals at Meridiani Planum.**

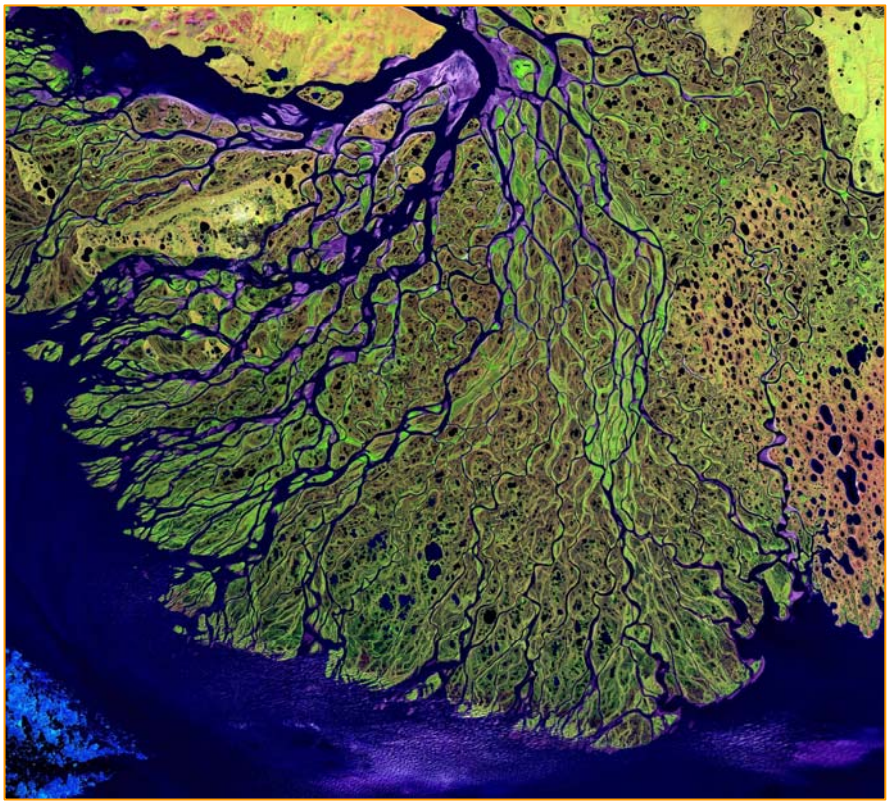
- **Distinctly different rippled layers imply flowing water**



First Views of a Martian Delta

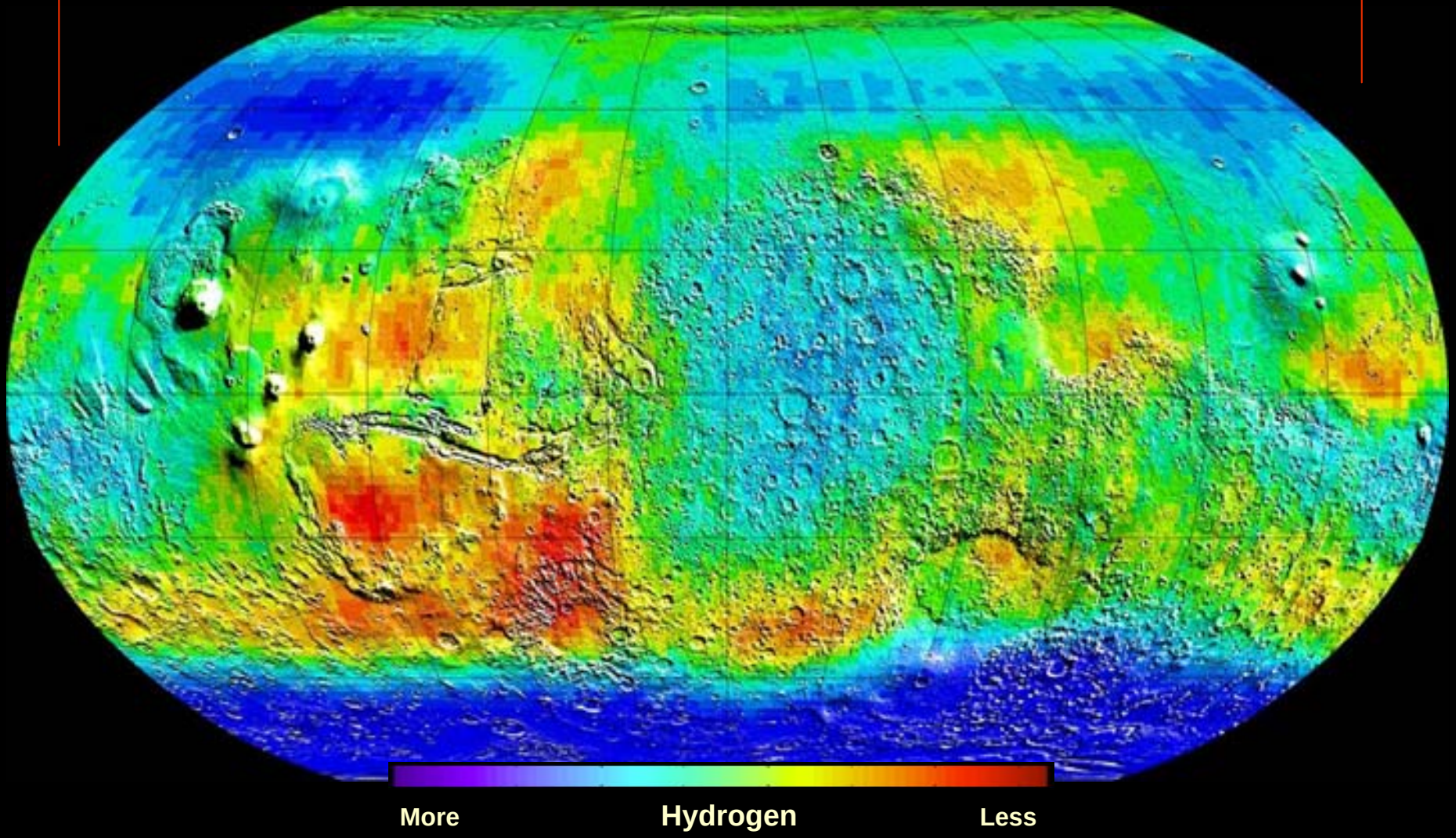


MSG MOC Image of "delta"system within Holden Crater on Mars (Malin et al, Science 2003)

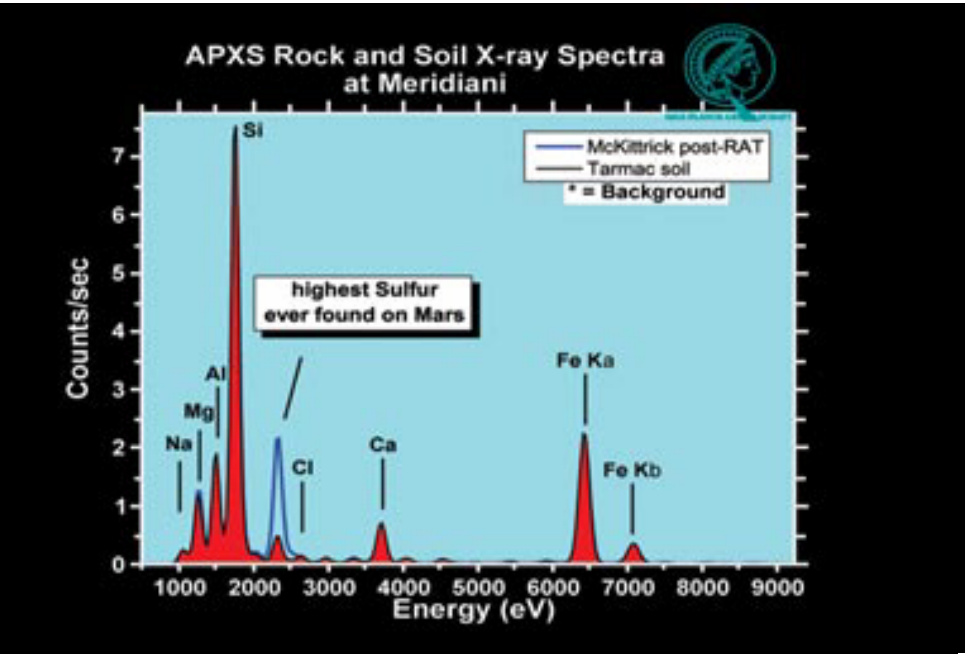


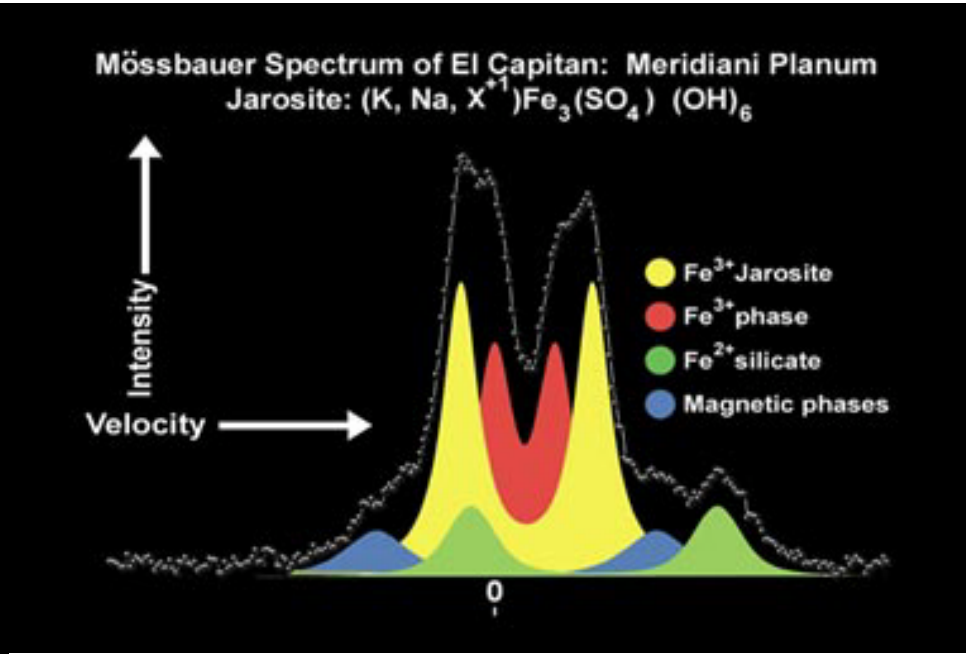
Lena Delta in Siberia (NASA Scientific Data Purchase/Landsat 7)

Abundant Water Ice at High Latitudes



Opportunity spectra





Opportunity **APXS spectrum with high sulfur content, implying sulphates and standing water**

Jarosite with sulphate and hydroxyl components from *Opportunity*, implying evaporation from a salty brine

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Mars exploration in the Vision for Space Exploration

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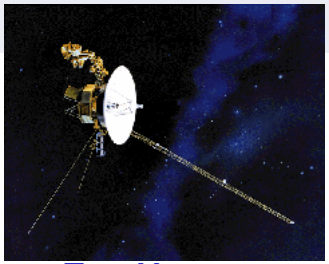
Sixteen JPL spacecraft, and five major instruments, now operating across the solar system

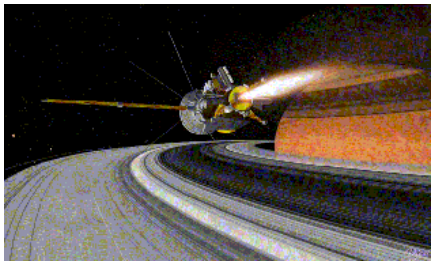
Spitzer studying stars and galaxies in the infrared

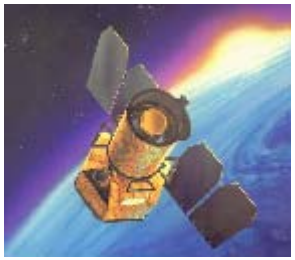


Two Voyagers on an interstellar mission

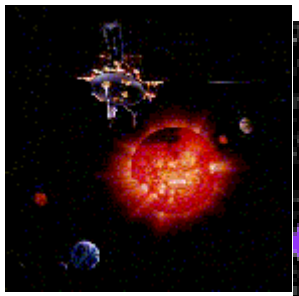
Ulysses, and ACRIMSAT studying the sun

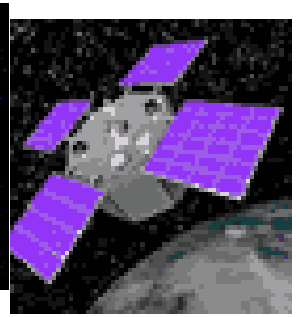
Cassini studying Saturn

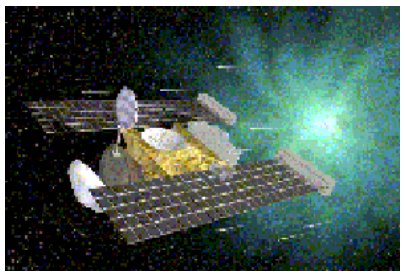




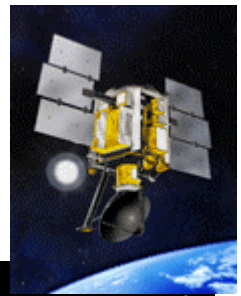
GALEX studying UV universe

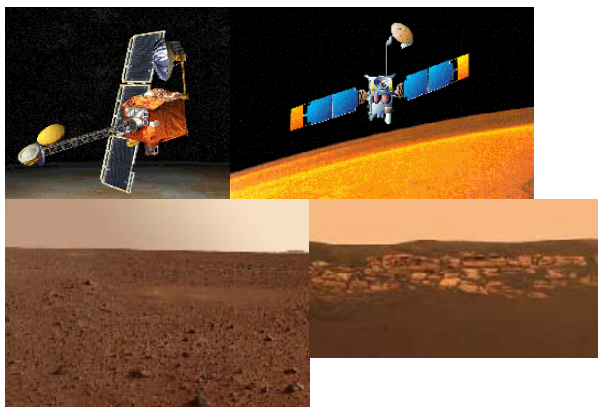






Stardust returning comet dust





Mars Global Surveyor and Mars Odyssey orbiters; "Spirit" and "Opportunity" on Mars

Topex/Poseidon, QuikSCAT, Jason 1, and GRACE (plus ASTER, MISR, AIRS, MLS and TES instruments) monitoring Earth

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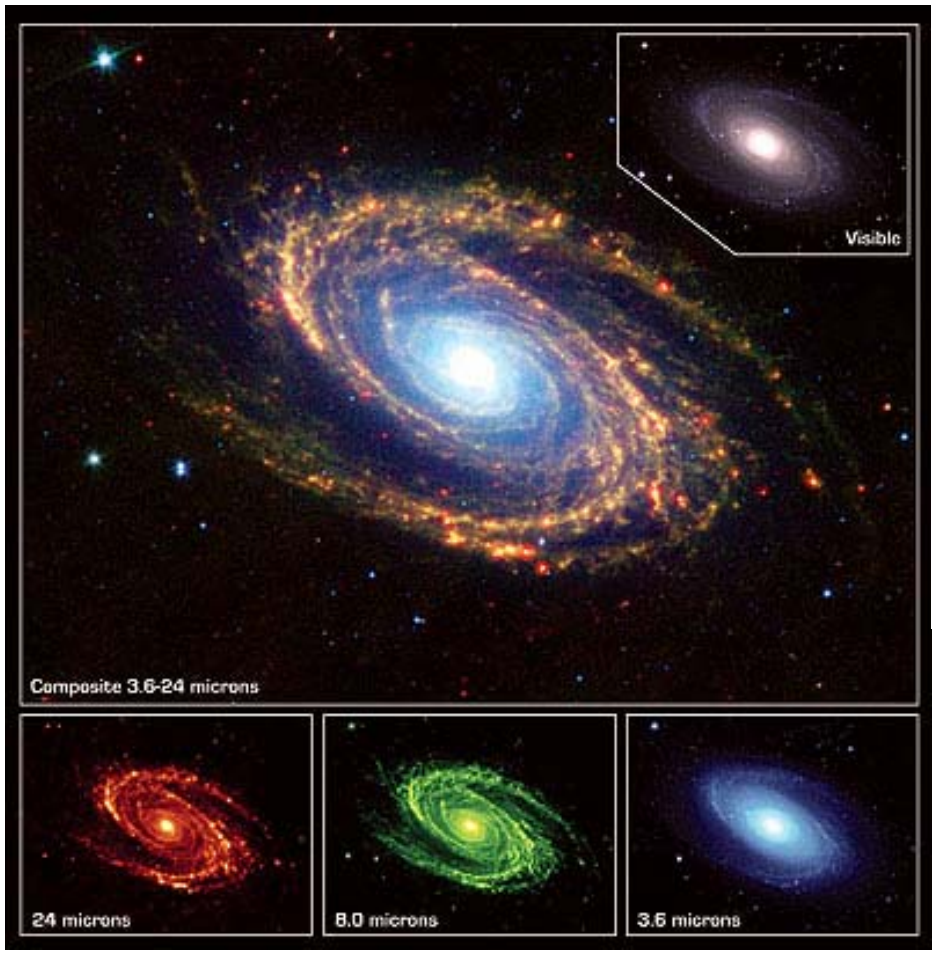
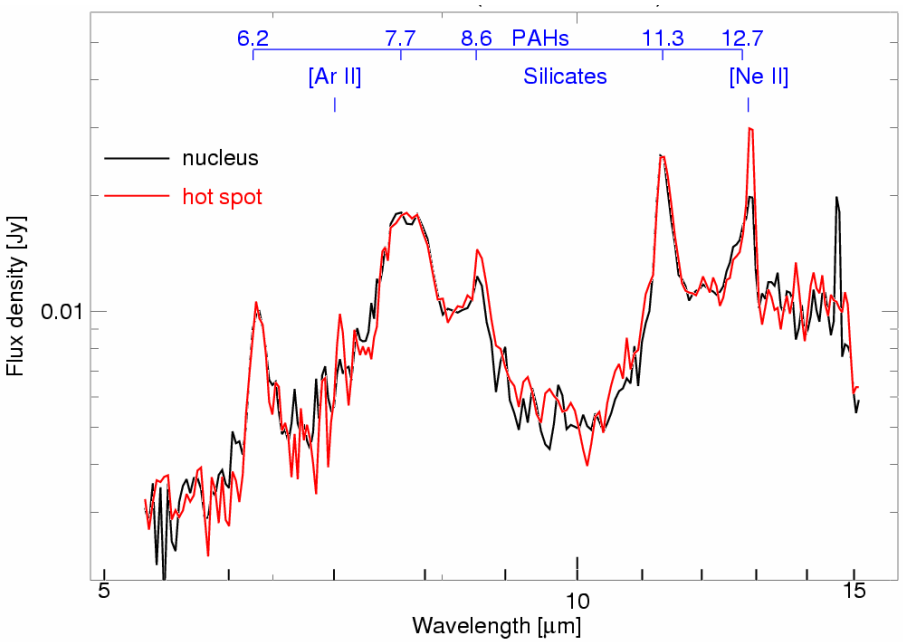
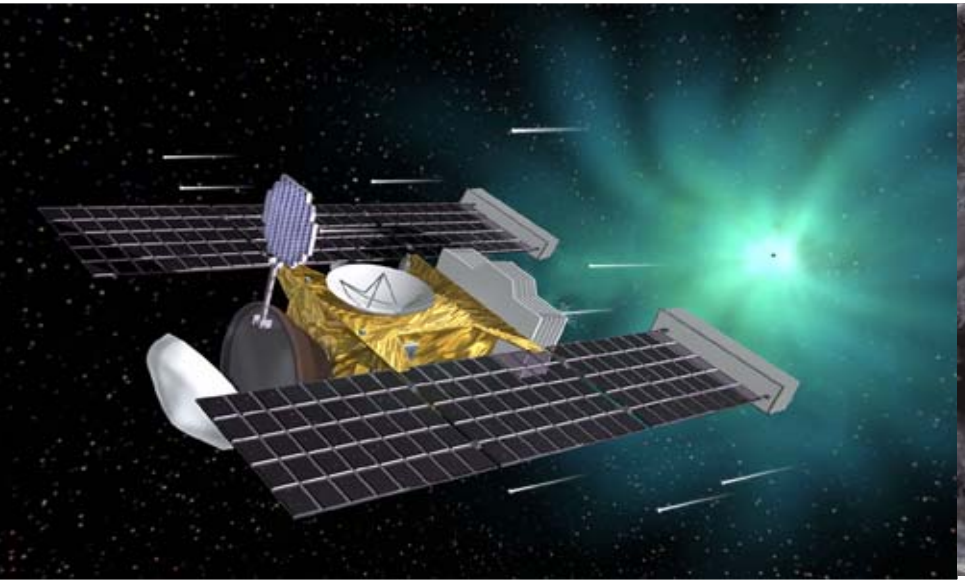
Spiral galaxy M81, 12 million light years away, in Ursa Major, as seen by Spitzer

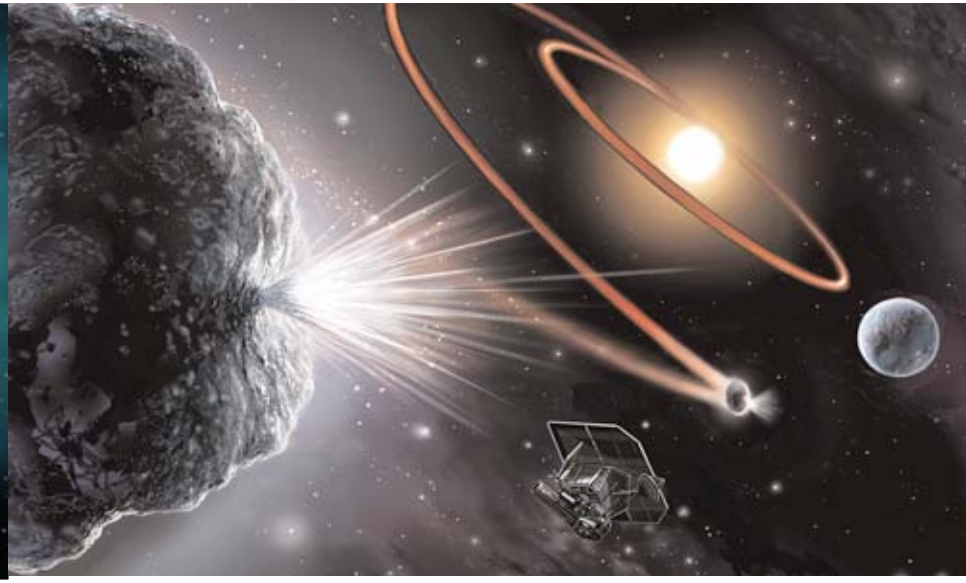




M81 has a spectrum with an 8µm bump indicating polycyclic aromatic hydrocarbons (e.g., diesel exhaust or barbecue grill gunk).

Studies of primordial comets by Stardust and Deep Impact





Stardust: Fly-by of comet Wild 2: January 2004
Sample Return January 2006

Deep Impact: Impact comet Tempel 1 on July 4, 2005

Genesis

- **Completed 27 months of solar wind collection.**
- **Earth return mishap led to hard-impact landing at Utah Test and Training Range on September 8.**
- **Work ongoing to recover science results from damaged sample canister.**
- **High likelihood that most of the highest priority science will be recovered.**

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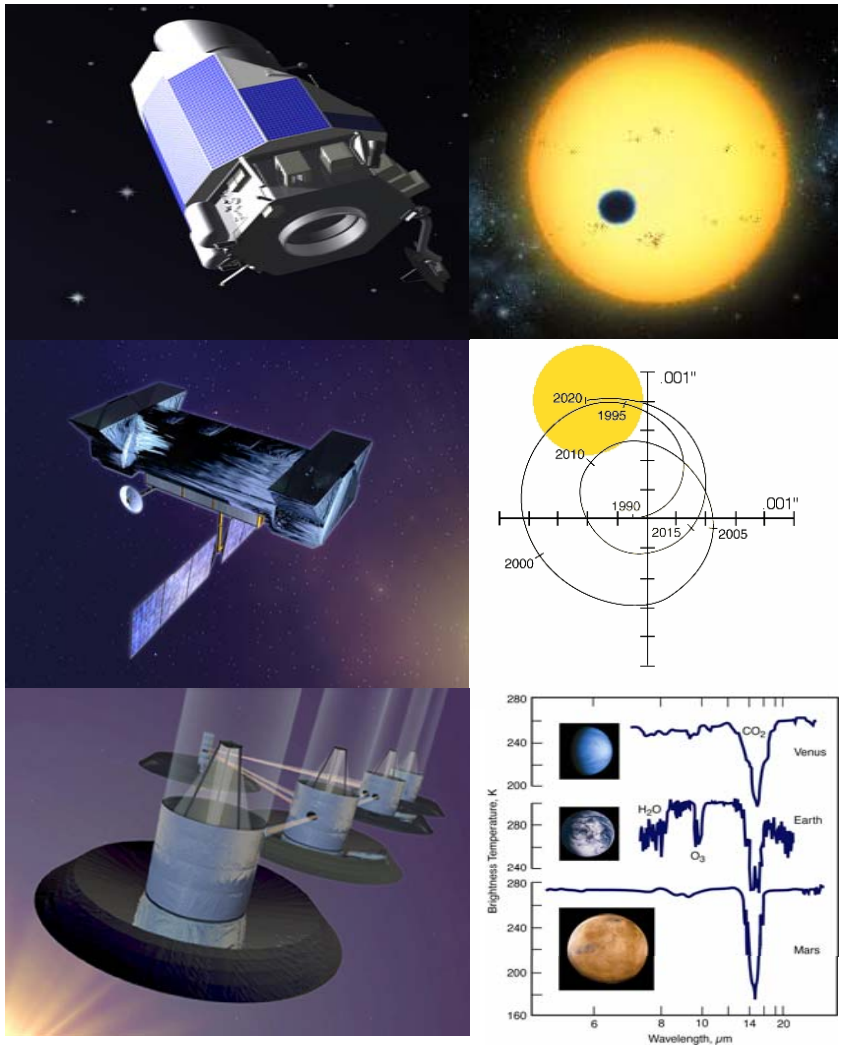
Future exploration of extrasolar planetary systems



- **Kepler Discovery mission in 2007 to observe transits of planets across stars**
- **Space Interferometry Mission (SIM), to launch in 2009, performs astrometry of extra-solar planets.**
- **Terrestrial Planet Finder (TPF), to launch in 2015, performs spectroscopy of extra-solar planets.**

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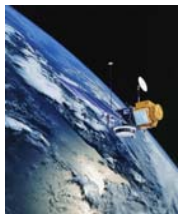
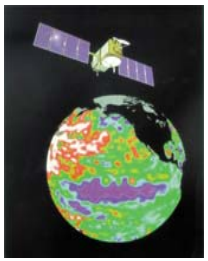
JPL Earth Science missions

Operational



TOPEX / Poseidon
(1992 - Present)

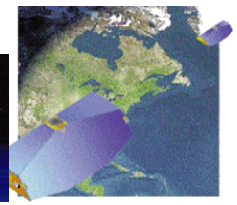
TES
(2004-present)



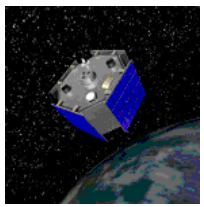
Jason-1
(2001 - Present)

QuikSCAT-
(1998 - Present)

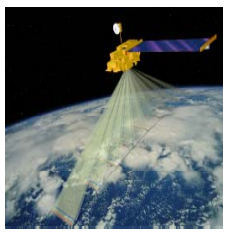
MLS
(2004-present)



GRACE
(2002 - Present)

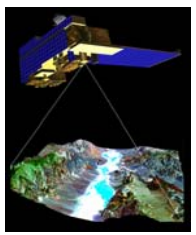


ACRIMSAT
(1999 - Present)



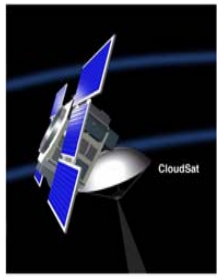
MISR
(1999 - Present)

AIRS
(2002 - Present)



ASTER
(1999 - Present)

Development

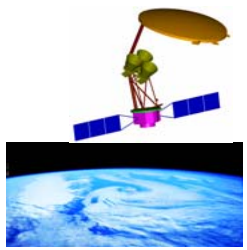


CloudSat
(2005)

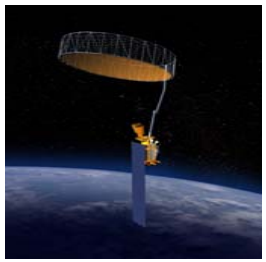
Formulation

Carbon Cycle:
OCO (2007)

Ocean Surface Topography
Mission: (2007)

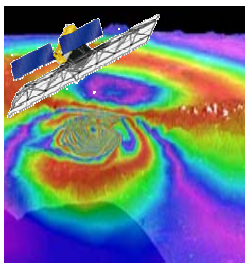


Sea Surface Salinity:
Aquarius (2008)



Soil Moisture &
Phase: HYDROS
(2010)

Ocean Vector Wind
Mission (TBD)



InSAR
(TBD)

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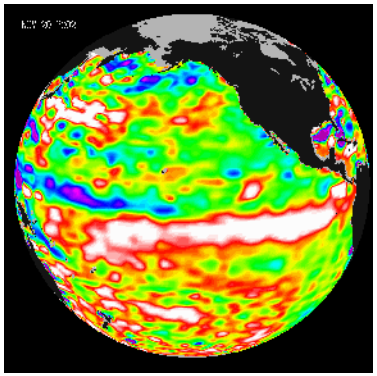
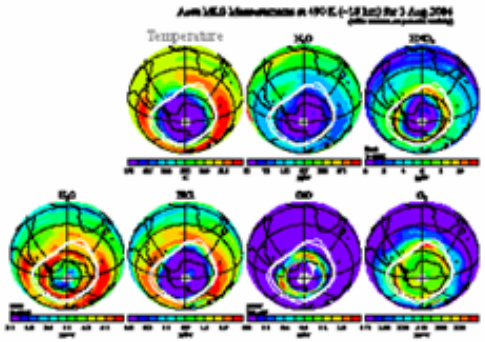
Examples of NASA/JPL spacecraft improving life on our own planet

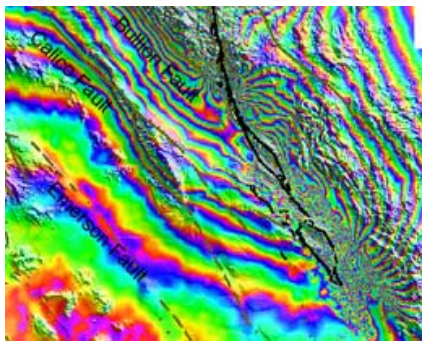
- **Ocean studies support long-term weather prediction.**



- **Atmospheric ozone studies monitor human-caused pollution.**



- **Solid Earth studies will aid in future earthquake prediction.**



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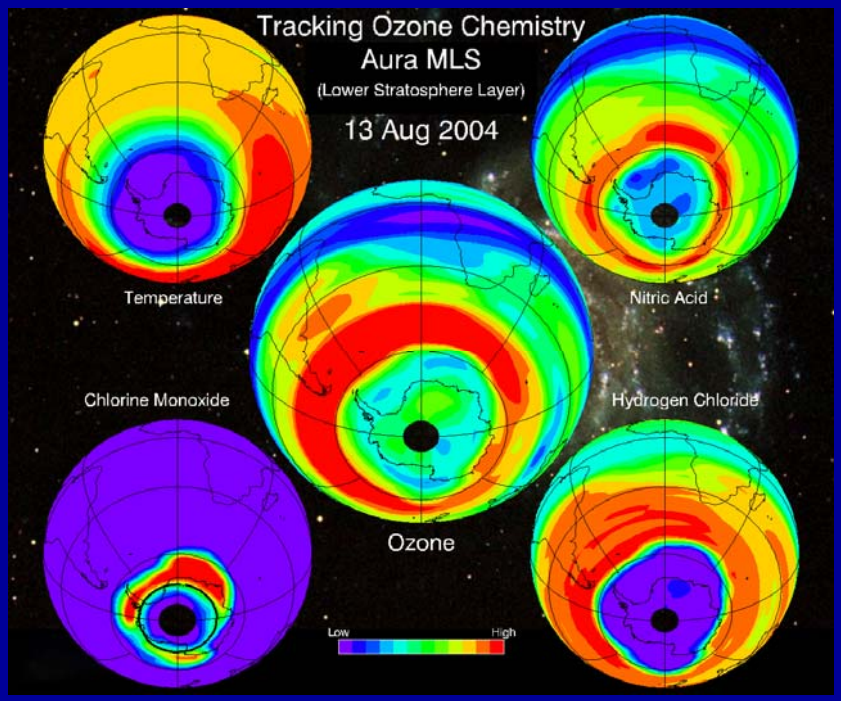
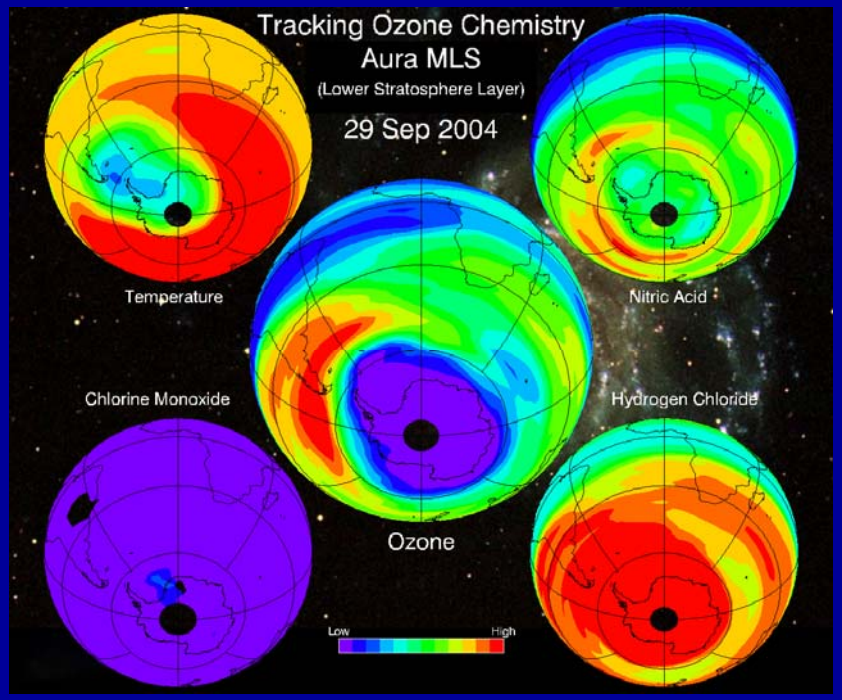
Antarctic ozone hole change, from JPL Microwave Limb Sounder (MLS) aboard NASA EOS Aura spacecraft

13 Aug 04

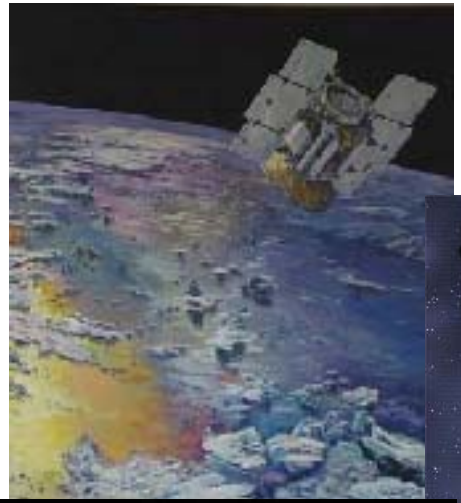


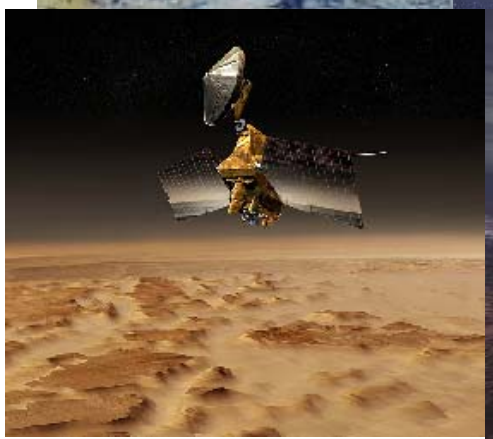
29 Sep 04

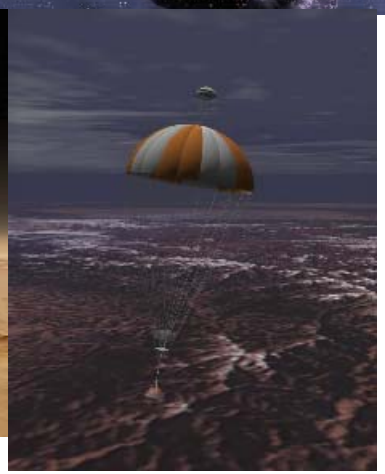


Upcoming JPL events

- **June 2005: Cloudsat launch;**
- **July 4: Deep Impact encounter with Tempel-1;**
- **August 10: Mars Reconnaissance Orbiter launch;**
- **January 15, 2006: Stardust Earth landing.**







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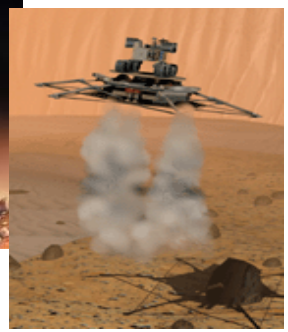
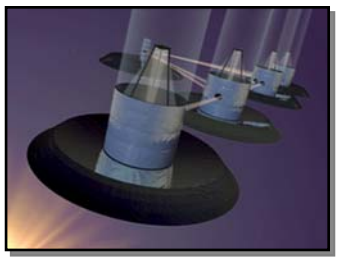
Our vision:
JPL's legacy by 2020

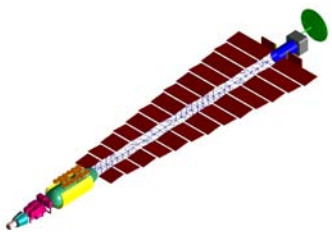
Established a continuous presence *around* and *on the surface* of Mars



Began exploring neighboring solar systems.

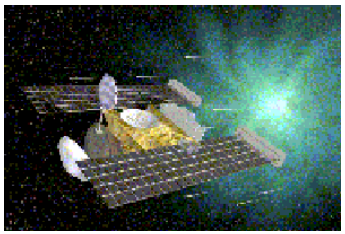


Enabled efficient access to all the bodies of the solar system



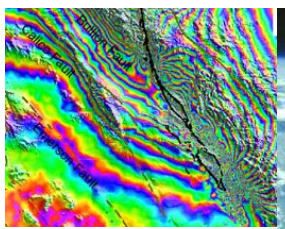
Explored the Jovian and Saturnian satellites in detail and probed their surfaces and interiors for possible pre-biotic and life-favorable environments.

Returned first samples from other solar system bodies beyond the moon.

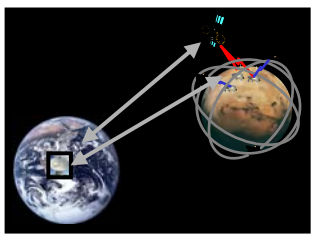


Explored the boundaries of physics to understand the forces that powered the Big Bang

Established operational capability to monitor dynamics of solid Earth and its oceans and atmosphere.



Established the Interplanetary Network, which is being commonly used by students.



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JPL missions under development for launch 2006–2010

- ***Dawn:*** *May 06*
- ***Kepler:*** *Jun 07*
- ***Phoenix:*** *Aug 07*
- ***Orbiting Carbon Observatory:*** *Oct 07*
- ***Ocean Surface Topography Mission:*** *Apr 08*
- ***Wide-Field Infrared Survey Explorer (WISE):*** *Jun 08*
- ***Aquarius:*** *Sep 08*
- ***Mars Telecommunication Orbiter:*** *Sep 09*
- ***Mars Science Laboratory:*** *Oct 09*
- ***Hydros:*** *Jan 10*
- ***Space Interferometer Mission (SIM):*** *10-11*
- ***Juno or Moonrise:*** *10*
- ***Major instruments (Herschel, Planck, MIRI)***

Plus:

- ***TBD Discovery, Explorer, ESSP, New Frontier, Einstein probes***
- ***InSAR***
- ***Project Prometheus***

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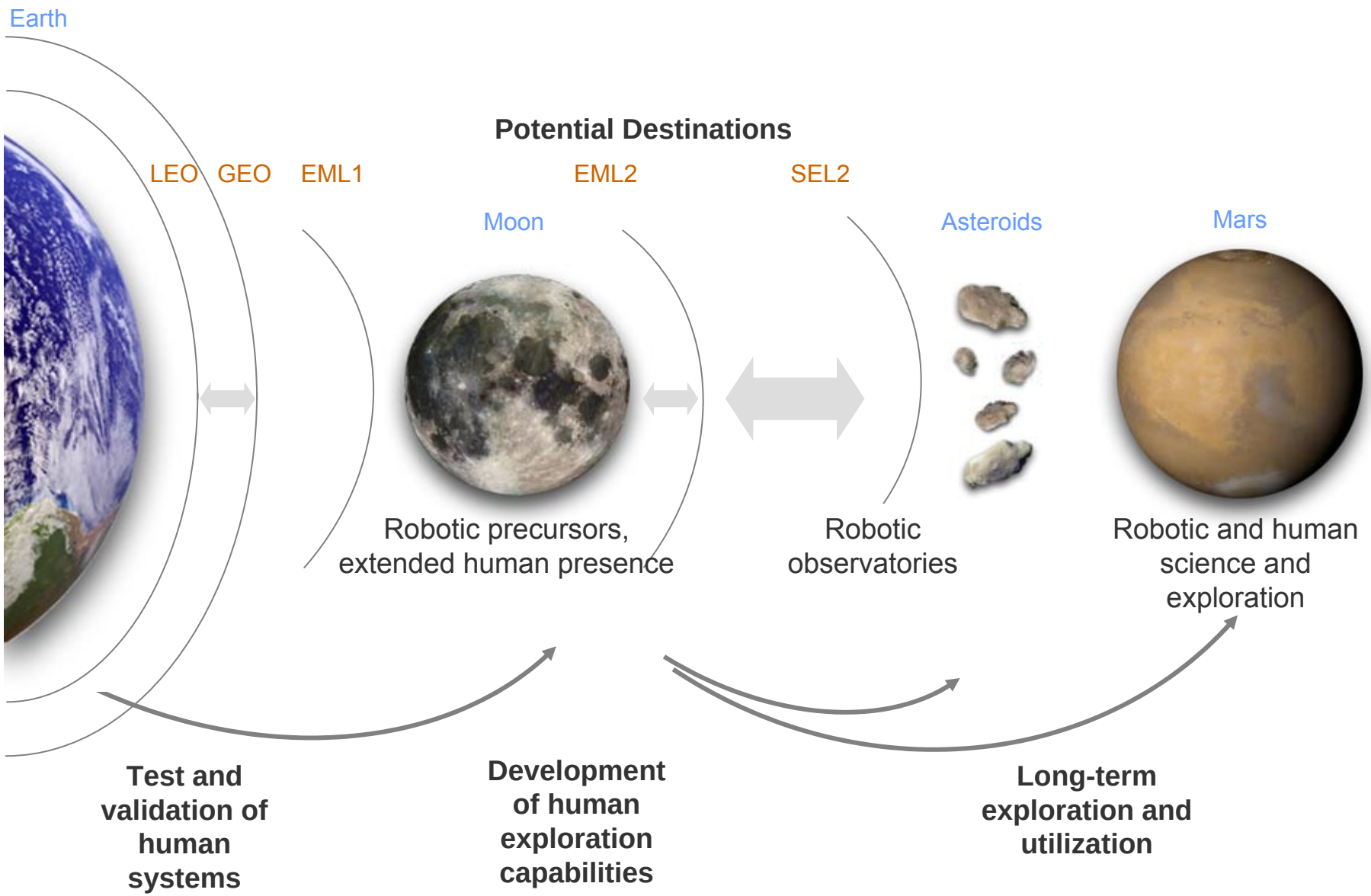
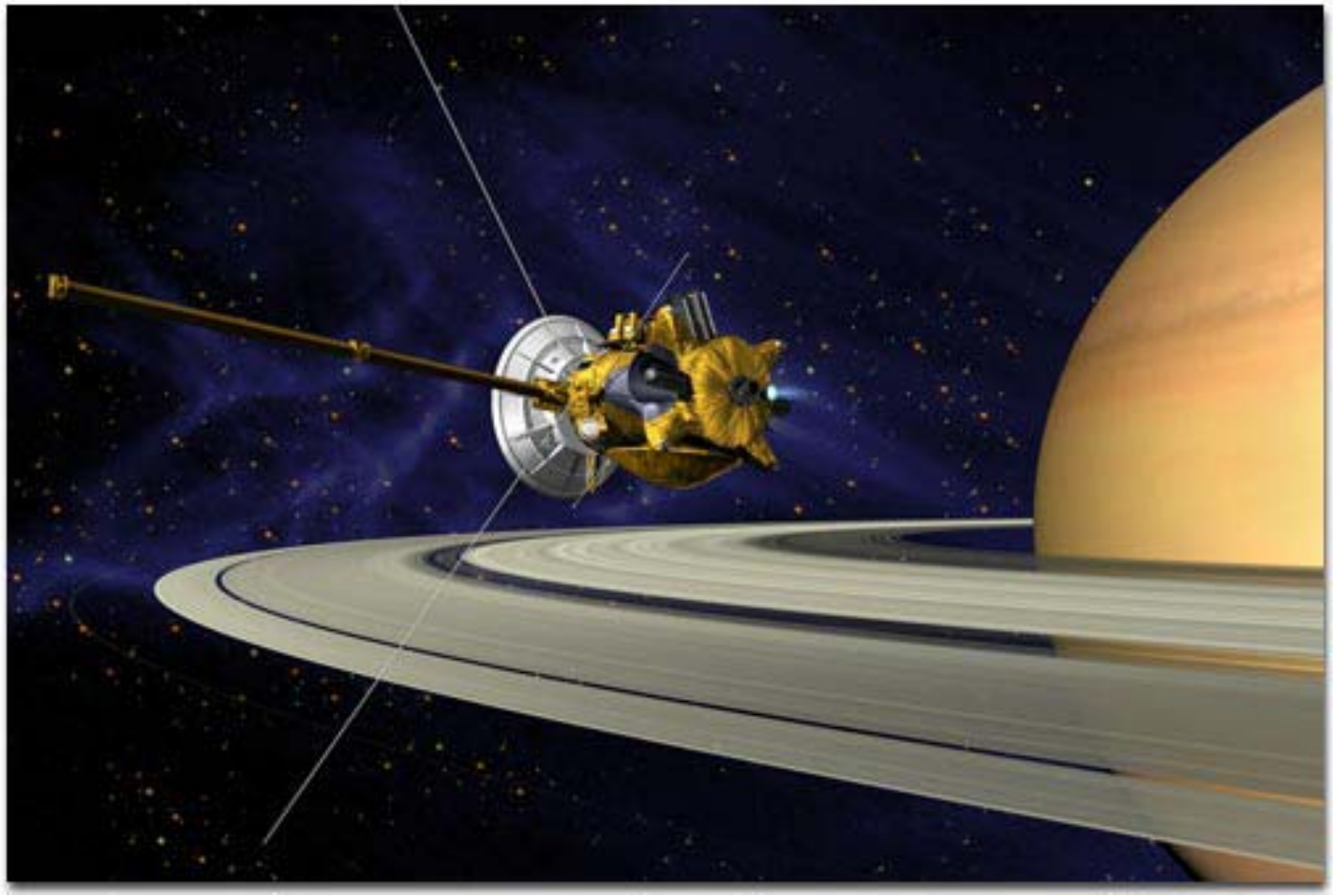
Integrated Robotic and Human Exploration



On June 30, 2004:
Cassini Saturn orbit insertion



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Saturn from Cassini, April 2004

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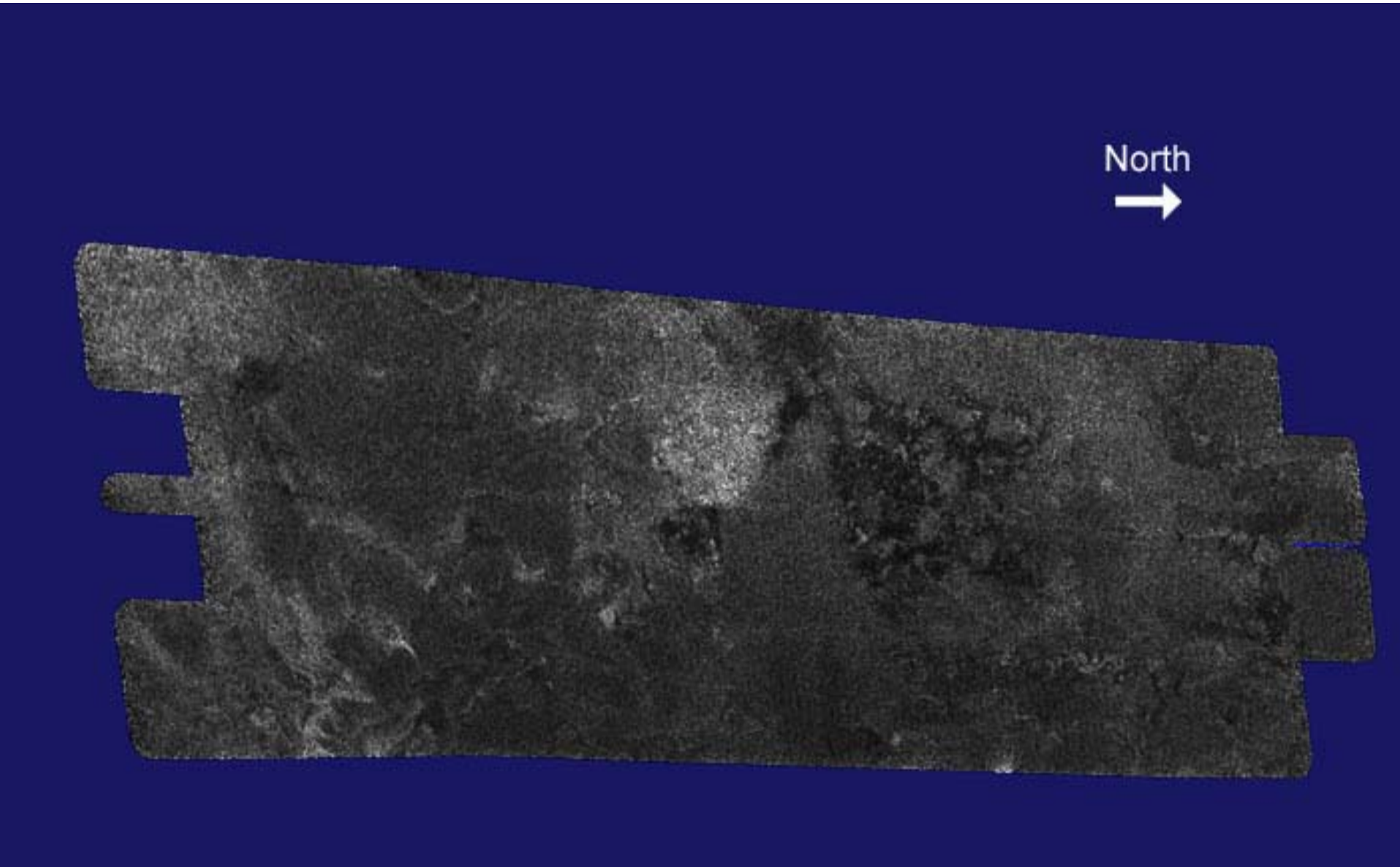
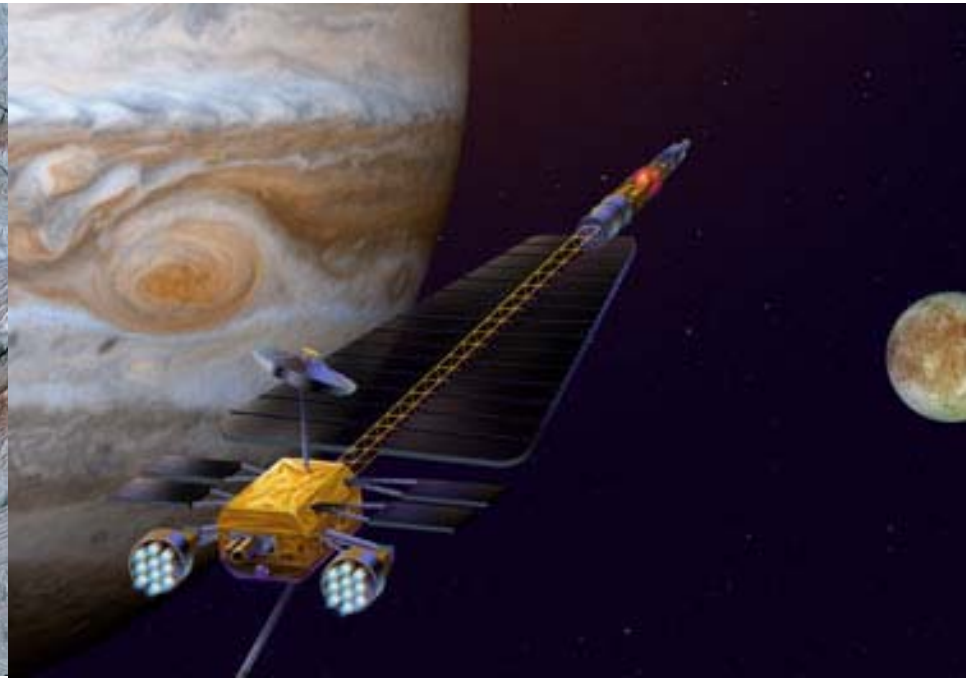
Radar image of Saturn's moon Titan, taken 10/26/04 by Cassini/Huygens, from 1000 miles away; 100 miles by 300 miles area in northern hemisphere



Future outer planets exploration using nuclear electric propulsion and power

Upwelling “lenticulae” on the surface of Jupiter’s icy moon Europa



Jupiter Icy Moons Orbiter using 100kW fission reactor nuclear electric propulsion to conduct long-term reconnaissance

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Saturn's rings from Cassini-Huygens, near closest approach, July 1, 2004

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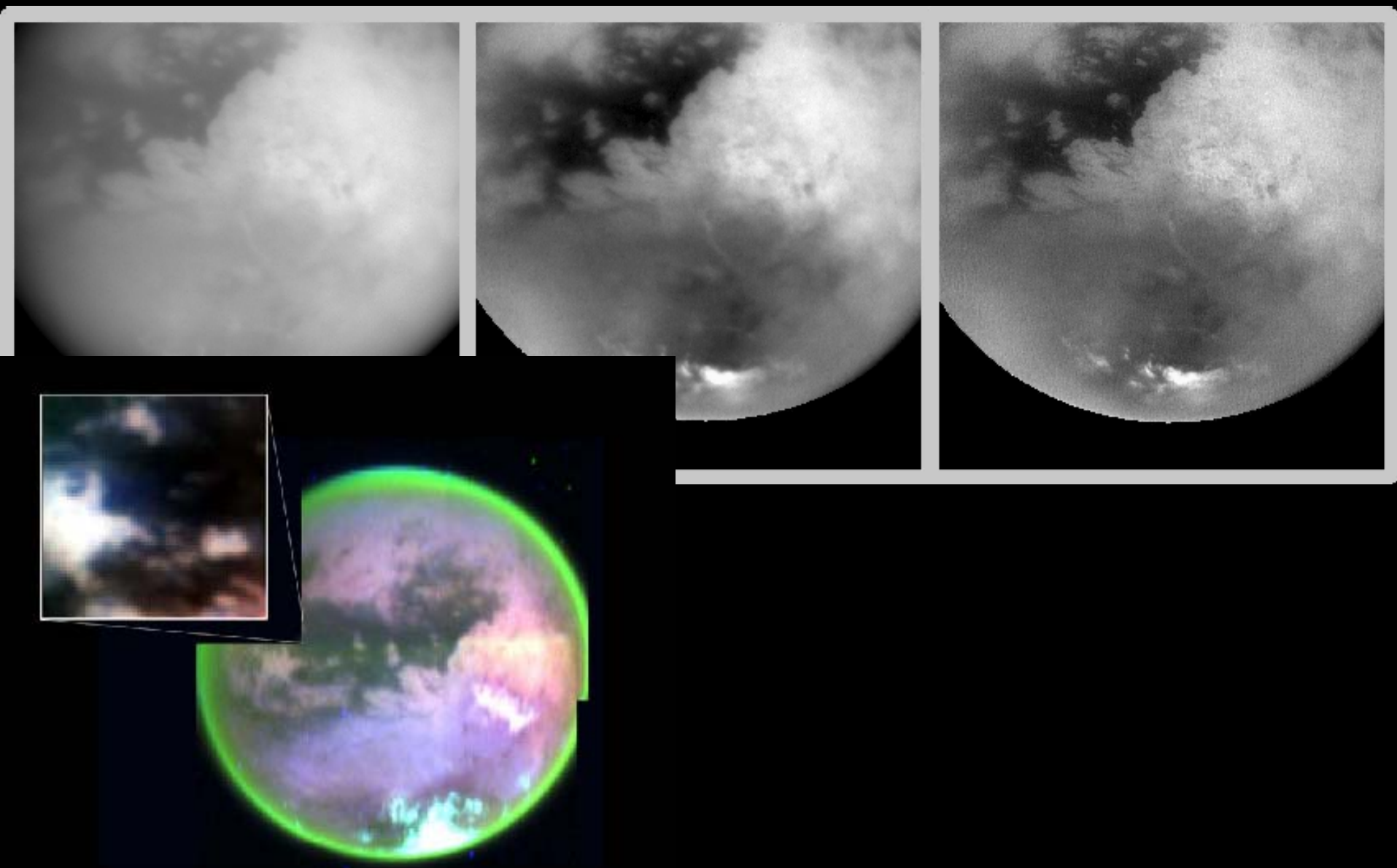
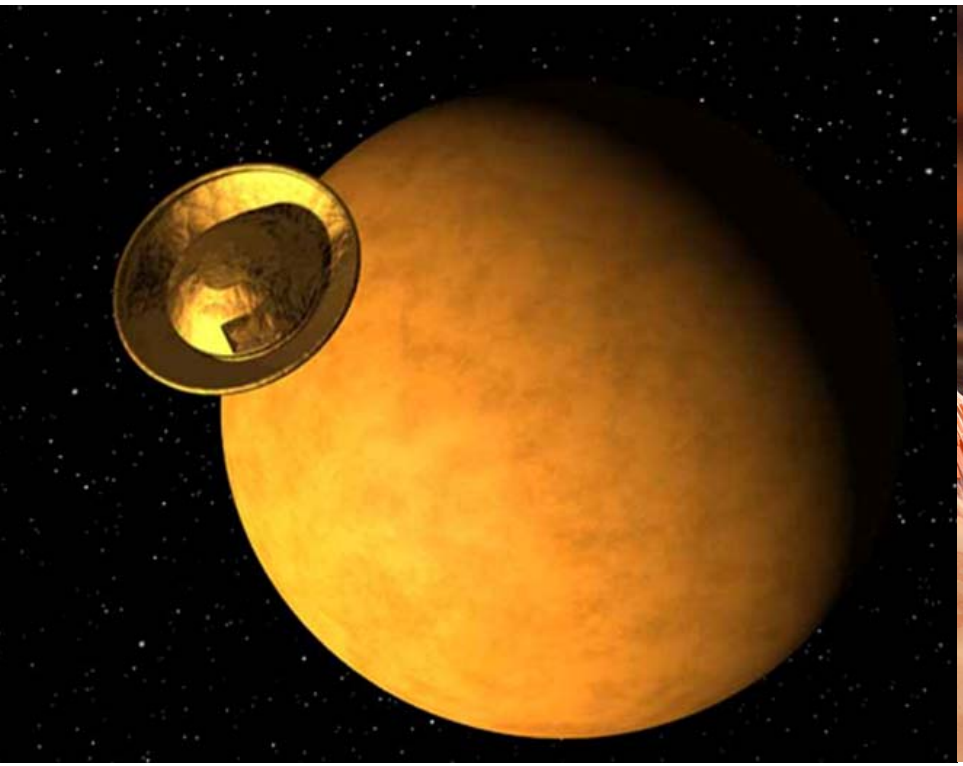
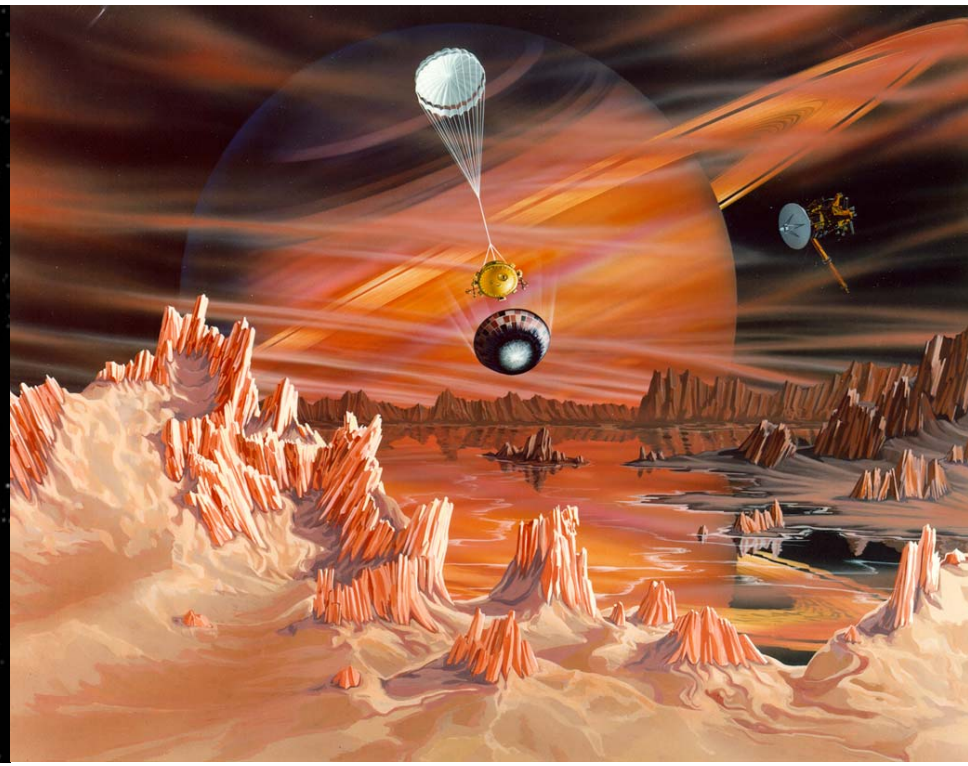
Saturn's moon Titan on October 25, 2004, showing increasing image enhancement to show feature edges in bright "Xanadu"

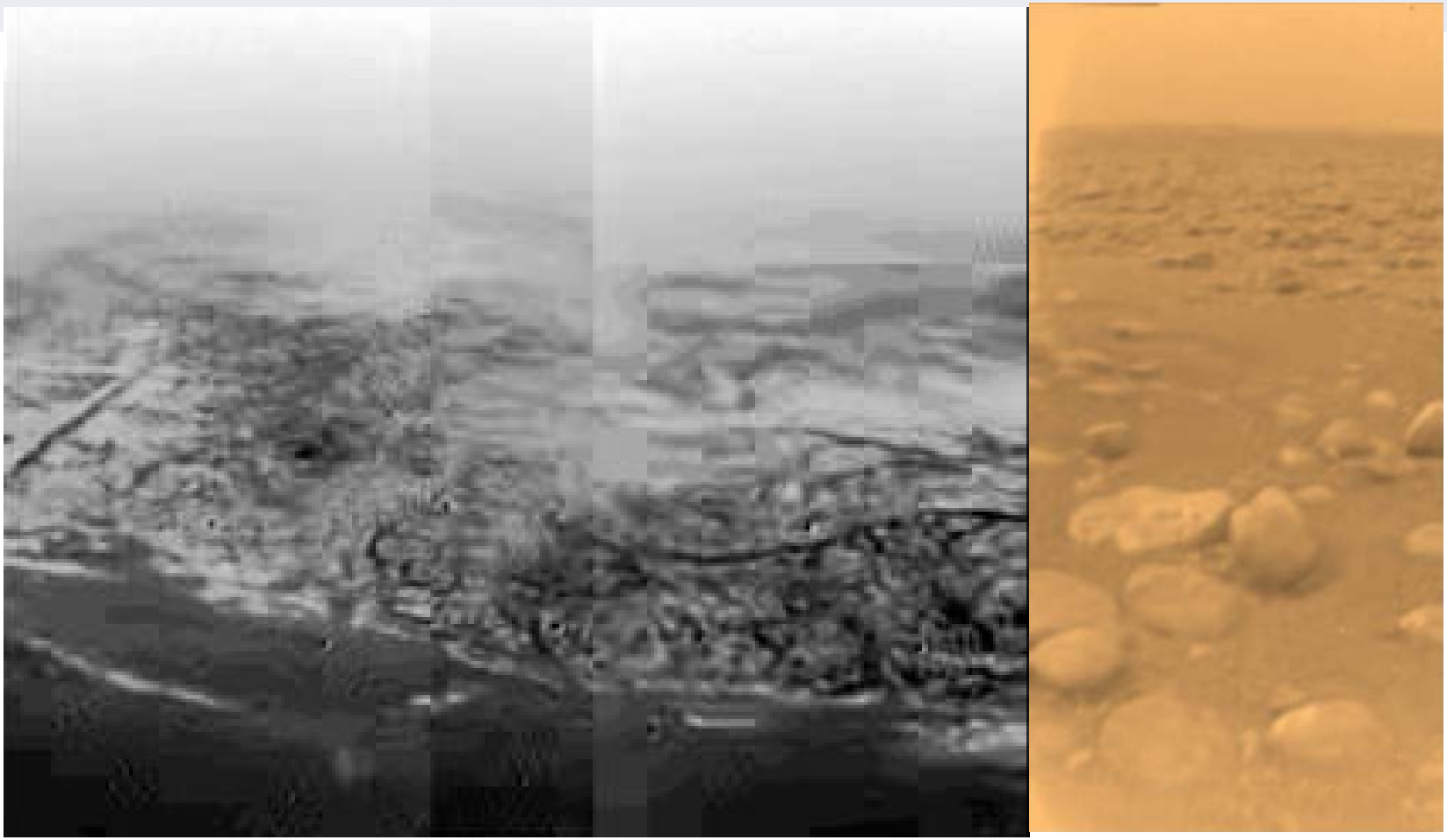


Exploration of Saturn's moon Titan by Cassini-Huygens in 2005



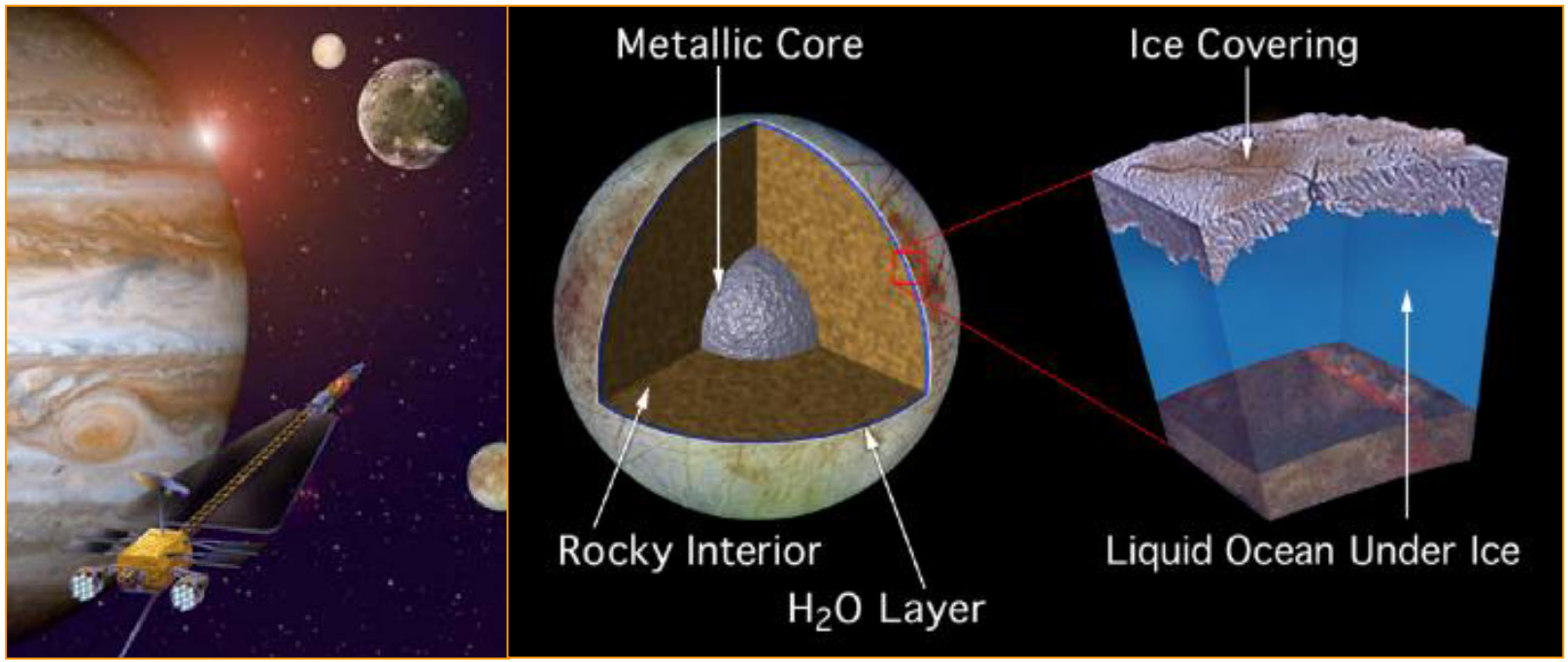


Huygens on Saturn's moon Titan



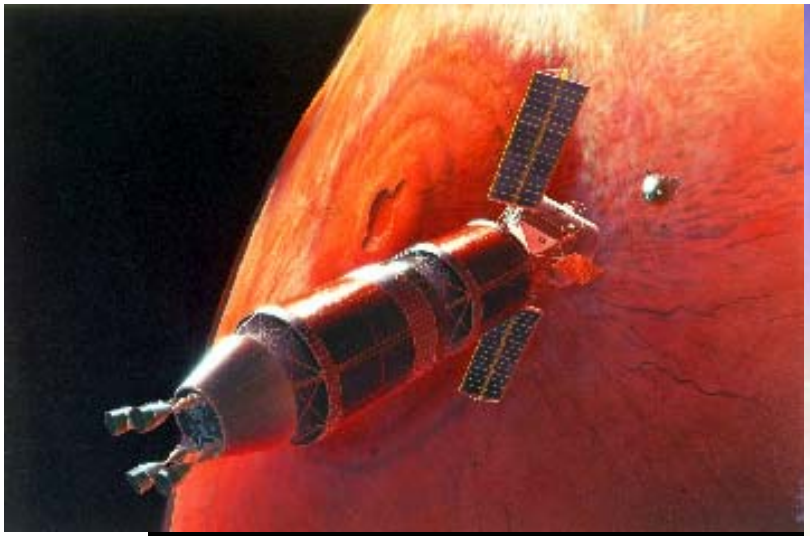
- **ESA Huygens probe landed on Titan January 14, 2005.**
- **Huygens deployed from, and data relayed through, Cassini orbiter**
- **Images are from about 10 miles altitude and on surface.**

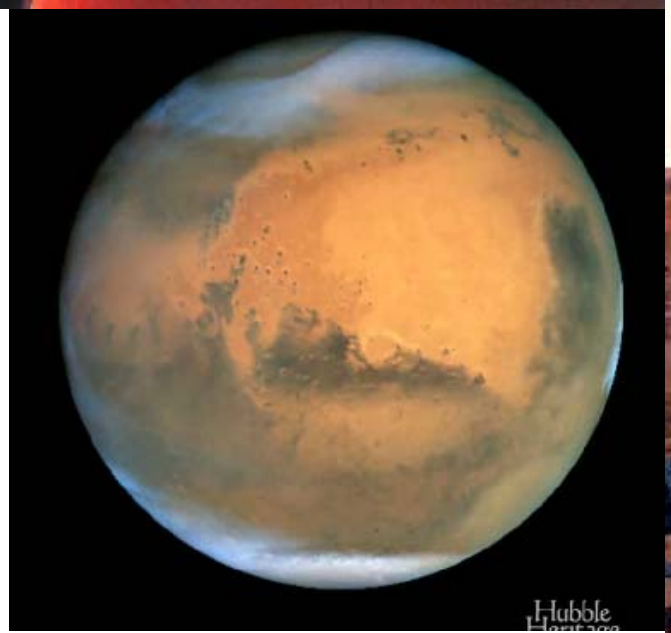
Science Interests

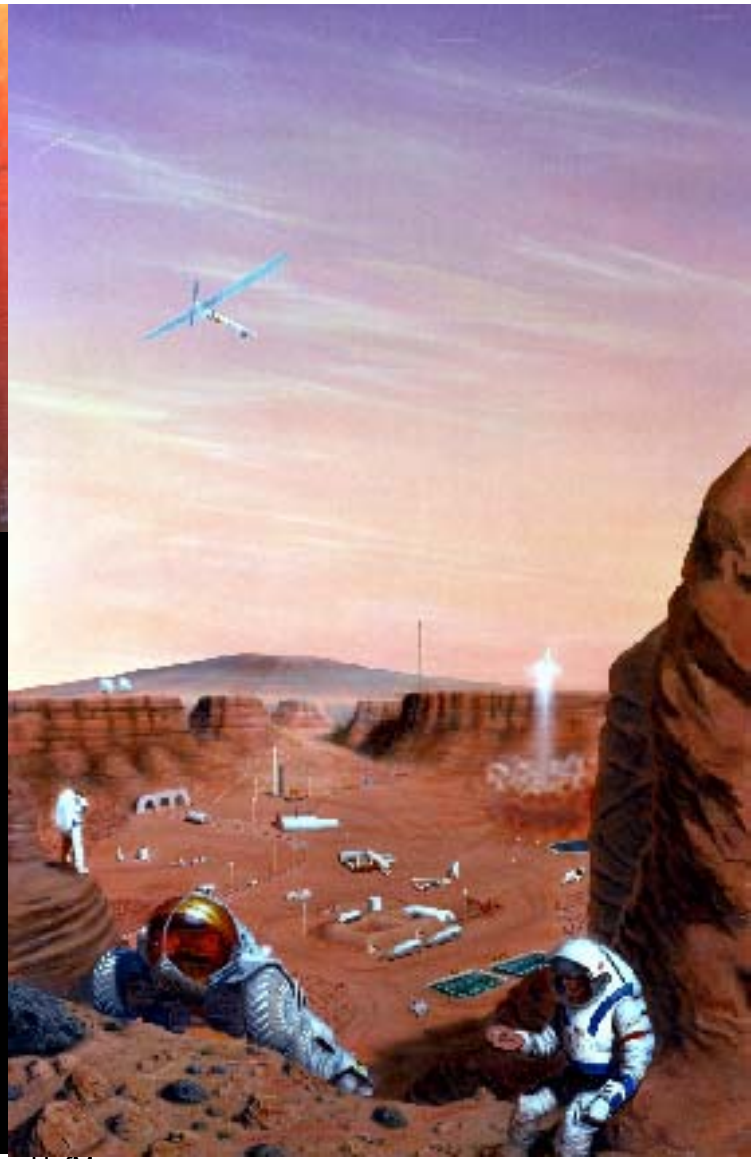


- Confirm the existence of oceans on multiple Jovian moons
- Characterize ice crust thickness and ocean depth
- Identify areas on Europa where the ocean has recently exchanged with the surface and/or where the ocean is most accessible beneath the surface
- Locate and characterize organic material and begin the astrobiology exploration of these moons, identifying regions of prime interest for future exploration

Future Colonies with Nuclear Power





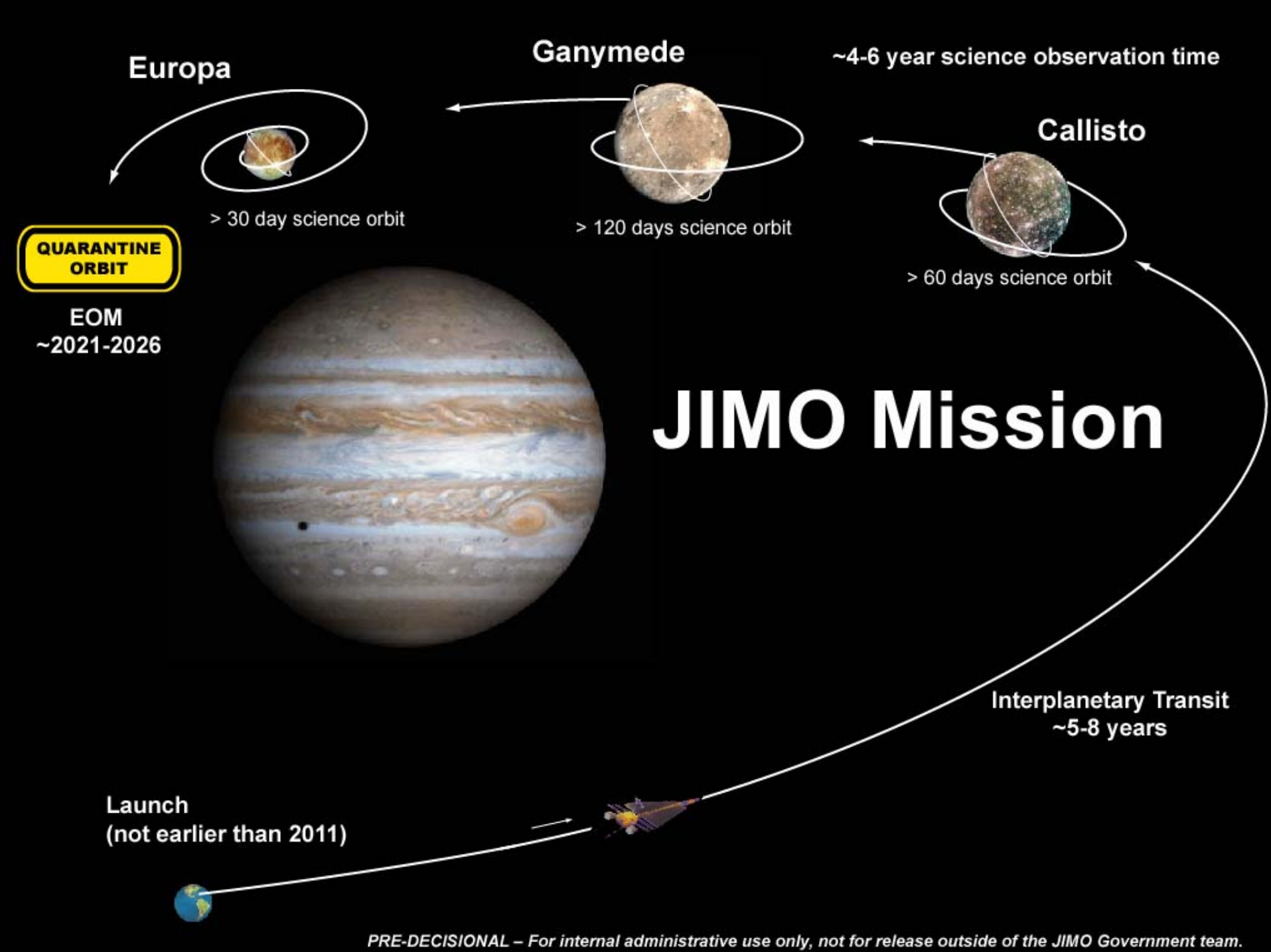


JIMO Mission Background

- The Prometheus Project, Jupiter Icy Moons Orbiter (JIMO) mission responds to the National Academy of Sciences' recommendation that a Europa orbiter mission be the number one priority for a flagship mission in Solar System exploration
- JIMO will search for evidence of global subsurface oceans on Jupiter's three icy moons: Europa, Ganymede, and Callisto.
- JIMO will be the first flight mission to use fission nuclear power and propulsion technologies.
- This mission will set the stage for the next phase of exploring Jupiter and will open the rest of the outer Solar System to detailed exploration.

Overarching Objectives

- **Technology**
  - **Develop a nuclear reactor powered spacecraft and assure that it can be processed, launched, and operated safely and reliably in deep space for long-duration deep space exploration**
- **Science**
  - **Explore the three icy moons of Jupiter – Callisto, Ganymede, and Europa -and return science data that will meet the highest scientific goals as set forth in the Decadal Survey Report of the National Academy of Sciences.**
- **Follow-on Missions**
  - **Developed technologies shall be designed as to be extensible to future Lunar and Mars missions**



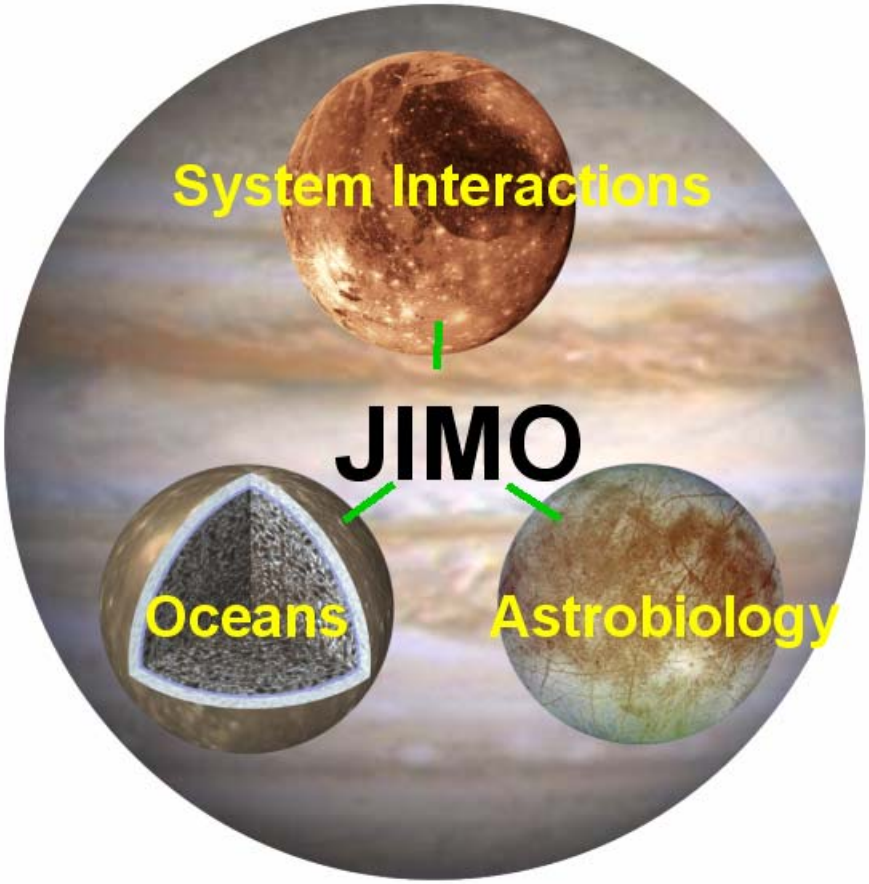
PRE-DECISIONAL – For internal administrative use only, not for release outside of the JIMO Government team.

Overarching Objectives

- Technology
  - Develop a nuclear reactor powered spacecraft and show that it can be processed safely, launched safely, and operated safely and reliably in deep space for long-duration deep space exploration
    - In so doing, the technology and manufacturing industrial infrastructure for building space nuclear reactors will be established
- Science
  - Explore the three icy moons of Jupiter – Callisto, Ganymede, and Europa and return science data that will meet the highest scientific goals as set forth in the Decadal Survey Report of the National Academy of Sciences.
    - The high power and high data rate afforded by nuclear power will enable science data return that is unprecedented in quality and quantity.

Three Cross-cutting Science Themes and Investigations*

Explore the icy moons of Jupiter and determine their habitability in the context of the Jupiter system



Oceans:

Liquid water, Icy Crustal Structure and Active Internal Processes

Astrobiology:

Volatiles, Organics and Surface Processes

Jovian System Interactions:

Satellite Atmospheres, Surfaces and Interiors

* "Exploration of the solar system and beyond will be guided by compelling questions of scientific and societal importance. NASA exploration programs will seek profound answers to questions about the origins of our solar system, whether life exists beyond Earth, and how we could live on other worlds."

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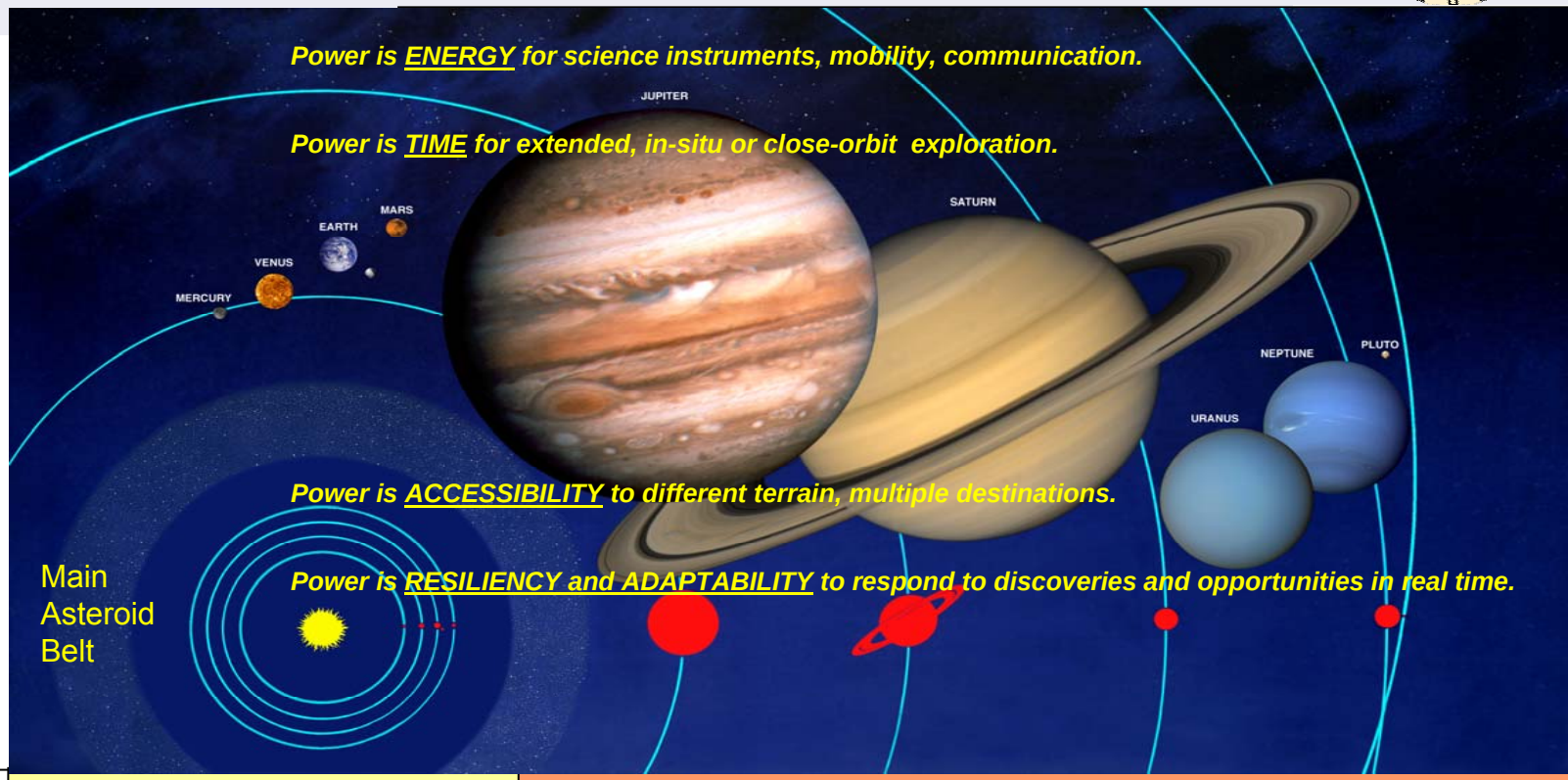
Match the Power System to the Destination

Relative Size of Planets



Power and Propulsion Systems

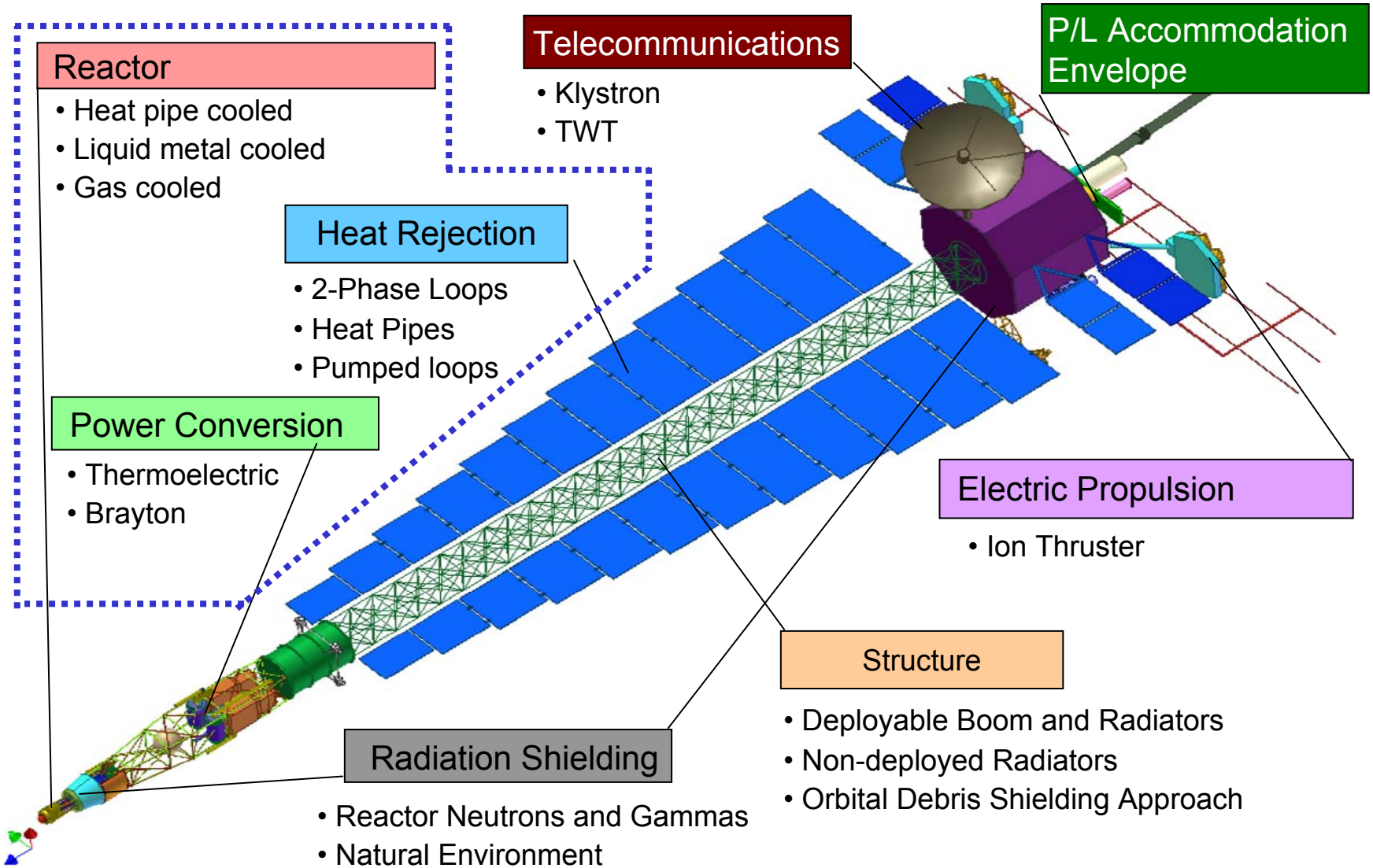
Solar Electric Best Suited to Inner Solar System
- – Also limited reach to large outer planetary bodies with aerocapture (Jupiter, Saturn, Uranus, Neptune only)

Radioisotope Electric for New Frontiers Class Outer Solar System Missions
- 500-1,000 W
- <50 kg payload
- 5 MT EELV ~ high energy earth departure

Nuclear Fission Electric for Large Flagship Missions to Outer Planets
- 10s – 100s kW
- >500 kg Payloads
- 20MT EELV ~ low energy earth departure

RTG for Surface Lander and Fission Reactors for Planetary Bases

Trade Options and Technologies Under Consideration

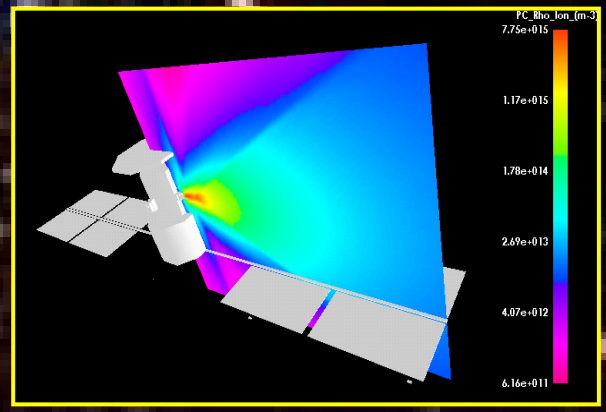


The Radiation Environment Challenge

An image of the Sun in soft x-rays.
The white (brightest) region on the right hand side shows *post-flare loops*, hot loops that remain after a solar flare.
(Image from the Yohkoh Soft X-Ray Telescope

Space Environments and Effects Modeling, Characterization, and Tool Development

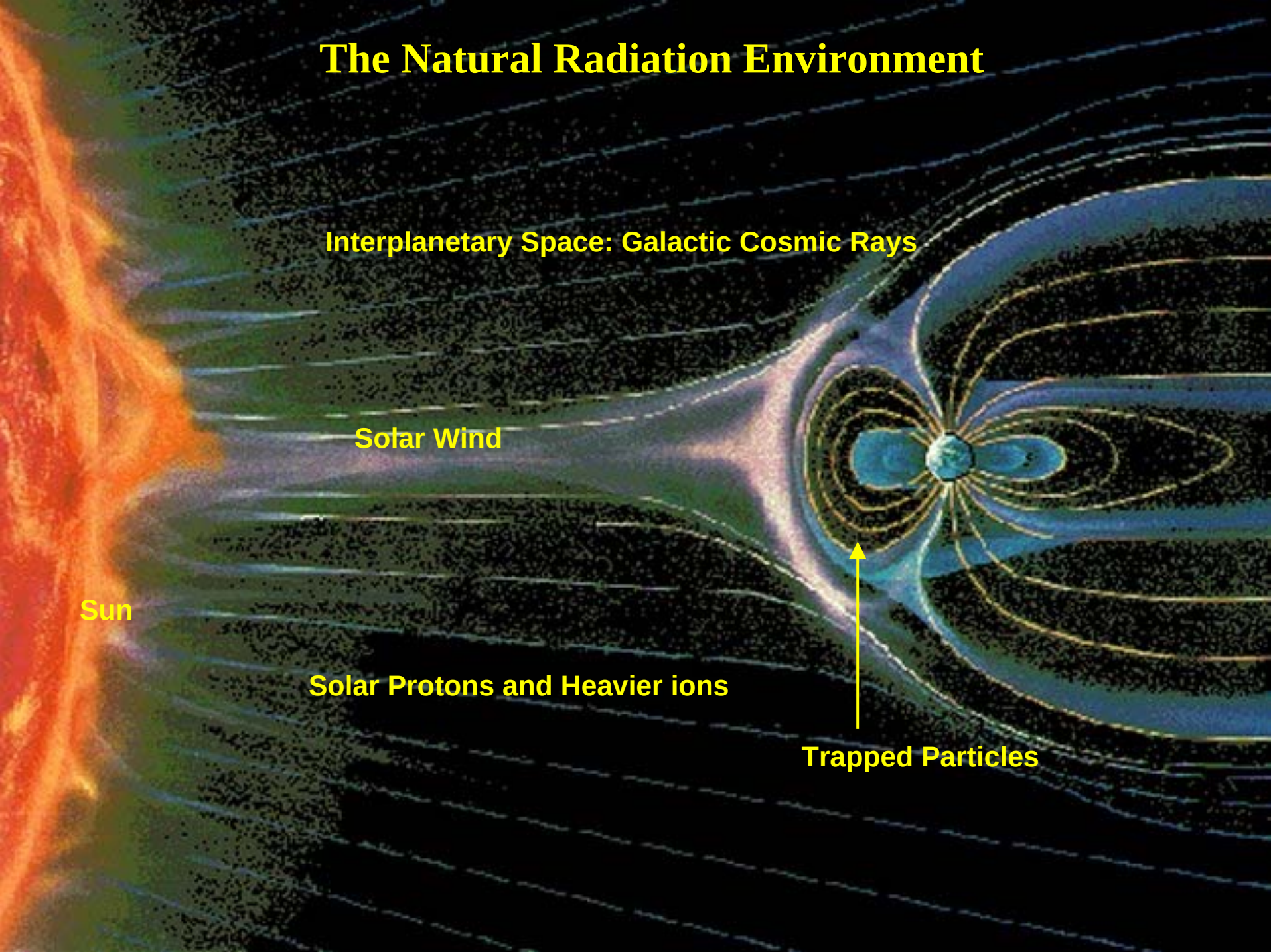
- Provides a coordinated and focused organization to deliver needed JIMO space environment technologies, data and requirements:
  - **Thruster plume characterization**
  - **3D Plume modeling and integrated tool**
  - **Arching in cabling and surface charging**
  - **Thruster plume contamination and effects**
  - **Jovian ionization radiation characterization/modeling**
  - **Jovian Meteoroid environment definition/modeling**
  - **Earth meteoroid/orbital debris environment definition**
  - **Hypervelocity, materials, & lubrication environmental testing**
  - **Nuclear environment effects sensor characterization**



Electric Propulsion Interactions

Arc Site Damage

The Natural Radiation Environment



Expected JIMO Radiation Levels

Spherical Aluminum Shielding Thickness	Total Ionizing Dose, krad(Si)	Displacement Damage Dose 1-MeV n/cm2
100 mil	**6000**	**8.62E12**
300 mil	**1660**	**2.78E12**
500 mil	**825**	**1.50E12**
1000 mil	**296**	**5.78E11**
2000 mil	**117**	**2.08E11**
3000 mil	**76**	**1.22E11**

Assumptions:

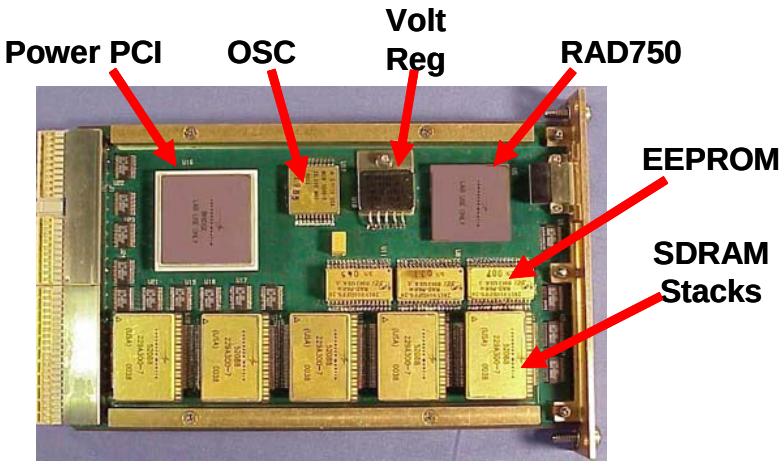
(1) Reactor Contribution = 25 krad(Si) or 5E10 n/cm2

(2) Earth Contribution from 1000 km

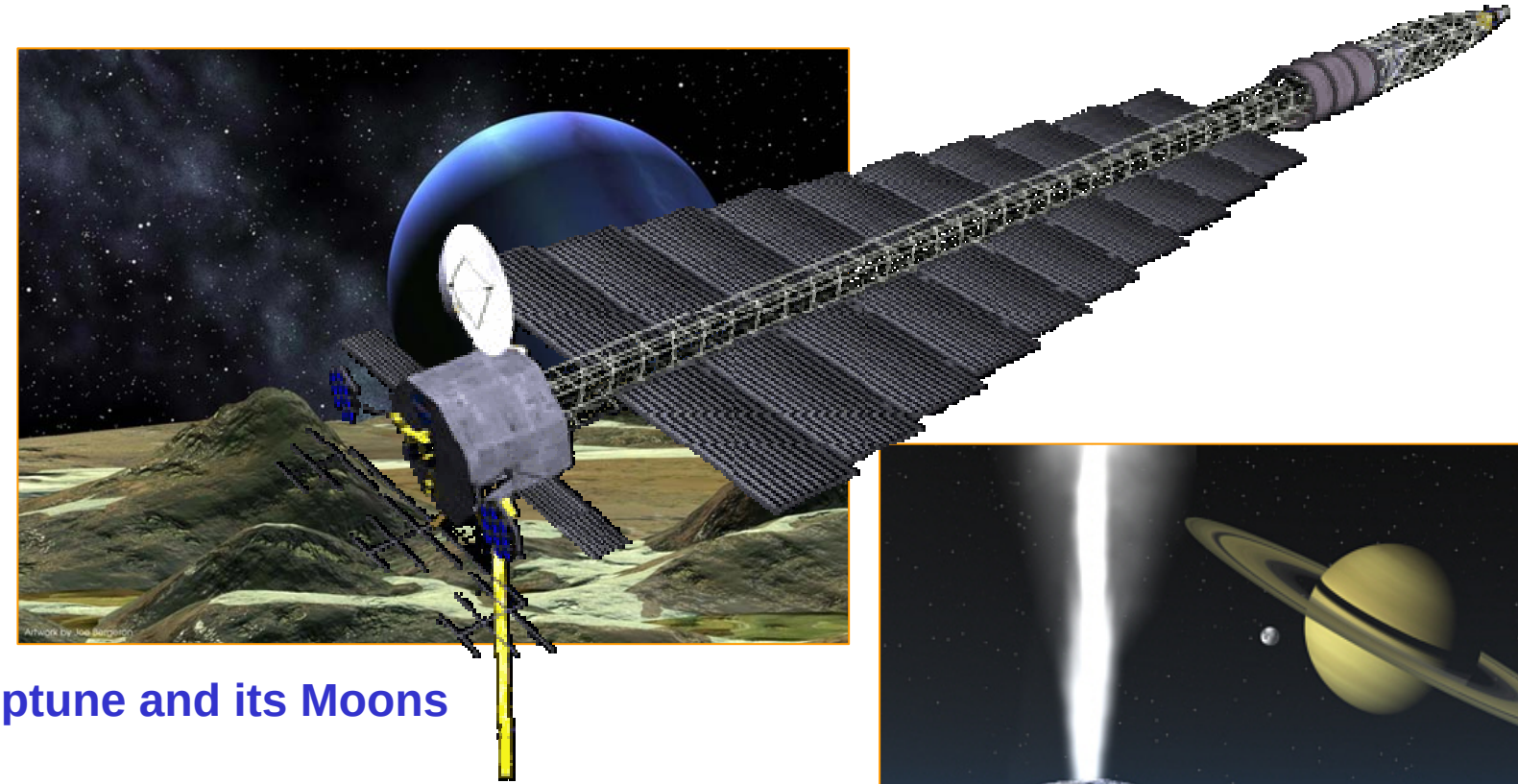
Application of JIMO Deep Space Avionics

Avionics required for diagnostics and unattended operations

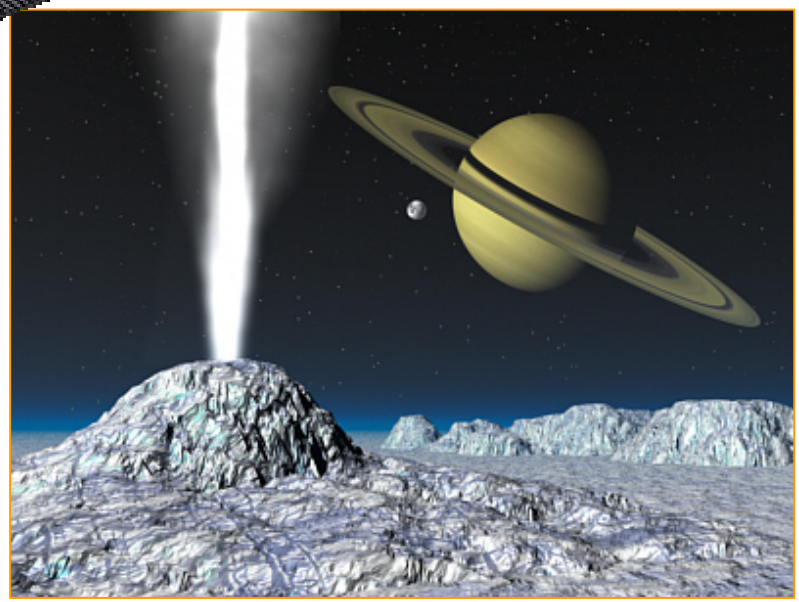
- Based on Commercial Standards for testability and compatibility
- Enhanced to improve fault detection and isolation
  - Improves reliability
  - Self-reconfigurable
- Computer capable of intense autonomous operations
  - Entry Landing and Descent
  - Hazard Avoidance
- Design incorporates long life design experience
- Modular and flexible
- Multiple data interfaces
- Demonstrated infrastructure for Radiation hardened designs
- Demonstration of complete computer system 6/15/04



Future Travels with Nuclear Propulsion



Neptune and its Moons



Saturn and its Moons

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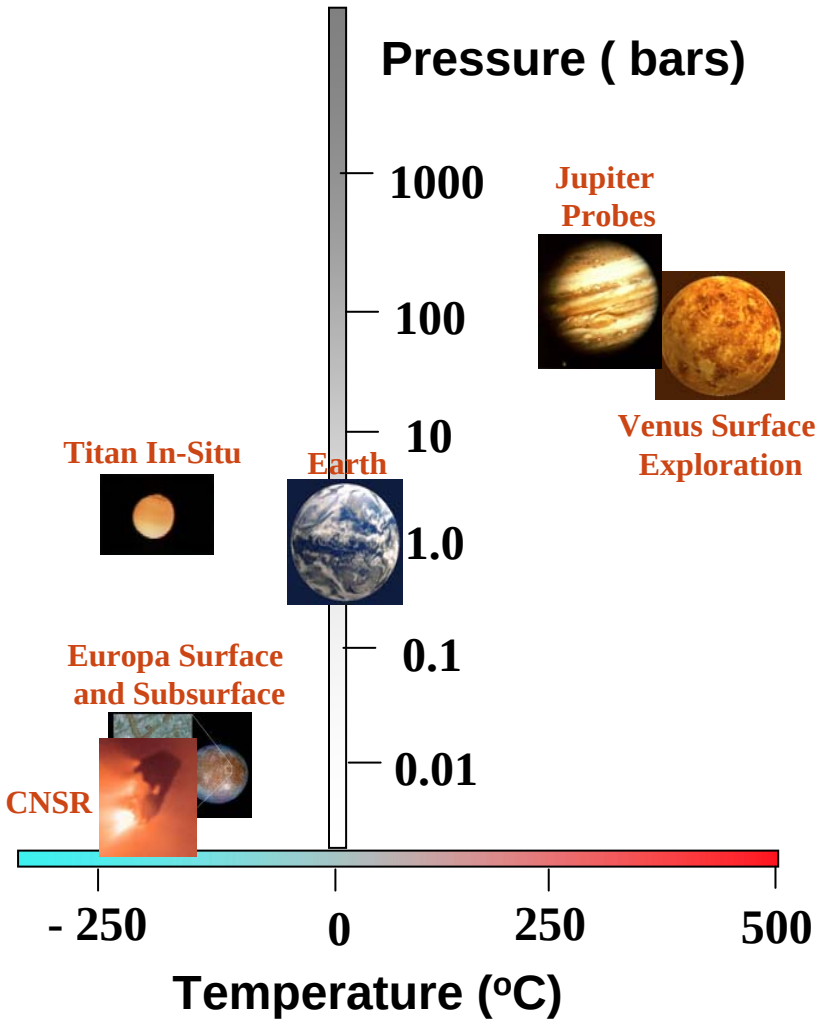
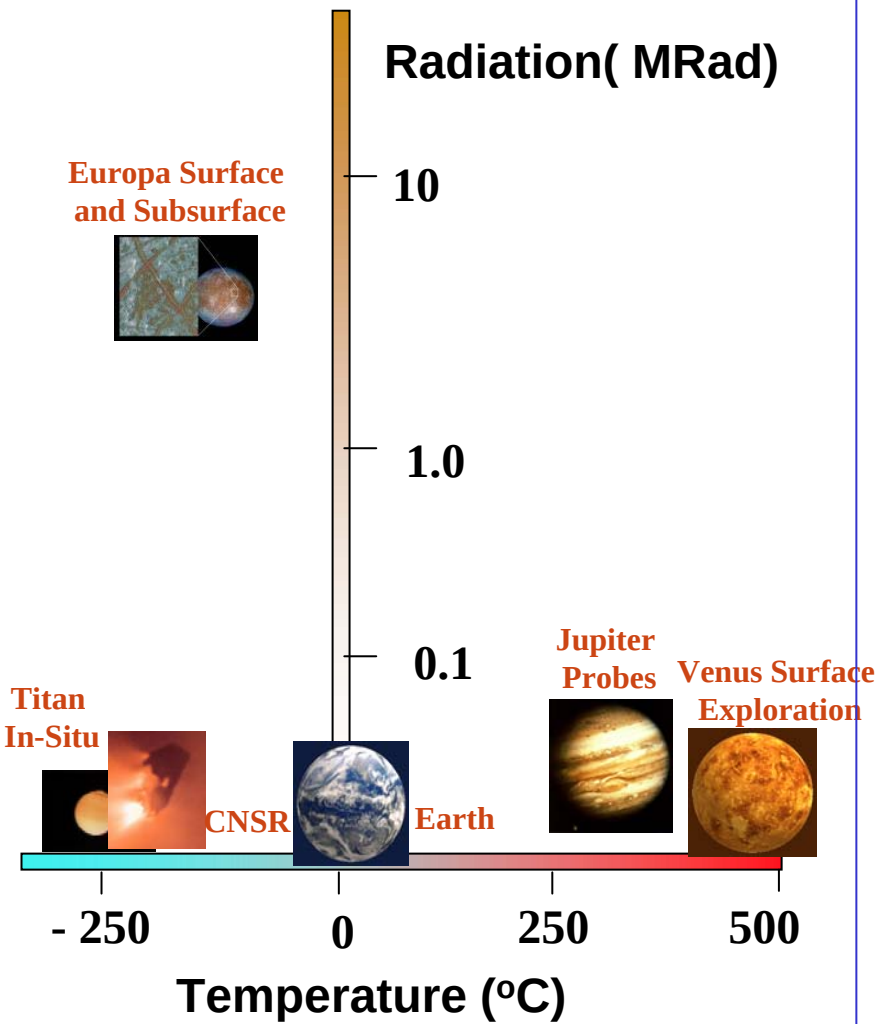
Temperature, Pressure, and Radiation in Reference Missions

Pressure vs. Temperature



Radiation vs. Temperature



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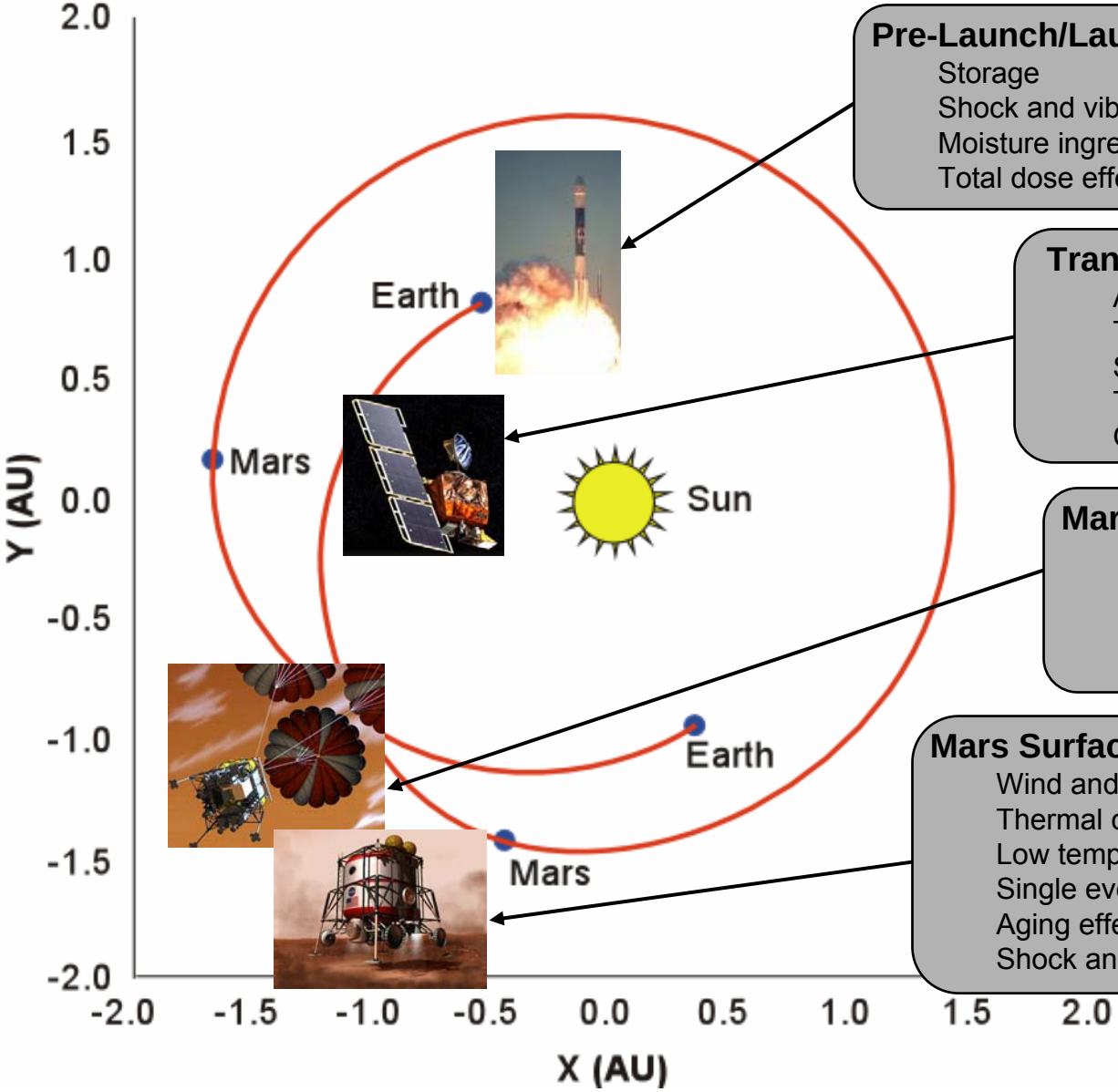
Reliability/Radiation Tolerance Essential for Surviving the Space Environment



Pre-Launch/Launch
- Storage
- Shock and vibration
- Moisture ingress
- Total dose effects due to passage through belts

Transit
- Aging effects
- Total dose effects due to flares
- Single event effects from GCR and flares
- Thermal cycling
- Outgassing

Mars Orbit/Descent
- Shock and vibration
- Charging effects in ionosphere
- Total dose effects from electrons/solar flares
- Single event effects

Mars Surface
- Wind and dust, contamination
- Thermal cycling
- Low temperatures
- Single event effects
- Aging effects
- Shock and vibration

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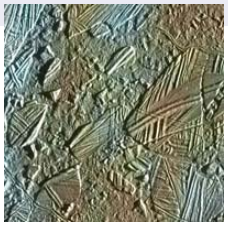
Europa Surface Exploration - Hybrid Solution

Avionics, Telecom, PMAD and Instruments in Thermally Controlled/Partially Radiation Shielded Environment

~ 0 C



Components needing development to survive and operate in low temperature/high radiation (- 160 C/5Mrad) Europa surface environment:

-160 C
5 Mrad

Sample acquisition (drilling in the ice, 0.5 m):
- Actuators
- Actuator Electronics and Packaging (Drivers)
- Coring/Drilling Tools

Sample Handling and Transfer Mechanism:
- Permanent Magnets

Sensors:
- Science sensors etc.
- Fiber-optic bundles
- Sensor's Interface Electronics
- APS camera

Energy Storage:
- LT Batteries

Avionics System (X2000) developed for Europa Orbiter can be used but thermal control and radiation shielding of avionics components will be needed

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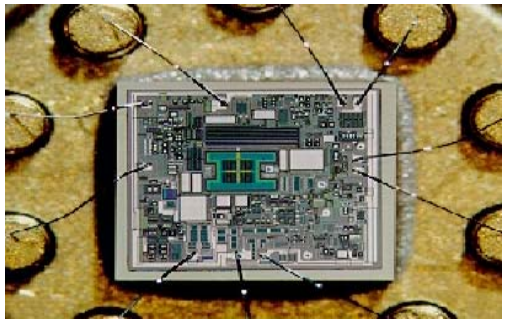
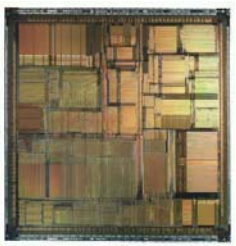
Key Technology Products

	State of the Art	Required
 **Low Temperature Electronics**	•IBM 0.12um digital SOI CMOS technology used for power PC is rated to –65 deg C. •TSMC 0.18um Bulk CMOS mixed signal technology is rated at –65 deg C. •TSMC 0.5um Bulk CMOS 40V technology is rated at –65 deg C. •Performance of these technologies at –180 deg C needs to be verified •Muses-CN nanorover electronics is tested for operation at -120 C	• Operation at> -180 C •Up to 15V(analog sensors) and 100V (actuators) Supply Voltage • 1MHz speed • Low noise (10nV/sqHz) •Analog input (I min = 10 pA/ Vmin= 1 UV) •Analog output (Vo min> 10 mV), • 0-100V digital output voltage for driving Piezo electric, Electro static or Electro magnetic actuators •Input capacitance <10pF •1 Meg ohm input resistance • Capable of driving 1 nF output capacitance
 **Rad Hard/ Low Temperature Electronics**	•Honeywell RICMOS5 (0.35um 3.3V, digital SOI CMOS) is rated at 1 Mrad, at –65 deg C. •Honeywell RICMOS4 (0.8um, 5Vmixed signal SOI CMOS) is rated to 2 Mrad at –65 deg C. •Honeywell 40V LDMOS transistors on RICMOS4 are rated at –50 Deg C.	•Electronic performance is the same as above •Operate at –160 C and 5 Mrad

Recent Radiation Environment Work

- **Developing models of the Terrestrial, Jovian, and Saturnian trapped radiation environments**
- **Updating Interplanetary Solar Proton Event models**
- **Advanced radiation shielding design for extreme radiation environments and nuclear reactors**

Proton and Electron Intensities at Earth and Jupiter

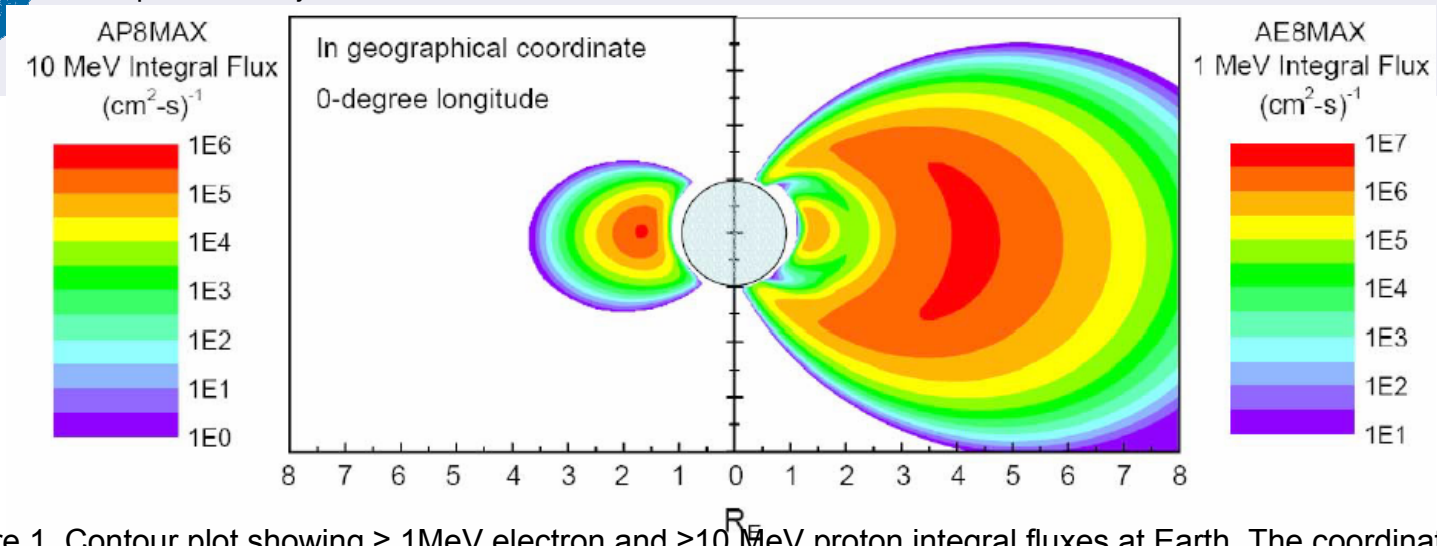


Figure 1. Contour plot showing ≥ 1MeV electron and ≥10 MeV proton integral fluxes at Earth. The coordinate system used in this plot is geographical, rather than B-L. The models used are the AP8 solar maximum model and the AE8 solar maximum model. The contour plane is for the 0- degree meridian.

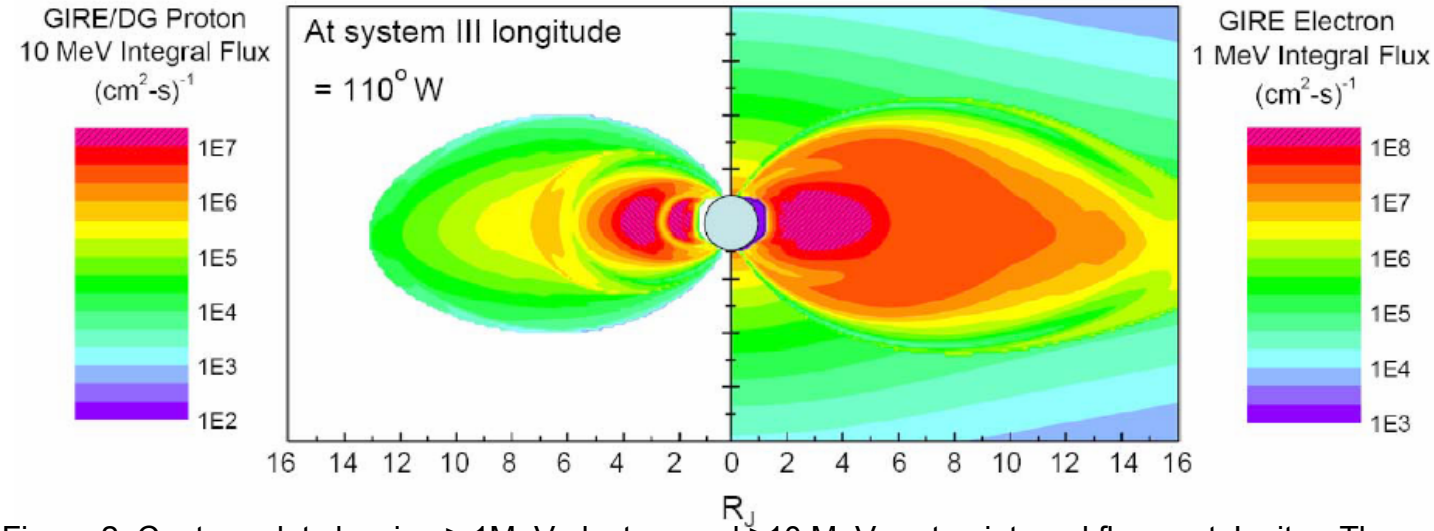


Figure 2. Contour plot showing ≥ 1MeV electron and ≥10 MeV proton integral fluxes at Jupiter. The coordinate system used in this plot is jovi-centric, rather than B-L. The models used are the AP8 solar maximum model and the AE8 solar maximum model. The contour plane is for the System III 110-degree west meridian.

Jovian Versus Terrestrial Radiation Enviornments

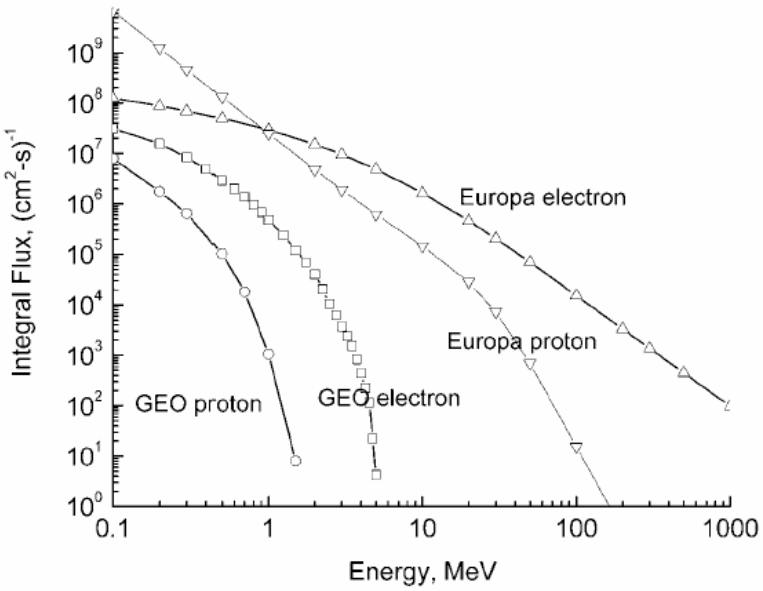


Figure 3. Trapped electron and proton spectra at geosynchronous orbit and at Europa orbit.

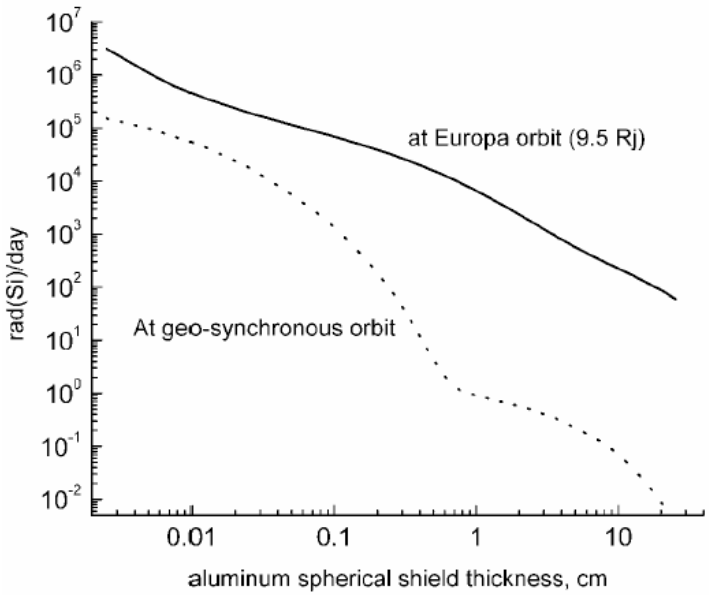


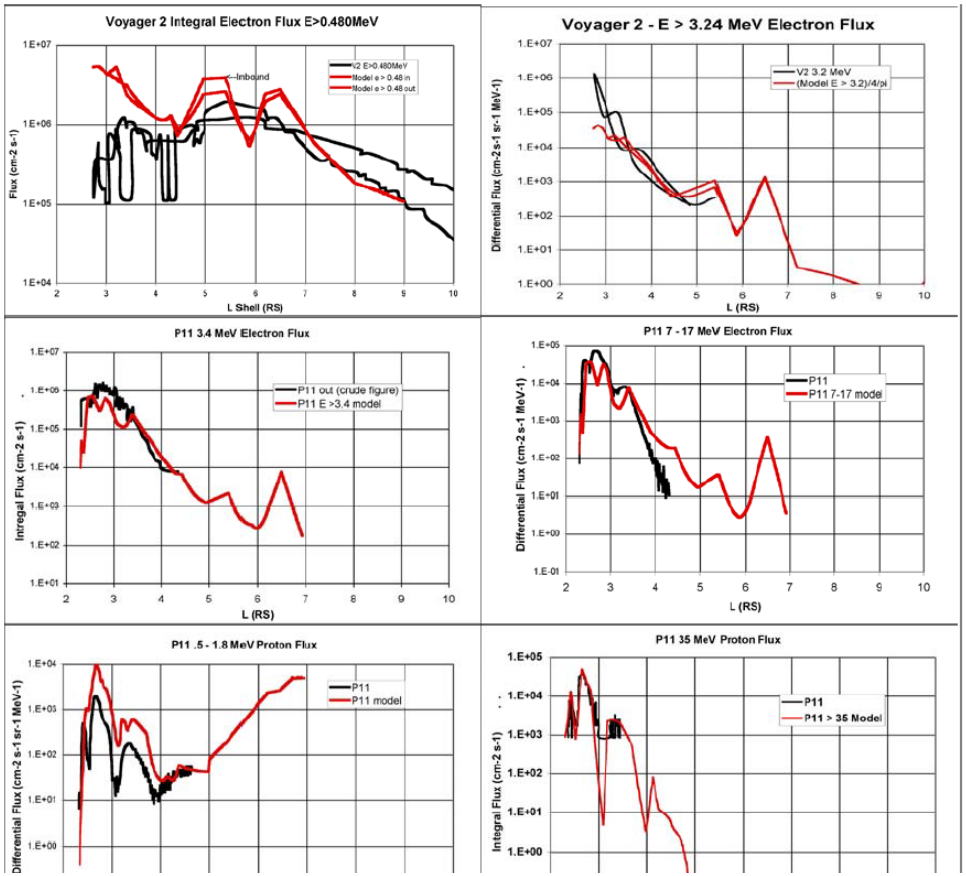
Figure 4. Total ionizing dose-depth curves corresponding to the particle spectra shown in Figure
6 as functions of aluminum spherical shell thickness.

SATRAD – Saturn Radiation Model

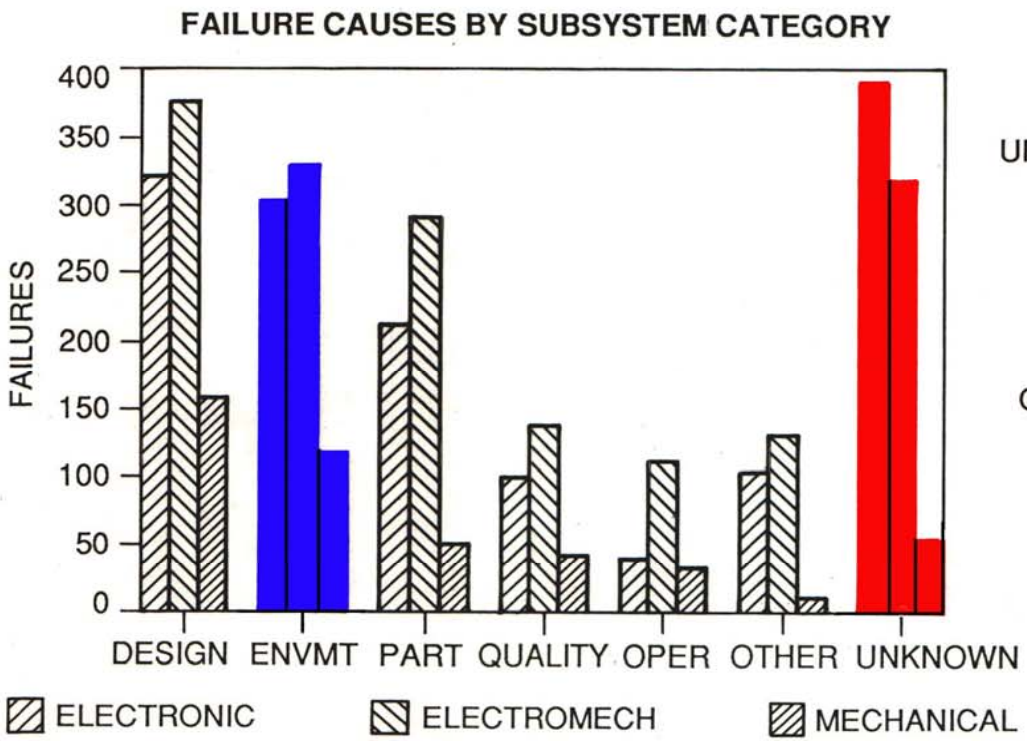
COMPARISONS BETWEEN PIONEER 11 AND VOYAGER 2 HIGH ENERGY ELECTRON AND PROTON DATA AND THE PROMETHEUS SATRAD MODEL

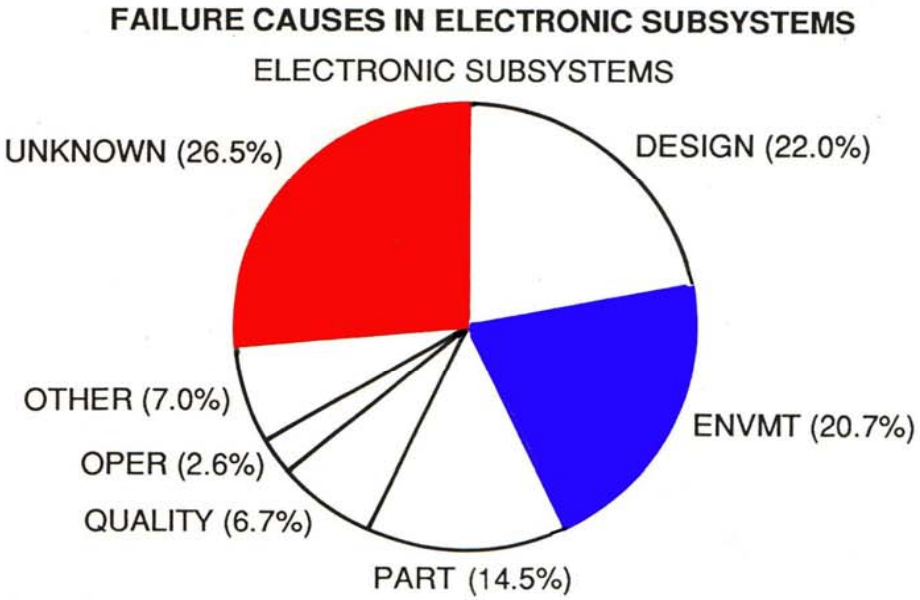
CURRENT EFFORT:

- –Collected Pioneer and Voyager high energy electron and proton in-situ data
- –Data scanned in and grided. Following determination of geometric factors, converted to fluxes and compared to in-situ data at:
  - –Electrons: >0.48, >3.24, >3.4, 7-17 MeV
  - –Protons: 0.5-1.8, >35 MeV
- –Considering the age of the data and approximations involved, agreement is quite good (see Figures at right)



Subsystem In-flight Failure Causes (Hecht, 1985)





THE IMPACT OF THE SPACE ENVIRONMENT ON SPACE SYSTEMS†

Distribution by Anomaly Diagnosis

Diagnosis	Number of Forms
ESD - Internal Charging	74
ESD - Surface Charging	59
ESD - Uncategorized	28
Surface Charging	1
Total ESD & Charging	**162**
SEU - Cosmic Ray	15
SEU - Solar Particle Event	9
SEU - South Atlantic Anomaly	20
SEU - Uncategorized	41
Total SEU	**85**
Solar Array - Solar Proton Event	9
Total Radiation Dose	3
Materials Damage	3
South Atlantic Anomaly	1
Total Radiation Damage	**16**
Micrometeorid/Debris Impact	10
Solar Proton Event - Uncategorized	9
Magnetic Field Variability	5
Plasma Effects	4
Atomic Oxygen Erosion	1
Atmospheric Drag	1
Sunlight	1
IR background	1
Ionospheric Scintillation	1
Energetic Electrons	1
Other	2
Total Miscellaneous	**36**

†Koons, H.C., J. E. Mazur, R. S. Selesnick, J. B. Blake, J. F. Fennell, J. L. Roeder, and P. C. Anderson, "The Impact of the Space Environment on Space Systems", presented at Charging Conference, Nov 1998.

Missions Lost/Terminated Due to Space Environment

Vehicle	Date	Diagnosis
DSCS II (9431)	Feb 73	Surface ESD
GOES 4	Nov 82	Surface ESD
DSP Flight 7	Jan 85	Surface ESD
Feng Yun 1	Jun 88	ESD
MARECS A	Mar 91	Surface ESD
MSTI	Jan 93	Single Event Effect
Hipparcos*	Aug 93	Total Radiation Dose
Olympus	Aug 93	Micrometeoroid Impact
SEDS 2*	Mar 94	Micrometeoroid Impact
MSTI 2	Mar 94	Micrometeoroid Impact
IRON 9906	1997	Single Event Effect
INSAT 2D	Oct 97	Surface ESD

*Mission had been completed prior to termination

Technology areas of strategic importance to JPL

1. Large aperture systems* (Optical, IR and radar; filled and sparse)
2. Precision flying*
3. Detectors and sensors*
4. Low temperature systems*
5. *In-situ* planetary exploration*
6. Planetary protection
7. Survivable systems for extreme environments
8. Deep space communications*
9. Deep space navigation*
10. Engineering systems
11. Flight computing*
12. High capability computing

Proposing to JPL

- **Analyze the request for proposal (RFP)**
  - **Identify minimum, mandatory requirements**
  - **Identify requirements that are hard for you to meet**
    - If you can't meet the minimum requirements, *don't bid*
  - **Identify areas that offer you a competitive advantage**
  - **Verify that you can meet the delivery schedule**
  - **Understand the evaluation factors and their relative importance:**
    - Technical
    - Management
    - Cost or price
    - Financial capability
    - Past performance

Proposal Preparation

- **Review proposal instructions**
- **Identify critical requirements and brainstorm cost-effective solutions**
- **Decide whether to bid**
- **Establish a proposal team:**
  - Accountable leader
  - Specialists for evaluation factors and compliance topics
- **Create a "compliance matrix" listing every requirement in statement of work and specification. Assess your ability to meet every one**
- **Create a proposal theme: e.g.; "high reliability," or "innovative"**
- **Format the proposal to match the proposal instructions**
- **Respond to every instruction and requirement**
- **Support your assertions**
- **Ask questions, but only of contracting officer/negotiator**
- **Consult legal counsel if RFP restricts competition**

Connecting with the JPL Business Opportunities Office

- ***The JPL Business Opportunities Office is responsible for:***
  - ***Small Business Programs***
  - ***Small Disadvantaged Business Programs***
  - ***Woman-Owned Business Programs***
  - ***Historically Black Colleges and Universities Programs***
  - ***HUBZone Businesses Programs***

Tom May
Manager
(818) 354-2121

- ***JPL uses the Small Business Administration's (SBA) internet database, PRONet, to identify small businesses***
  - ***http://pro-net.sba.gov***

How to Contact JPL

- **Jet Propulsion Laboratory**
  - **Phone: (818) 354-4321**
- **Business Opportunities Office**
  - **Thomas May, Manager (818) 354-2121**
    thomas.h.may@jpl.nasa.gov
  - **Art Duran (818) 354-7531**
    arthur.a.duran@jpl.nasa.gov
  - **Margo Kuhn (818) 354-5722**
    margo.p.kuhn@jpl.nasa.gov
  - **Martin Ramirez (818) 354-6093**
    martin.m.ramirez@jpl.nasa.gov
  - **Mary Helen Ruiz (818) 354-7532**
    maryhelen.ruiz@jpl.nasa.gov

Job Requirements Engineering

- Positions available for full-time, part-time, summer internship, and co-op job seekers
- We are looking for the following types of majors: Aerospace Engineering, Computer Engineering, Electrical Engineering, Mechanical Engineering, System Engineering and other related disciplines
- Minimum GPA 3.0
- Opportunities available for all degree levels (B.S., M.S., Ph.D)
- Sample job title: Associate - Engineering

Job Requirements
Information Systems & Computer Science

- **Positions available for full-time, part-time summer internship, and co-op job seekers**
- **We are looking for the following types of majors: Computer Science & Information Science**
- **Minimum GPA 3.0**
- **Opportunities available for all degree levels (B.S., M.S., Ph.D)**
- **Sample job title: Staff – Associate – IS&CS – Member of Info Systems & Computer Science**

Opportunities for Faculty, Students at JPL

- **NASA Summer Faculty Research Opportunities:**
  - http://www.asee.org/nffp/

- **Undergraduate Student Research Program:**
  U. S. undergraduate opportunity to conduct research at JPL. Virginia Space Grant Consortium manages USRP. Full details about the program can be found on the web at: <<http://www.vsgc.odu.edu/Menu3_1_3.htm>http://www.vsgc.odu.edu/Menu3_1_3.htm>

- **National Space Grant College and Fellowship Program [Space Grant]:**
  Distributes funds through fifty-two university-based Space Grant consortia in the fifty states, the District of Columbia, and Puerto Rico. Students receive $5,000 stipend and travel costs from their state consortia. Students stay at Caltech student houses [at a cost of $1100 for the ten weeks]. Solicitation and the screening of student applicants are done by the various Space Grant consortia. Undergraduates make up most of contingent, but graduate students are also eligible. For questions about Space Grant at JPL: Linda.L.Rodgers@jpl.nasa.gov, or William.M.Whitney@jpl.nasa.gov.

Strategic University Research Partnership Program Long-Term Goals

- **Develop Partnerships that Create Exceptional, New Space Exploration Capabilities for the Nation through: Exchange of Personnel, Joint Research, Leveraged Facilities, and Joint Proposals.**
- **Help Further the Educational Experience for the Next Generation of Space Scientists and Technologists.**
- **With Our Partners, Enhance the Recruiting and Hiring Pipeline.**
- **For information on Stategic University Research Partners, contact Merle.McKenzie@jpl.nasa.gov**

JPL Approach to Working With Strategic University Partners

- **FY98 - FY02**
  - Activity was MOU-Driven with Implementation Assigned to Program Offices
- **FY03**
  - New Strategic University Research Partnership Office was Formed and Staffed
  - Primary Focus was Jointly Funding a New Collaboration Area to Seed Future Joint Proposals
  - Secondary Focus was Contributing to Students' Educational Experience
- **FY04 and Beyond**
  - For Long-standing MOU Partners, Continue Funding Targeted Research Collaboration Up to 3 Years; Initiate New Exchanges/Interactions with Limited Additional Funding.
  - For New MOU Partners, Encourage Proposals to Competed DRDF Cycle. Jointly Fund Multiple Researcher-Interactions That Lead to a Broad Base of Research Collaborations. Interactions Include:
    - Seminars
    - Workshops
    - Student, Post-Doc, and Faculty Summer Research at Each Other's Facility
    - 2-4 Week Researcher Exchanges
    - Joint Proposals (Using Joint B&P)
    - Joint Appointments (Eventually)
  - Encourage Educational Experiences
  - Begin to Facilitate a Joint Recruiting and Hiring Pipeline

FY03 Status Indicators for JPL-University Research

- **25 Active National Programs for Students, Post-Doctoral Fellows, and Faculty, Managed Locally by JPL and Caltech**
  - 140 Students Hosted at JPL
  - 85 Post-Doctoral Fellows Hosted at JPL (Conversion Rate of 30%)
  - 40 Faculty Hosted at JPL
- **300 Academic Part-time Employees (Students)**
- **80 Co-op Program Students**
- **145 Summer Employment Students**
- **$83.3M in Contracted Research to Universities**

Education Office Programs

Program: Center for Astronomy Education:

Description: A professional Development resource for the Introductory Astronomy community, with an emphasis on community colleges. Workshops for faculty, teaching tips and strategies, and educational links.

Eligibility: Teachers of the astronomy survey course.

Deadline: None

Contact: Richard Alvidrez, (818) 354-1214

Link: http://astronomy101.jpl.nasa.gov/

Program: Faculty Awards For Research:

Description: Provides opportunities for faculty and students of HBCU/OMU institutions to contribute directly to NASA/JPL mainstream research activities.

Contact: Eva Graham, (818) 393-5917

Link: http://mured.nasaprs.com/awards/pi_awards/far/index.cfm

Education Office Programs

Program: JPL Community College Consortium:

Description: The Jet Propulsion Laboratory Community College Consortium (JPLCCC) is an alliance of community college faculty along mutual professional interests. Its mission is to enhance community college science, mathematics, and technology education using NASA/JPL resources and partnership opportunities.

Eligibility: All community colleges.

Deadline: None

Contact: Rich Alvidrez, (818) 354-1214

Link: http://jplccc.jpl.nasa.gov/

Program: NASA - ASEE Faculty Fellowship Program:

Description: In a series of collaborations between NASA research and development centers and nearby universities, engineering and science faculty members spend ten weeks working with professional peers on research. The Summer Faculty Programs Committee of the American Society for Engineering Education supervises the programs, which are operated by co-directors from the NASA centers and their collaborating universities.

Eligibility: Full-time faculty positions at US accredited colleges or universities. US Citizenship required.

Deadline: January

Contact: Linda Rodgers, (818) 354-3274

Link: http://www.asee.org/nffp/

Education Office Programs

Program: Space Grant:

Description: Space Grant is an national network of 52 state consortia to strengthen colleges and universities with interests and capabilities in aeronautics, space science and technology, and related field, and encourage cooperative programs among colleges, universities, business, federal, state, and local governments.

Eligibility: Faculty awards are provided to faculty whose research interests coincide with NASA's broad mission and with the economic and developmental needs of the state.

Deadline: See website for current information

Contact: Linda Rodgers, (818) 354-3274

Link: http://calspace.ucsd.edu/spacegrant/

Student Biographies
New Graduate Program

Name: Kari Risher

Education: B.S.E. University of Michigan, Aerospace Engineering

M.ENG University of Michigan, Space Systems

Job Title: Near Earth Mission Architect

Division: Systems Division

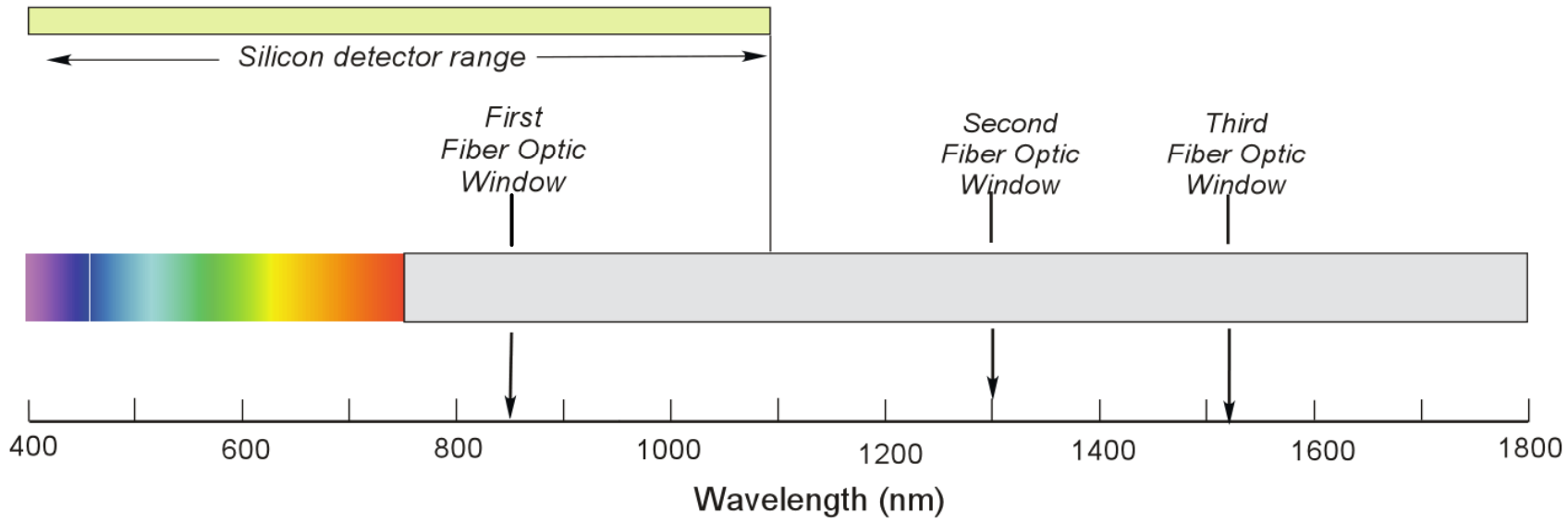
Job Responsibilities: "Turning dreams into reality." Working with scientists to turn scientific goals into the first cut at mission design.

Kari at her workstation in Building 301

NASA/JPL student employee profiles: Jessica Brooks

- U. Michigan
- Aerospace Engineering
- Co-op student
- Monitoring performance of Mars Exploration Rovers

Wavelengths of Interest



Three Fiber Optic Windows

- 850 nm, 1320 nm and 1550 nm
- Some interest in the visible spectrum as well (400 to 700 nm)
- Silicon detectors: limited to 1040 nm (bandgap edge)

Particles in Space Environments

- **Trapped Particles in the Van Allen Belts**
  - **Electrons with energies up to several MeV**
  - **Protons with a wide range of energies**
- **Solar Particles (Coronal Mass Ejections)**
- **Galactic Cosmic Rays**
  - **Heavy particles**
  - **Extremely high energies**

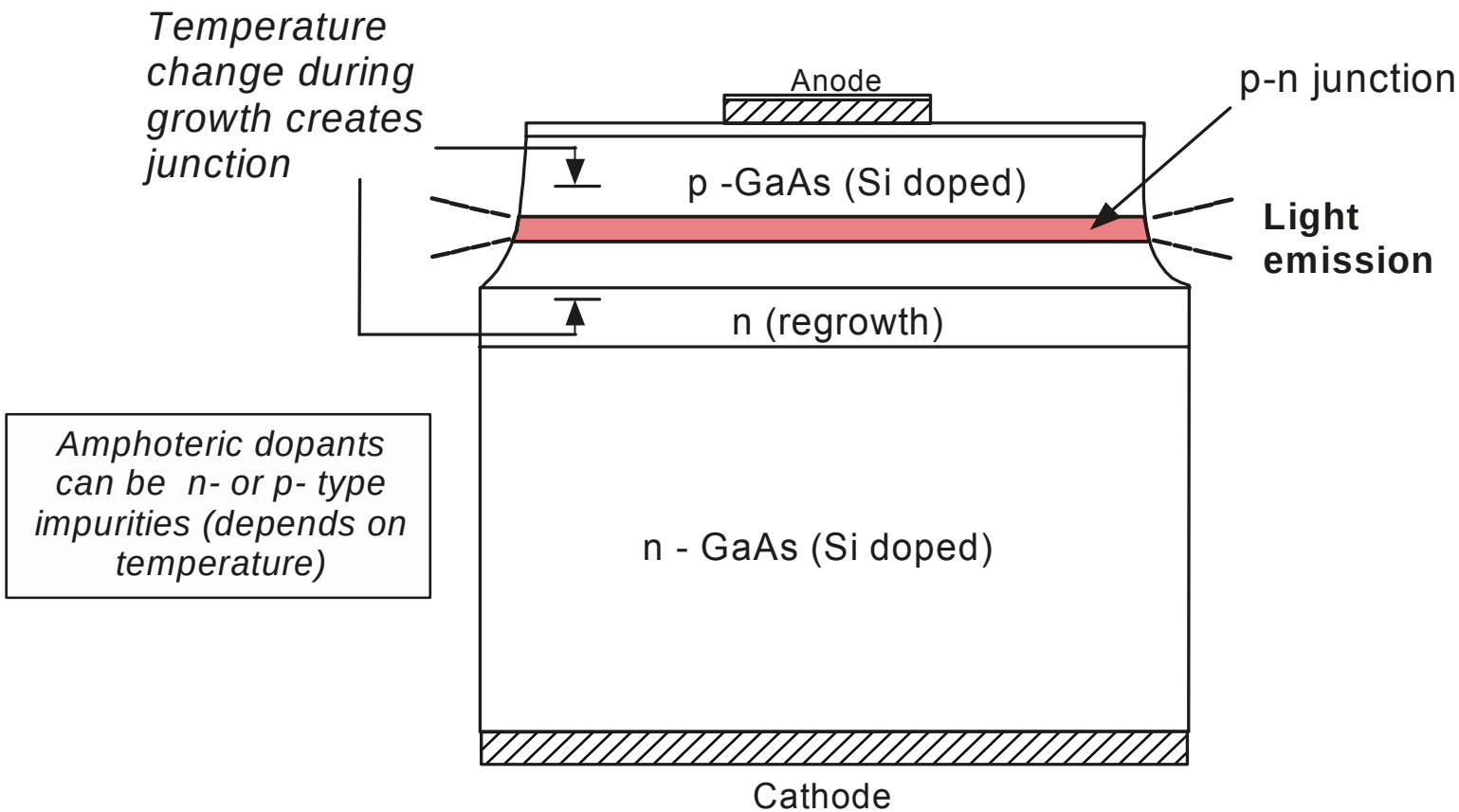
Key Radiation Issues for JPL Systems

- **SEU Effects in Advanced DRAMs**
  - **Used in solid-state recorders**
  - **Millions of upset will occur during mission life**
- **SEU Effects in Microprocessors**
- **Radiation Effects in Programmable Gate Arrays**
- **Radiation Effects in Power Control Elements**
  - **Hybrid power converters**
  - **High-voltage power systems (gate rupture in MOSFETs)**
  - **Low-dropout voltage regulators**
- **Radiation Effects in optoelectronics**

An Amphoterically Doped LED

Simple process developed in 1960's

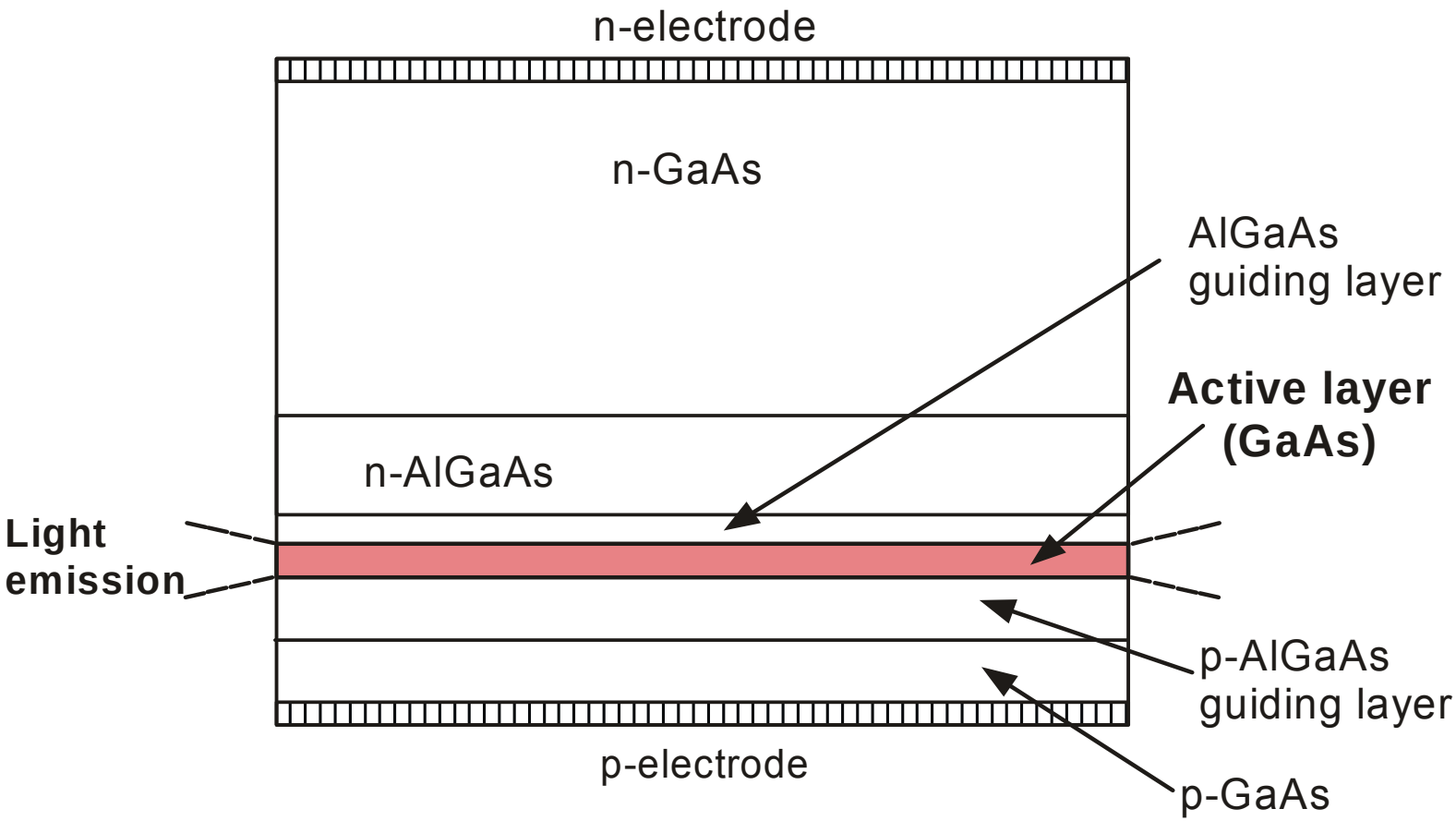
Highly efficient: 860 – 930 nm



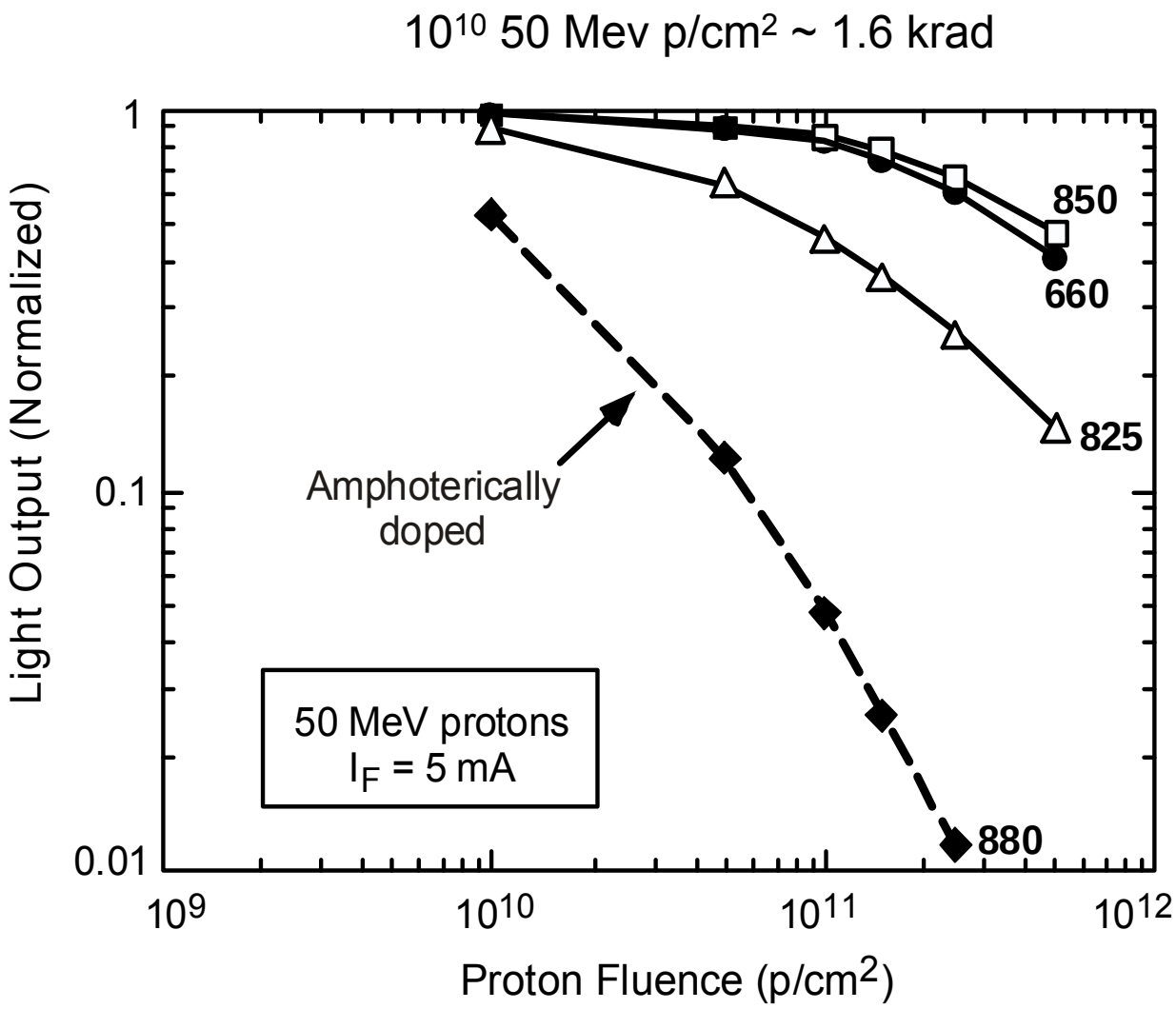
A Double-Heterojunction LED

Complex fabrication process with many layers

Produced LEDs with fast response times

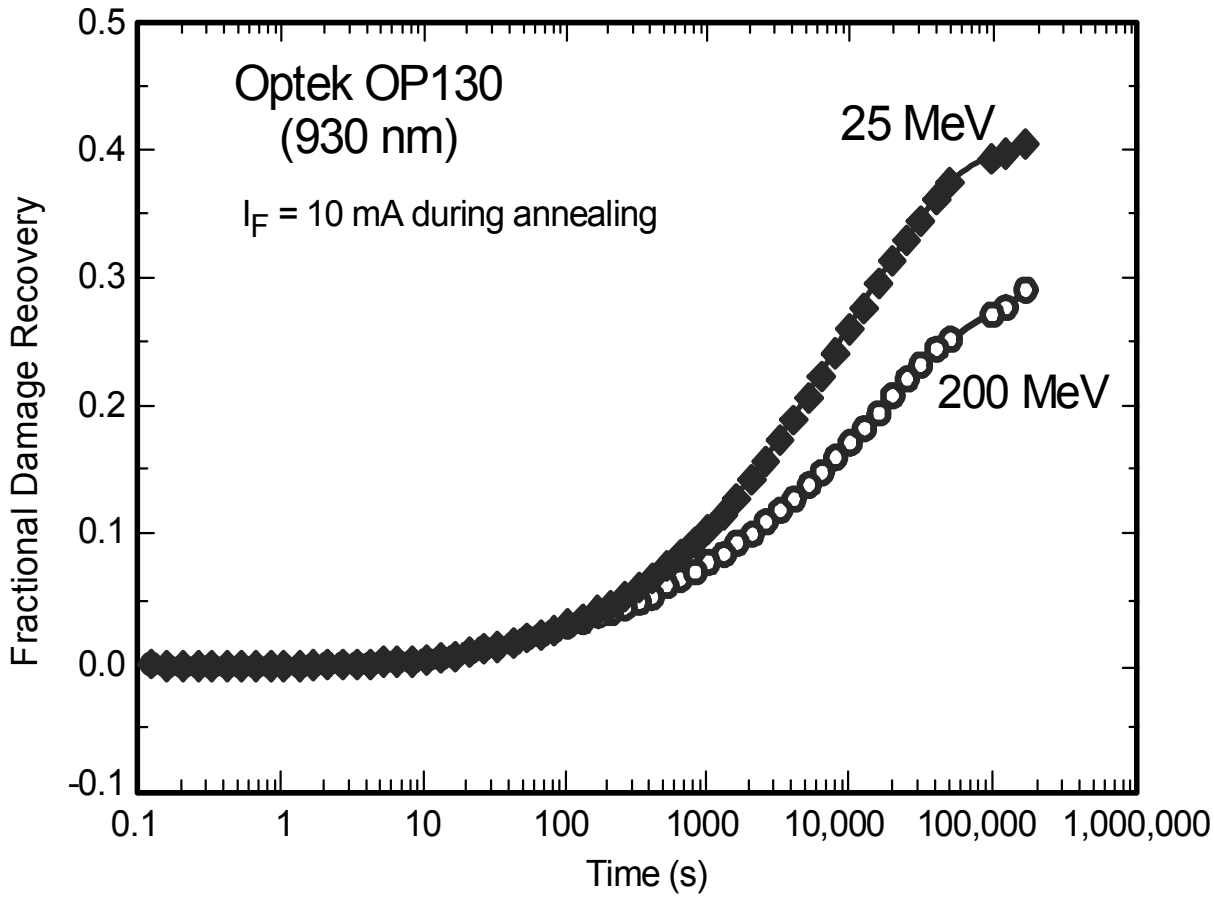


Degradation of LEDs after Proton Irradiation



Annealing of Amphoterically Doped LEDs after Proton Irradiation

Annealing does not occur until forward current is applied

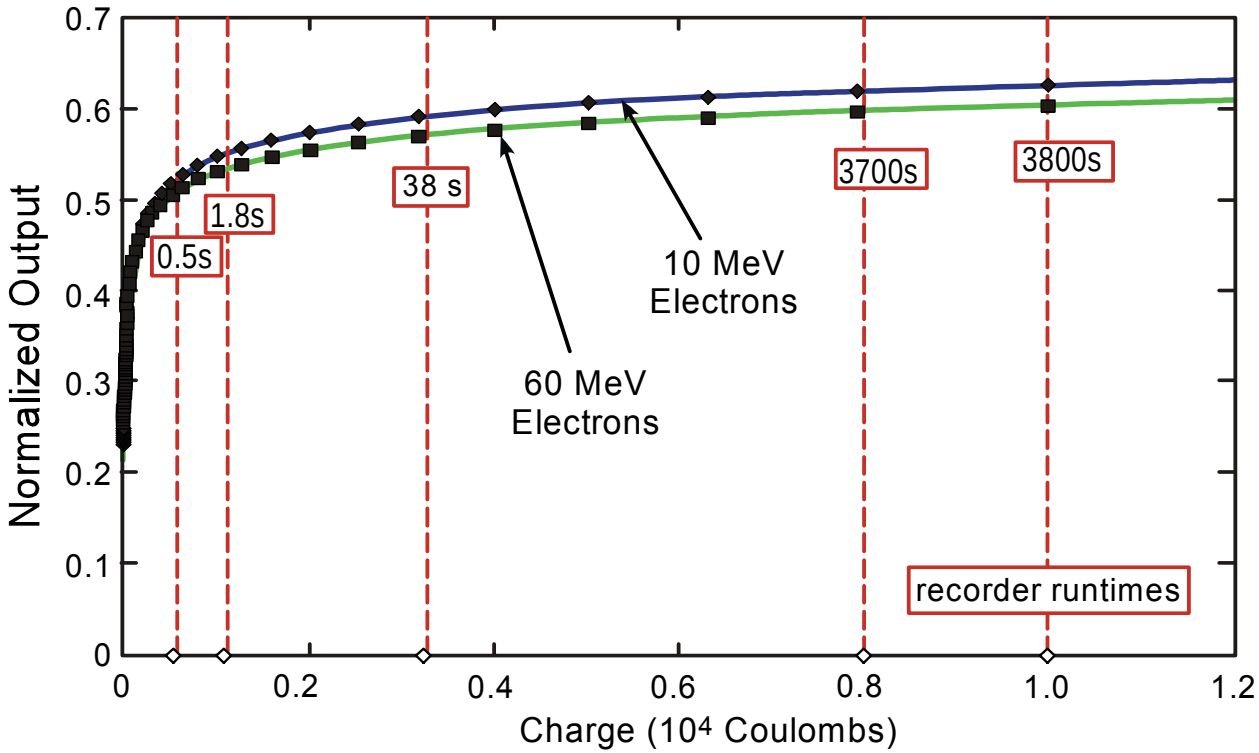


Recovery of LED Damage in Galileo Tape Recorder

Tape recorder stopped working after 34th orbit around Jupiter

Caused by LED degradation in control circuitry

Operation was successfully restored after forward biasing the LED to anneal the damage



After G. Swift, *et al*., IEEE Trans. Nucl. Sci., December, 2003

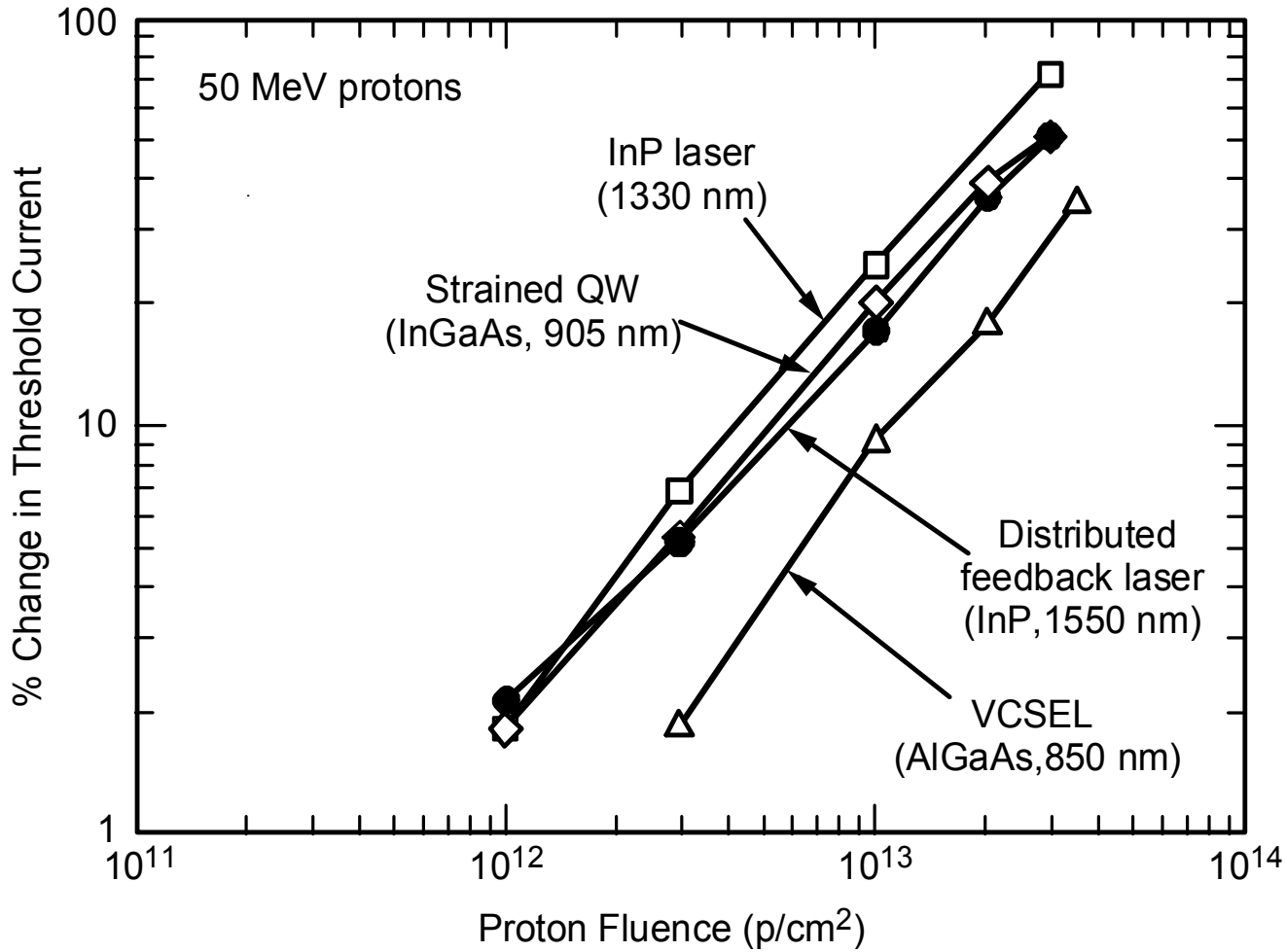
Optical Emitter Degradation: Summary

Amphoterically doped LEDs are one of the most sensitive components that can be used in space

Often used in optocouplers

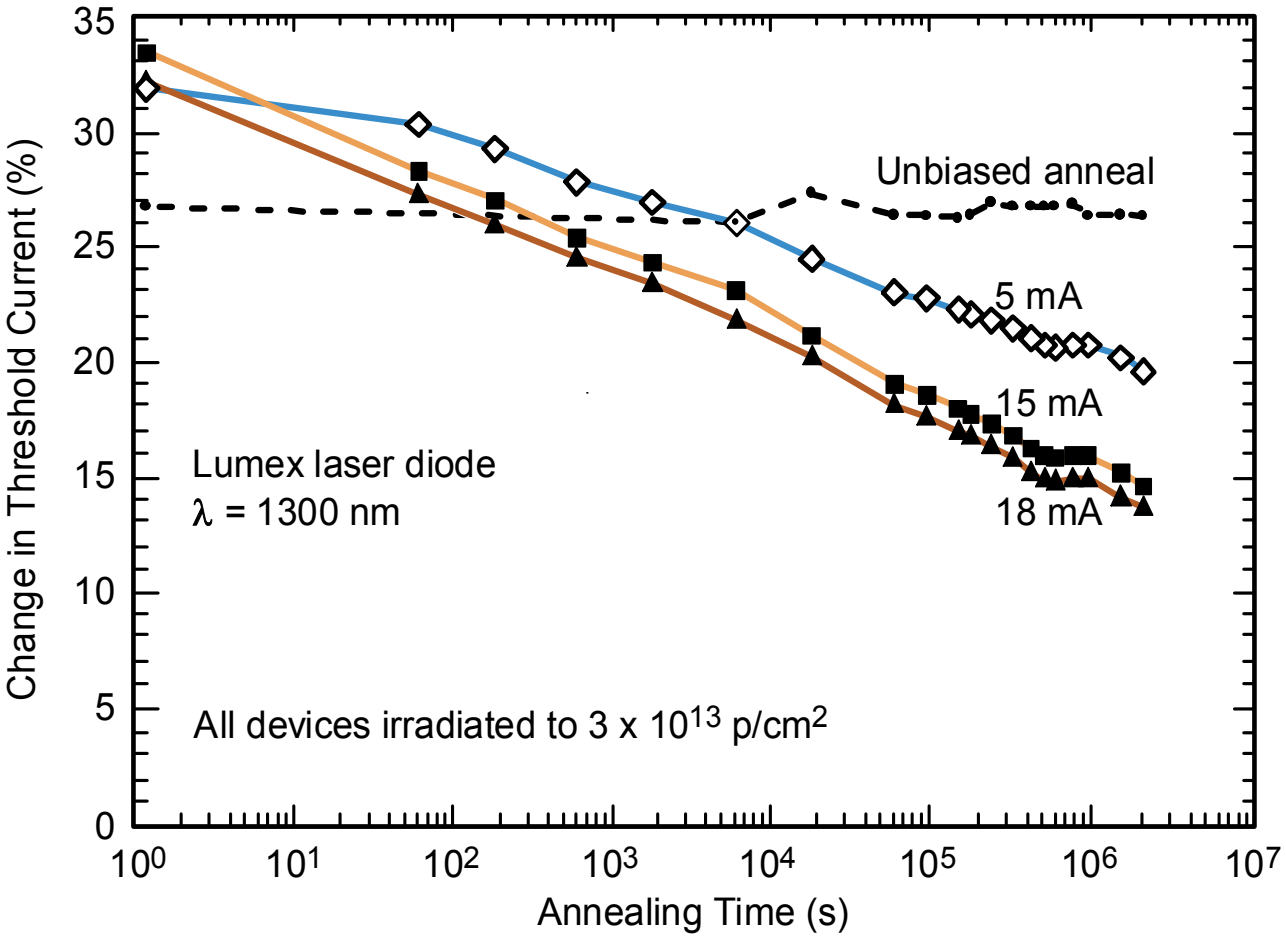
Device Type	Approximate Threshold for Degradation	Annealing Properties	Comments
Amphoterically Doped LED	5×10^9 p/cm^2	Strong	Extremely sensitive to radiation damage
Heterojunction LED	1×10^{11} p/cm^2	Very weak	
Laser Diode	1×10^{12} p/cm^2	Very Strong	Monitor diode degradation may be more significant

Degradation of Various Types of Lasers



Annealing of Laser Damage

Annealing proceeds more rapidly when lasers operate above threshold

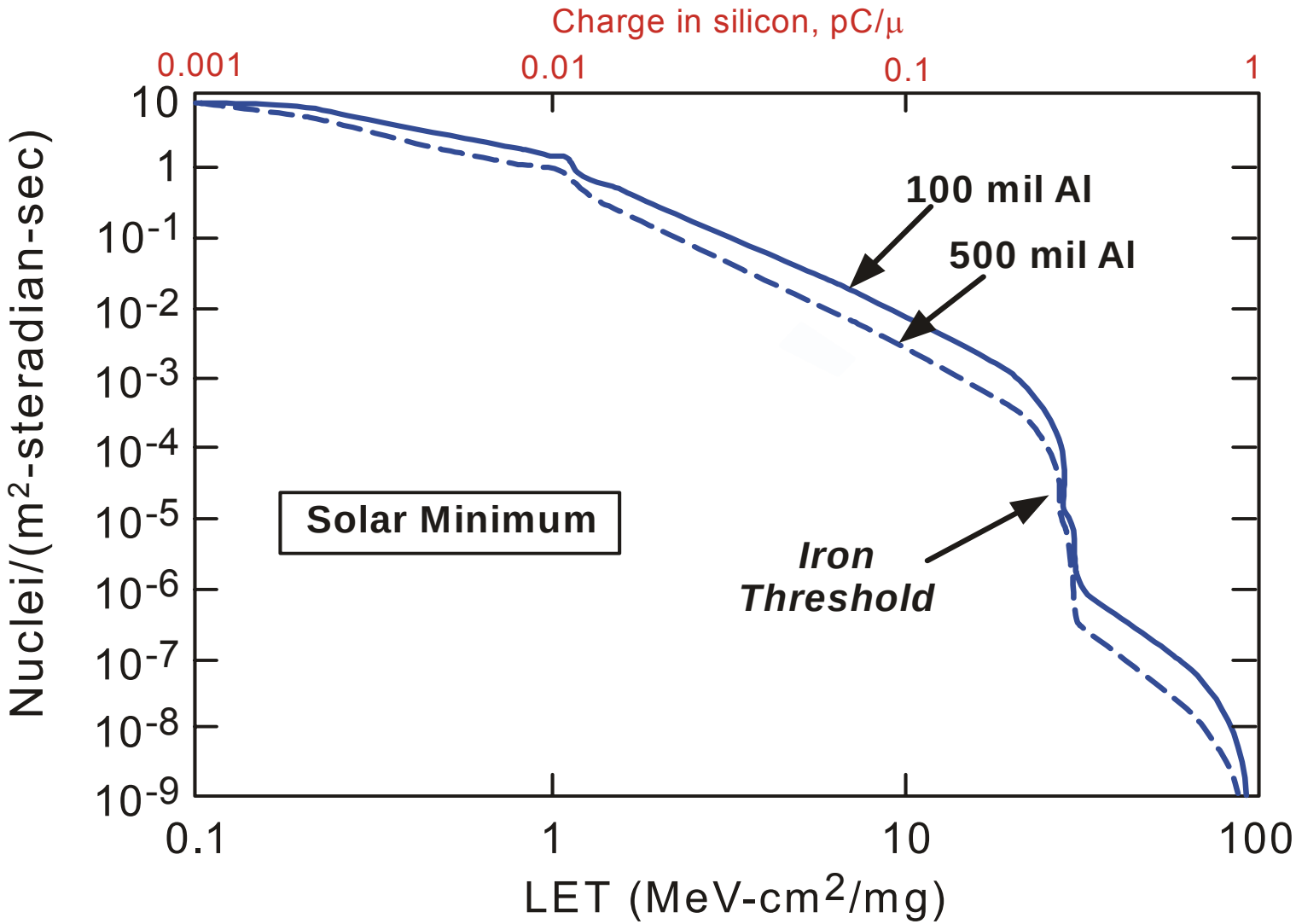


Summary *(Displacement Damage)*

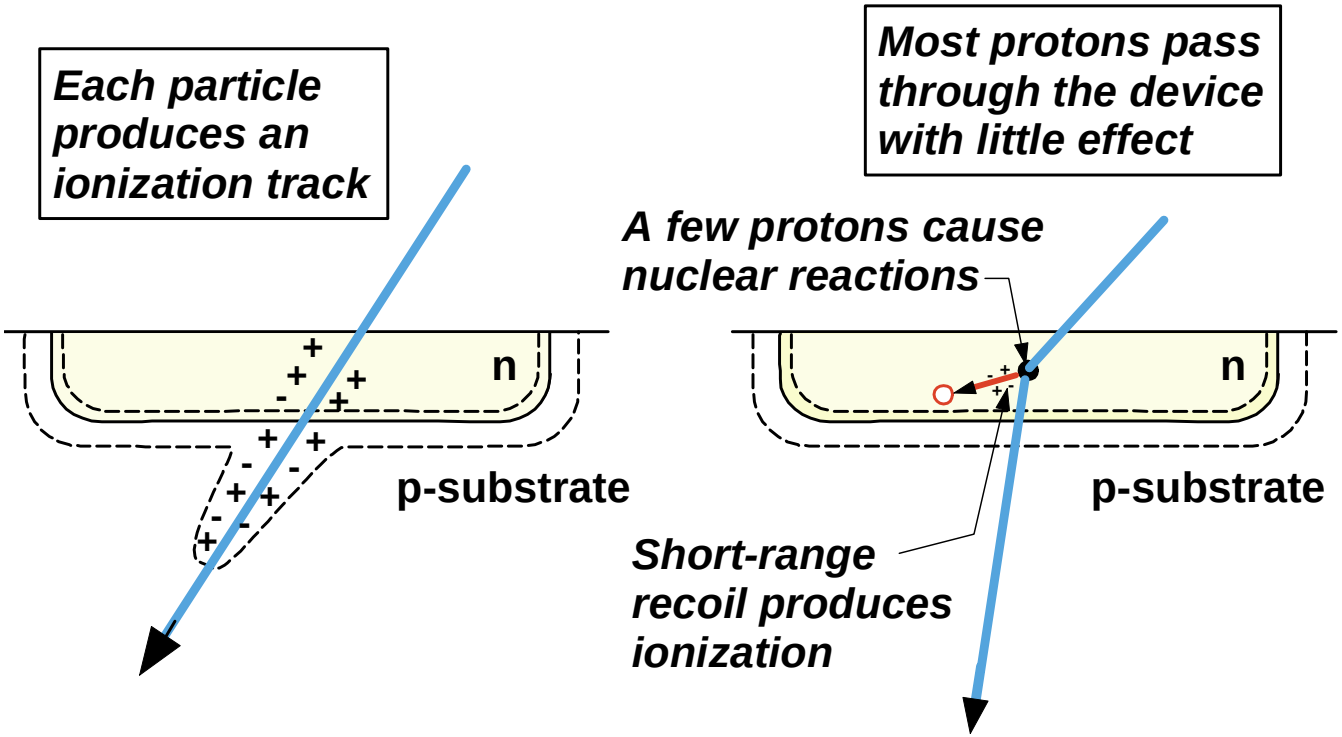
- **Optical Emitters**
  - **Discussed operating principles**
  - **Emphasized importance of proton displacement damage**
    - **Some types of optical emitters are severely degraded by protons with an effective total dose of 1-2 krad**
    - **Compared degradation of LEDs and lasers**
    - **Discussed injection-enhanced annealing**

- **Optocoupler Displacement Damage**
  - **Strongly affected by the type of LED used in the optocoupler**
  - **Decrease in diffusion length of conventional photodetectors and phototransistors dominates damage for optocouplers with less sensitive LEDs**

Integral Cosmic Ray Spectra



Charge Generation by Heavy Ions and Protons



a) Heavy Ions *(ionization by each particle)*

b) Protons *(nuclear reaction needed to produce recoil)*

Device Scaling

- **Three branches:**
  - **High performance**
  - **Low power**
  - **Memory**

"On/off current ratio is very different for the three branches

~ 1000:1 for high performance
~ 10^6:1 for memories

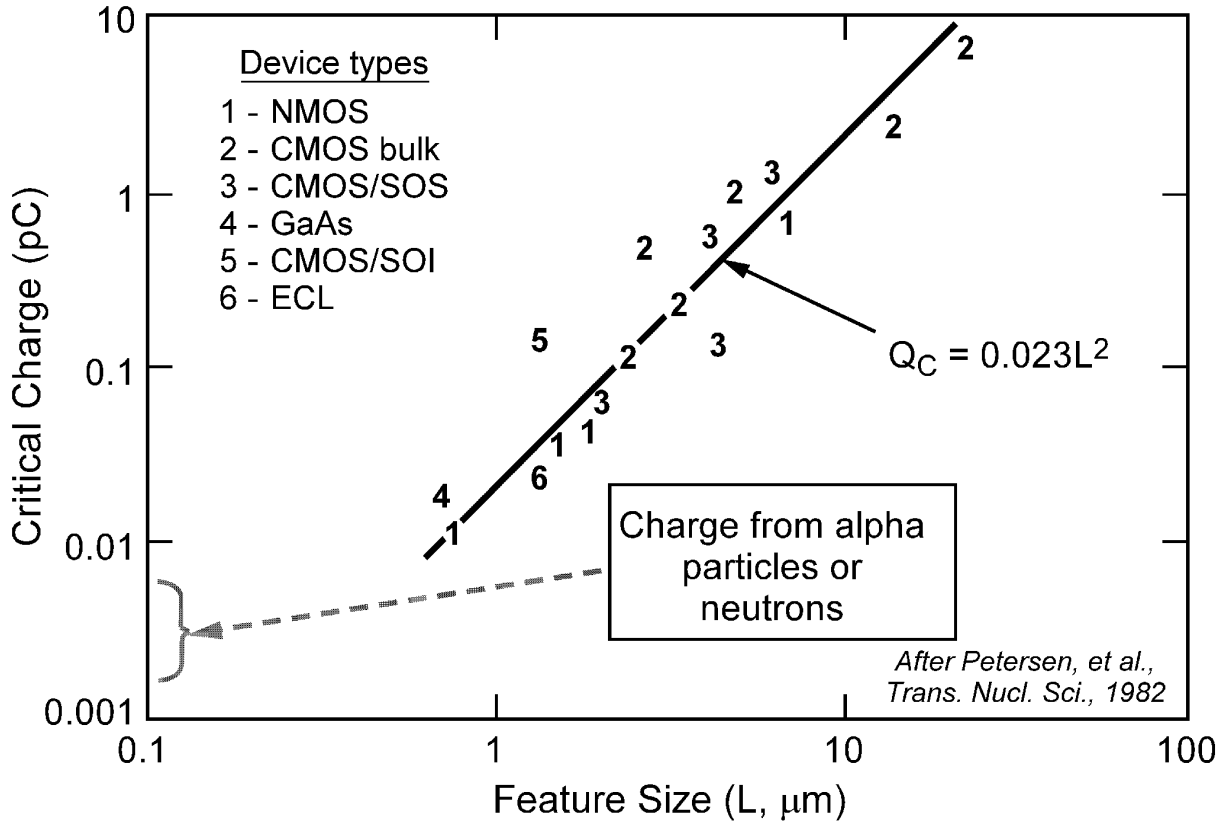
Year	2000	2001	2002	2003	2004	2005	2008	2011
T_{ox} (nm)	2.5	1.9	1.9	1.9	1.5	1.5	1.2	0.8
V_{dd} (V)	1.8	1.5	1.5	1.5	1.2	1.2	0.9	0.6
Gate Length (nm)	120	100	85	80	70	65	45	32
On/Off Ratio	107	94	75	58	47	38	19	9.4

Critical Charge

Q_C continues to decrease with scaling

Terrestrial radiation problems provide a practical limit

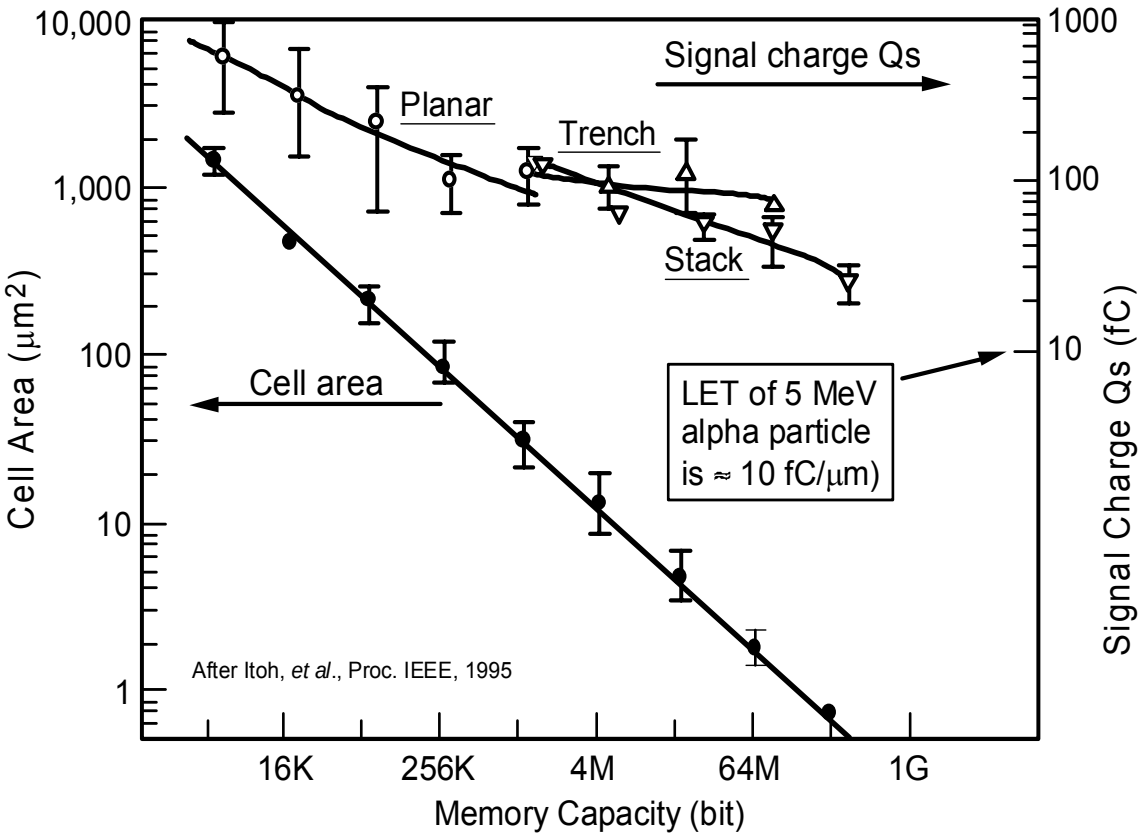
Collected charge also decreases with smaller feature size



Question: how does vulnerability in space change with scaling?

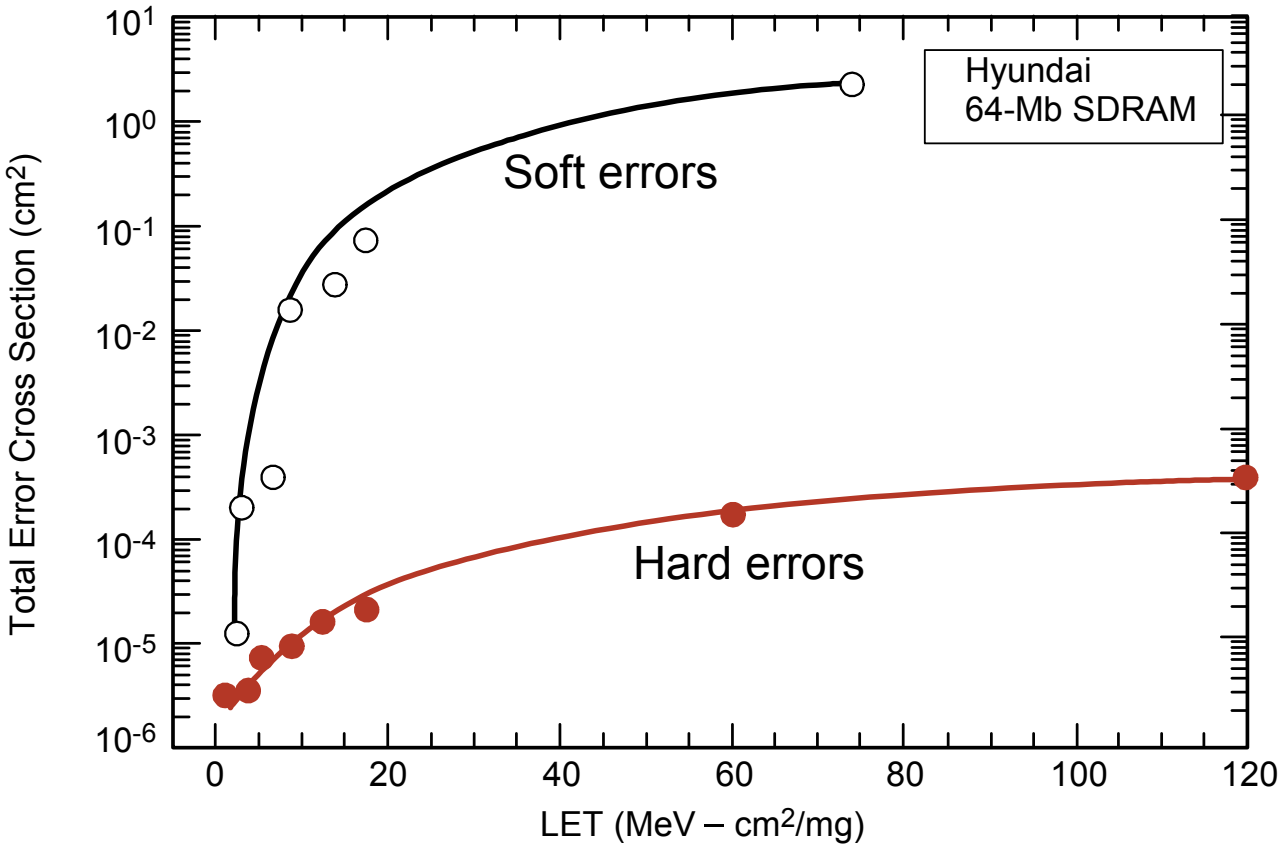
DRAM Scaling Predictions

- **Cell area decreases**
- **Stored charge changes far less**
- **Gate oxide must be thicker compared to logic devices because of retention time**



New Issues for Scaled DRAMs

- **Multiple-bit upset**
  - **> 100 errors are possible**
- **Stuck bits**
- **EDAC must remain effective for long missions**
  - **Many errors**
  - **Also affected by reliability**

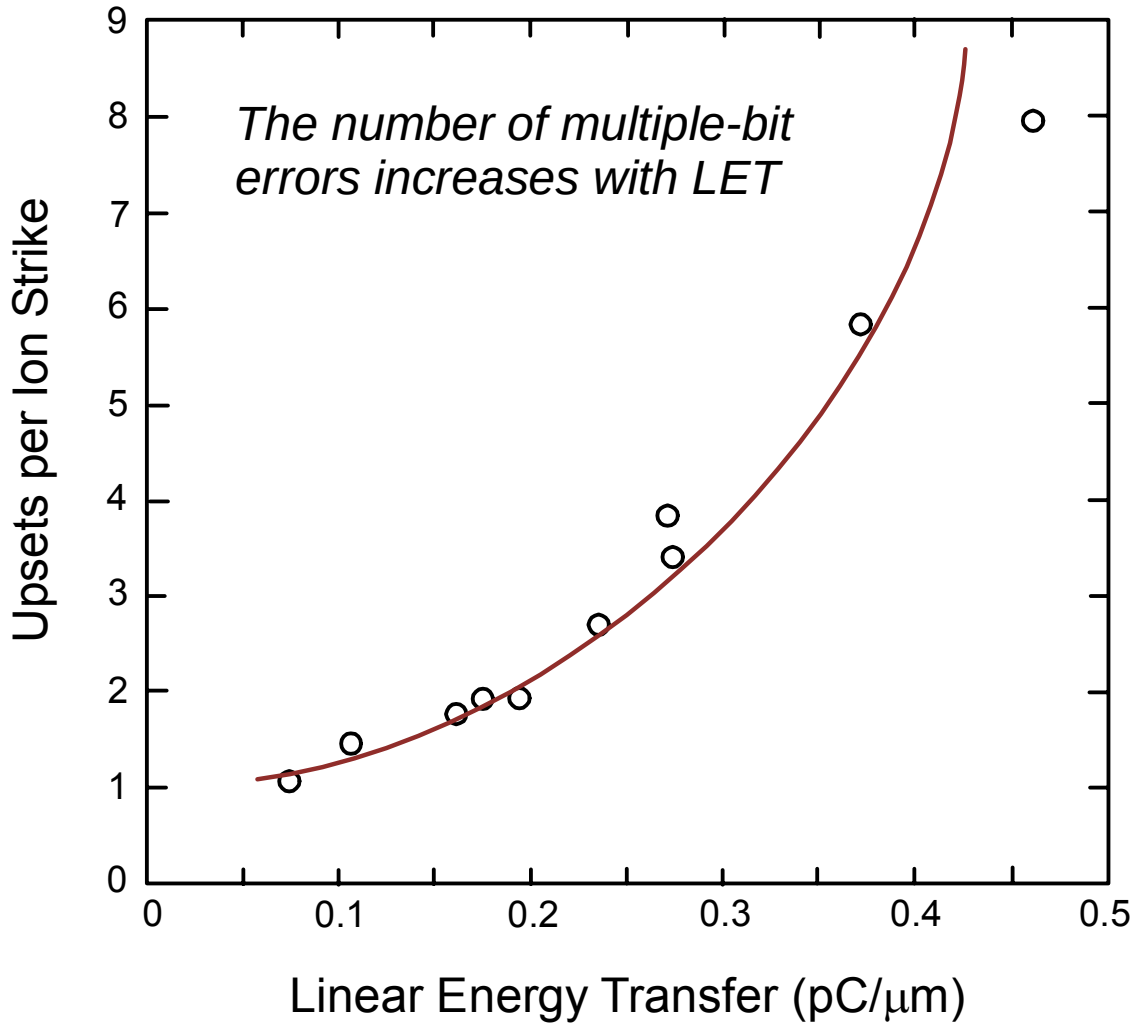


Multiple-Bit Upset Depends on LET

Charge deposition profile extends over many elements

More severe for the very high energy ions in space

Probably under estimated by laboratory testing

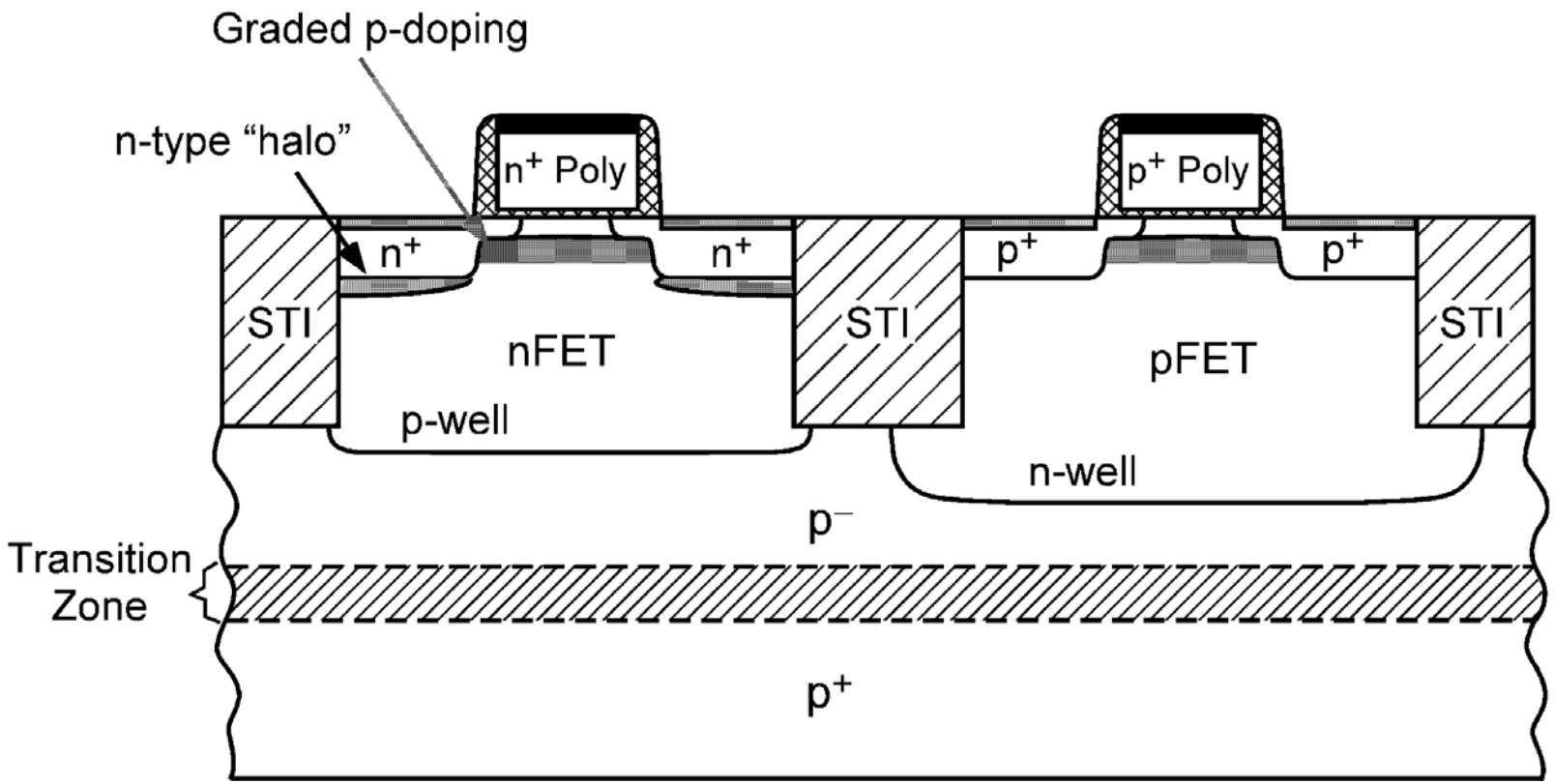


Upset in DRAMs

Size	Functional Interrupt	Stuck Bits	Latchup	Current Spikes
4-Mb	First discovery	Immune	Some manufact.	No
16-Mb	New modes	Just discernible	Immune	No
64-Mb	Complex internal state machine	Important	Catastrophic	Some evidence
512-Mb	Complex internal state machine	Important	Catastrophic	Yes

Potentially catastrophic new mechanism

Structure of MOSFETs in Advanced Logic Devices

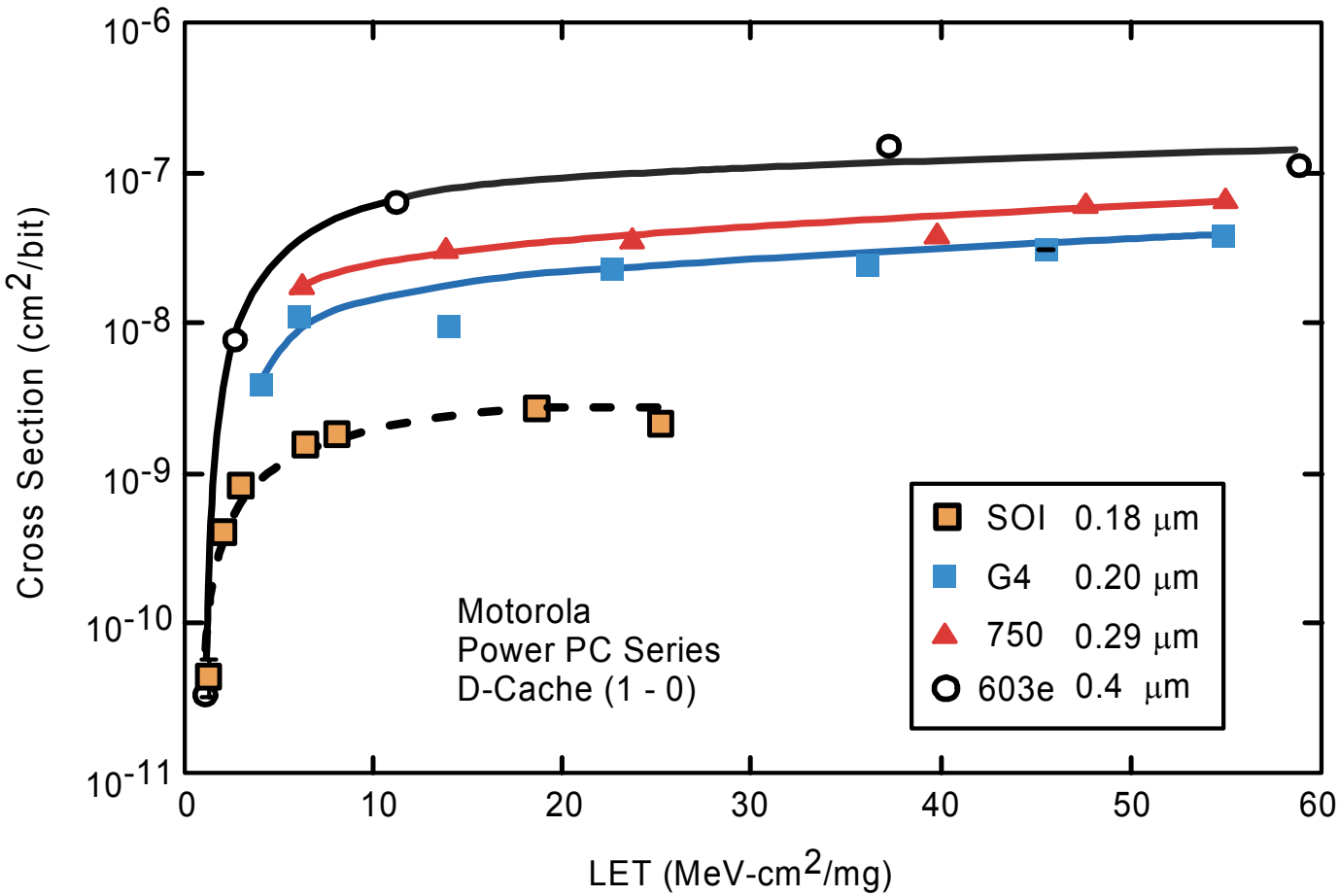


Microprocessors

More aggressive scaling compared to DRAMs

Silicon-on-insulator technology used commercially

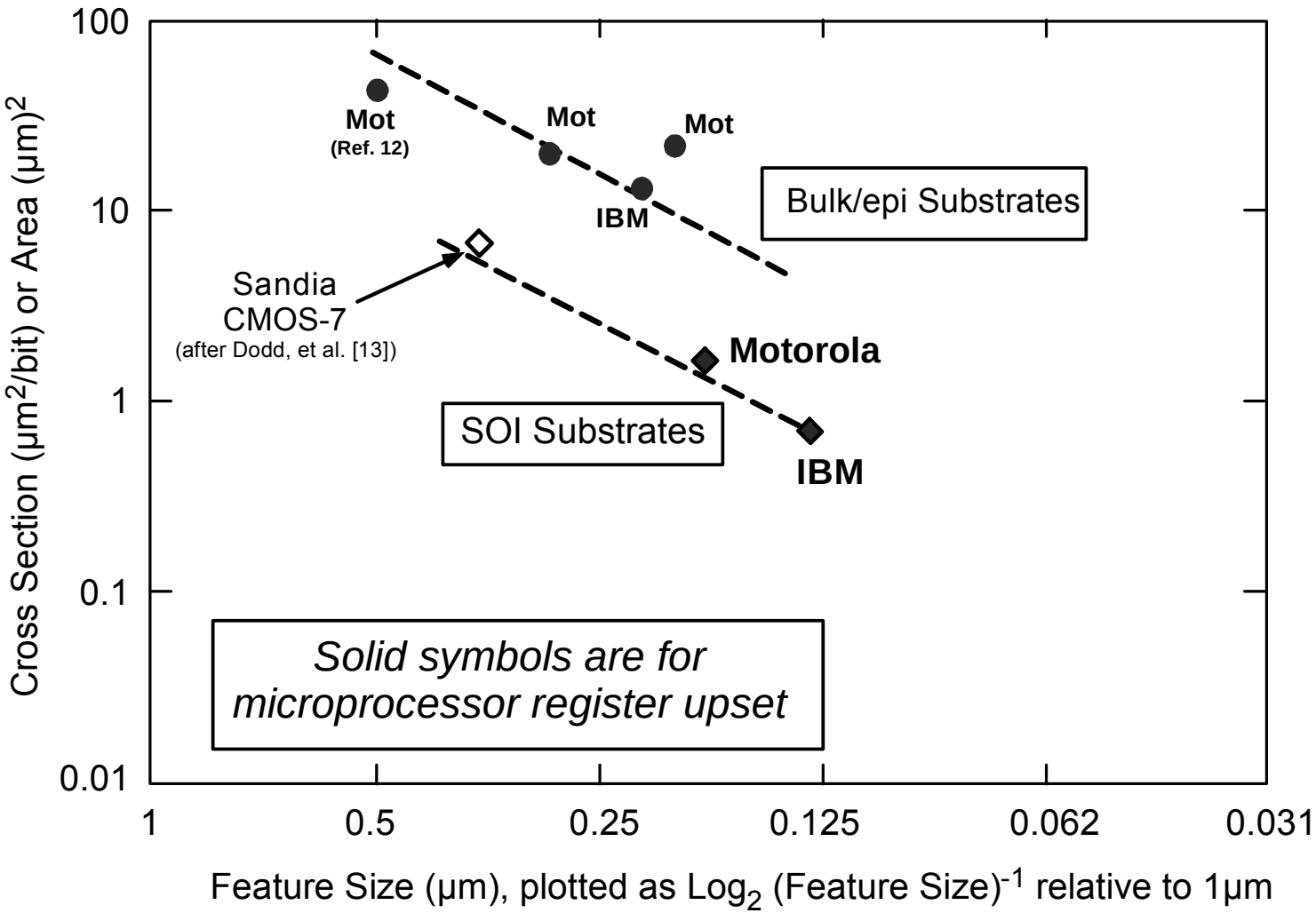
Threshold LET nearly the same!



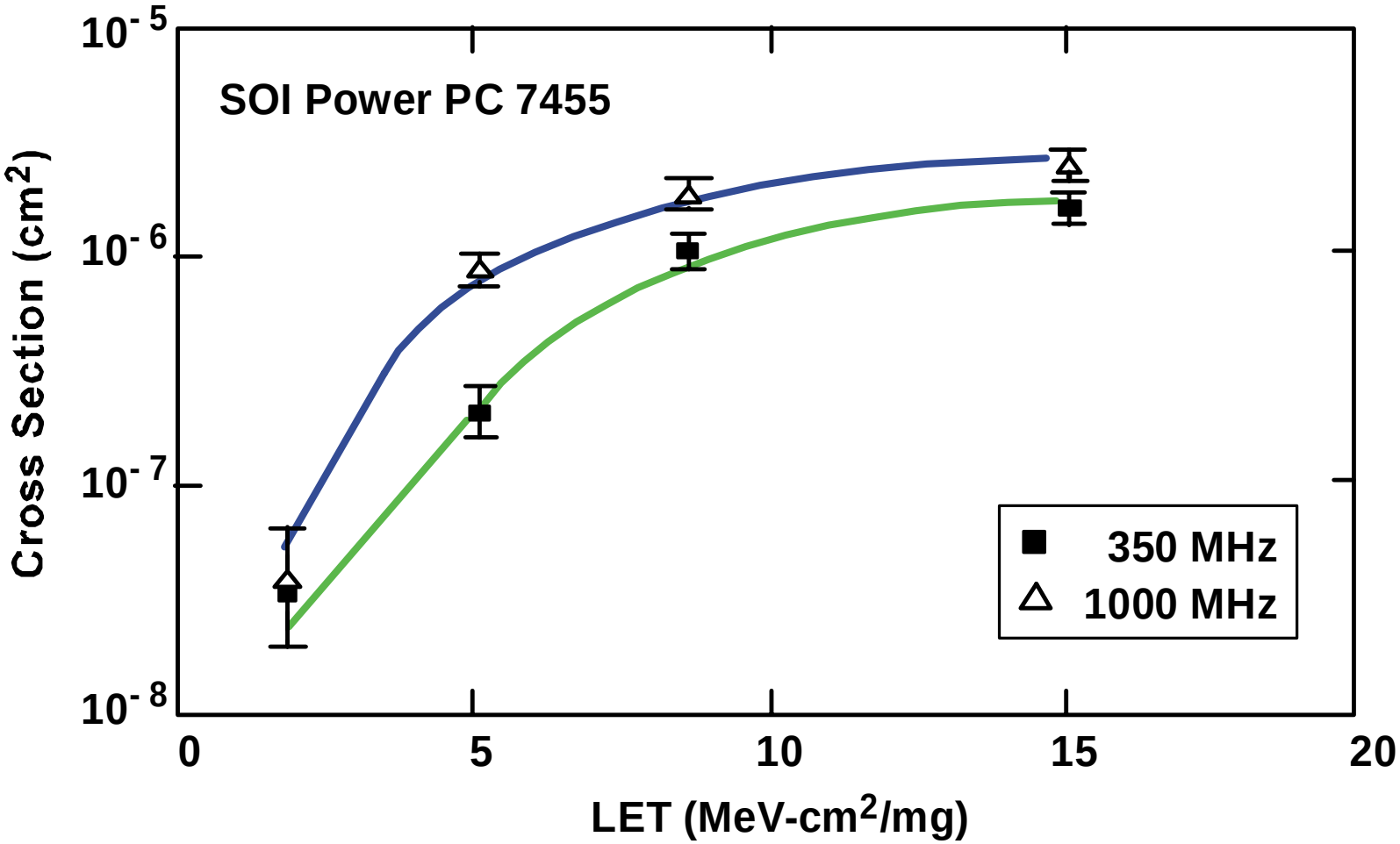
Space Error Rates for PC750 at Chip Level

- **Deep Space (Galactic Cosmic Rays)**
  - **Errors in registers and cache approximately every other day**
    - **Without cache, errors approximately every month**
    - **However, turning off cache adversely affects performance**
  - **Crashes may also occur (~ 1 to 2 per year)**
- **Solar Flare**
  - **Error rates approximately 400 times higher**
  - **Several hundred errors during "design-case" flare *(24 hours*)**
- **Earth Orbiting Applications**
  - **Daily average rate higher, dominated by trapped protons**
  - **Solar flare increases error rate by factor of 40**

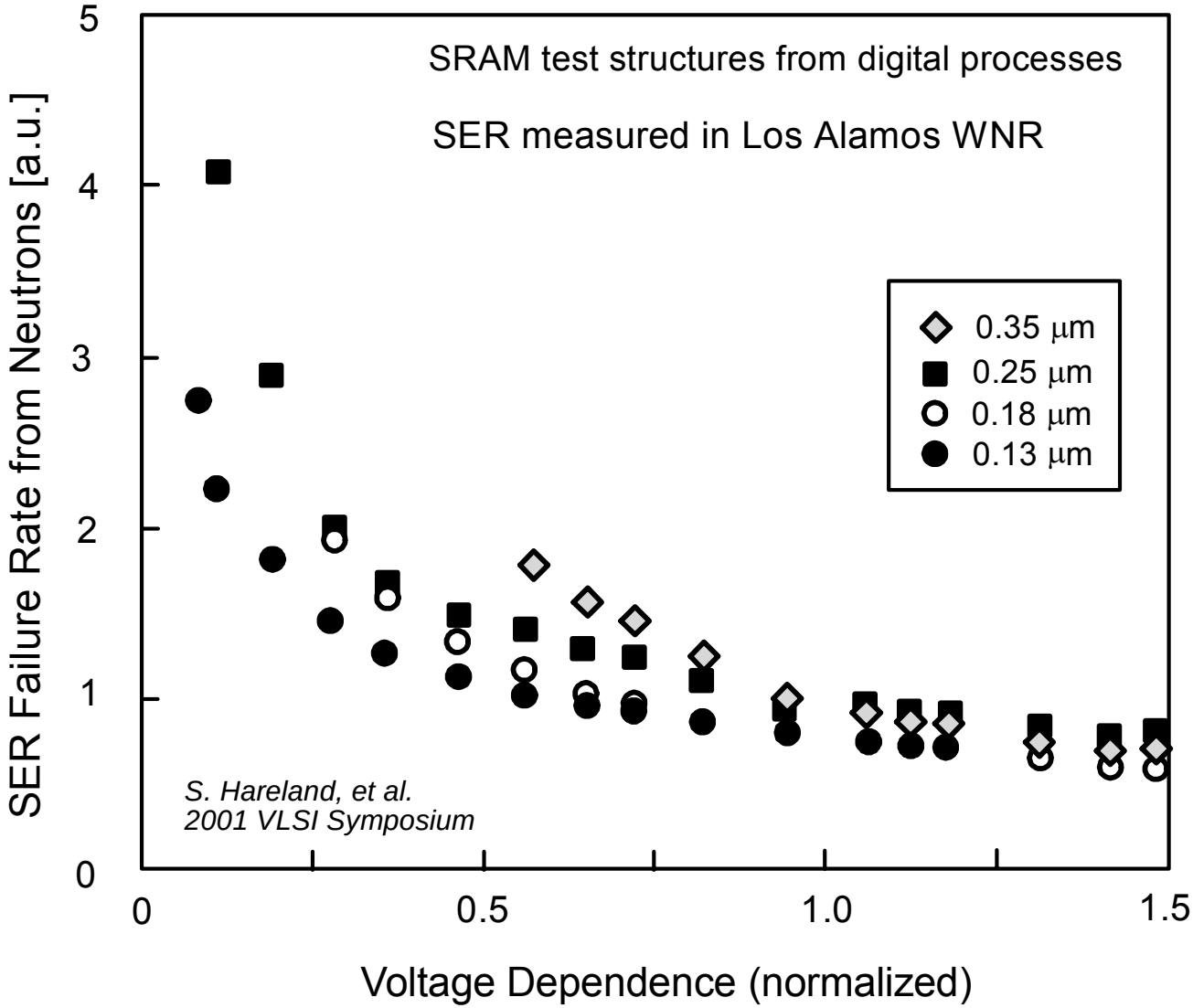
Microprocessor Scaling and Saturation Cross Section



Frequency Effects



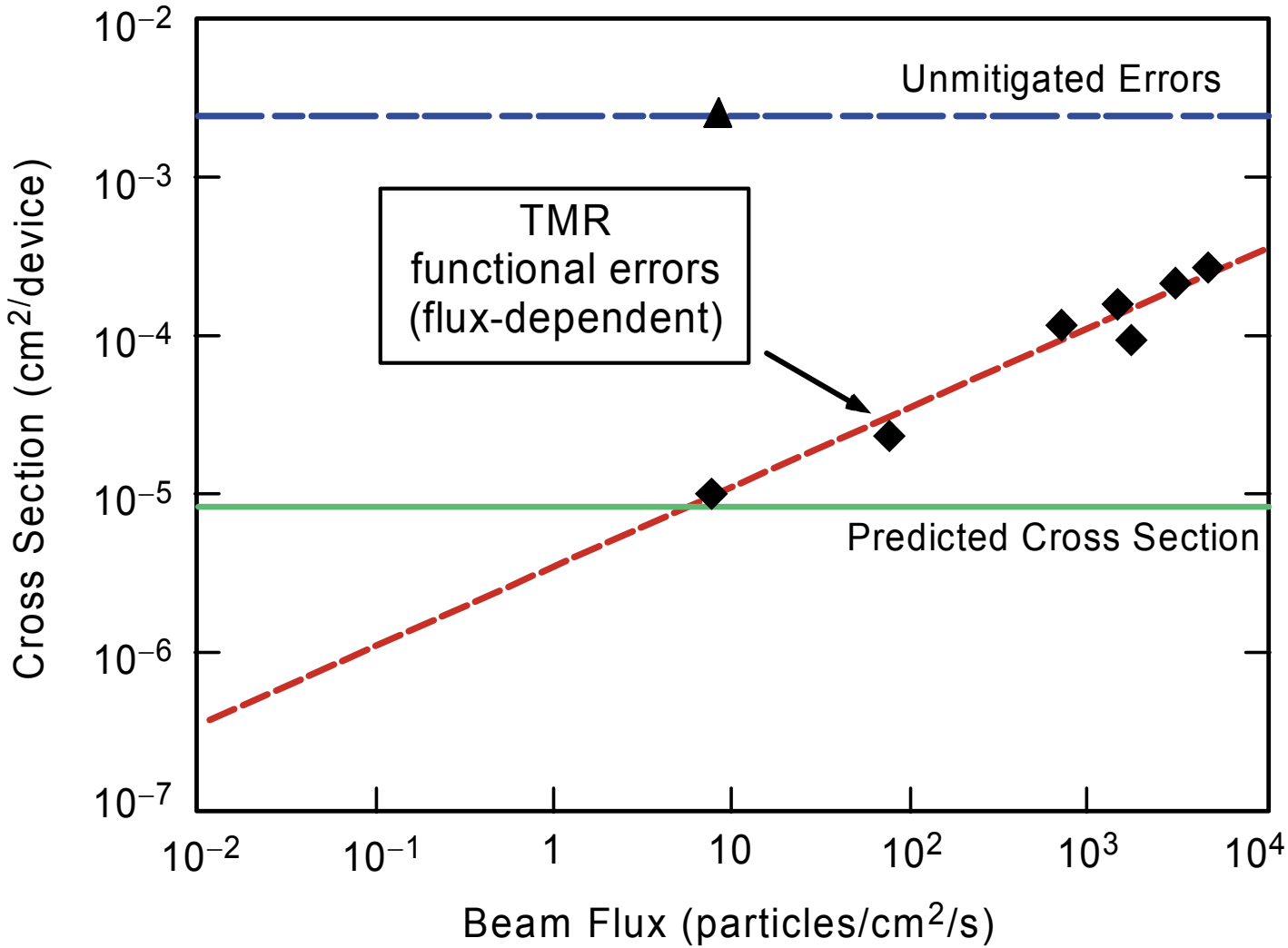
Neutron Test Results for SRAM Test Structures



SRAM-Programmable Gate Arrays

- Internal SRAM Determines Configuration
- Extremely Complex Devices
  - > 2M gates
  - I/O functions, logic levels and current can be programmed
  - Fabricated with deep submicron processes
- Intriguing Alternative to Anti-fuse Gate Arrays
  - Allows reconfiguration after launch
    - Potential to work around spacecraft problems
    - Particularly important for long-duration missions
  - Not susceptible to reliability issue that recently surfaced for anti-fuse technology

Test Results for SRAM-Programmable Devices with Internal Triple-Mode Redundancy



Other Radiation Issues

- Total Dose Effects in Linear Integrated Circuits
  - Enhanced damage at low dose rate
  - Effect of broad range of operating conditions
- Transients from Linear Integrated Circuits
- Gate Rupture and Burnout Effects
  - Usually handled by derating components
  - Can be a critical issue
- Interpreting Existing Data
  - Quality and applicability
  - When is the data too old?

Scaling Effects - Conclusions

- **Older Scaling Predictions Are Inconsistent with Test Results**
  - SEU rates are somewhat improved, at least to the 0.13 μm node
  - Collected charge decreases as well as critical charge
  - Atmospheric radiation problems are considered in commercial designs
- **Results Are Encouraging for Space Use as well as for Terrestrial Applications**
  - SOI technology will likely lead to even lower upset rate
  - However, lower switching voltage and higher speed may eventually reverse this trend
- **Complex Device Architecture also a Factor in Advanced Devices**
  - Upset detection may not be straightforward
  - Limits effectiveness of EDAC
  - Very large number of functions on single chip
  - Overall chip functionality may have larger error rates from scaling