Assessment of Space Solar Power Technologies for Next Decadal Planetary Science Missions

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Study Objectives
Solar Cell/Array Technology Assessment

- Review the space solar power system needs of future planetary science missions
- Assess the capabilities and limitations of state of practice space solar cell/array systems to meet the needs of future planetary science missions.
- Assess the status of advanced solar cell/array technologies currently under development at NASA, DOD, DOE and Industry and assess their potential capabilities and limitations to meet the needs of future planetary science missions.
- Assess the adequacy of on-going technology development programs at NASA, DoD, DOE and Industry to advance space solar power system technologies that can meet the needs of future planetary science missions.
- Identify technology gaps and technology programs to meet the needs of future planetary science missions.

Review Team
Solar Cell/Array Technology Assessment

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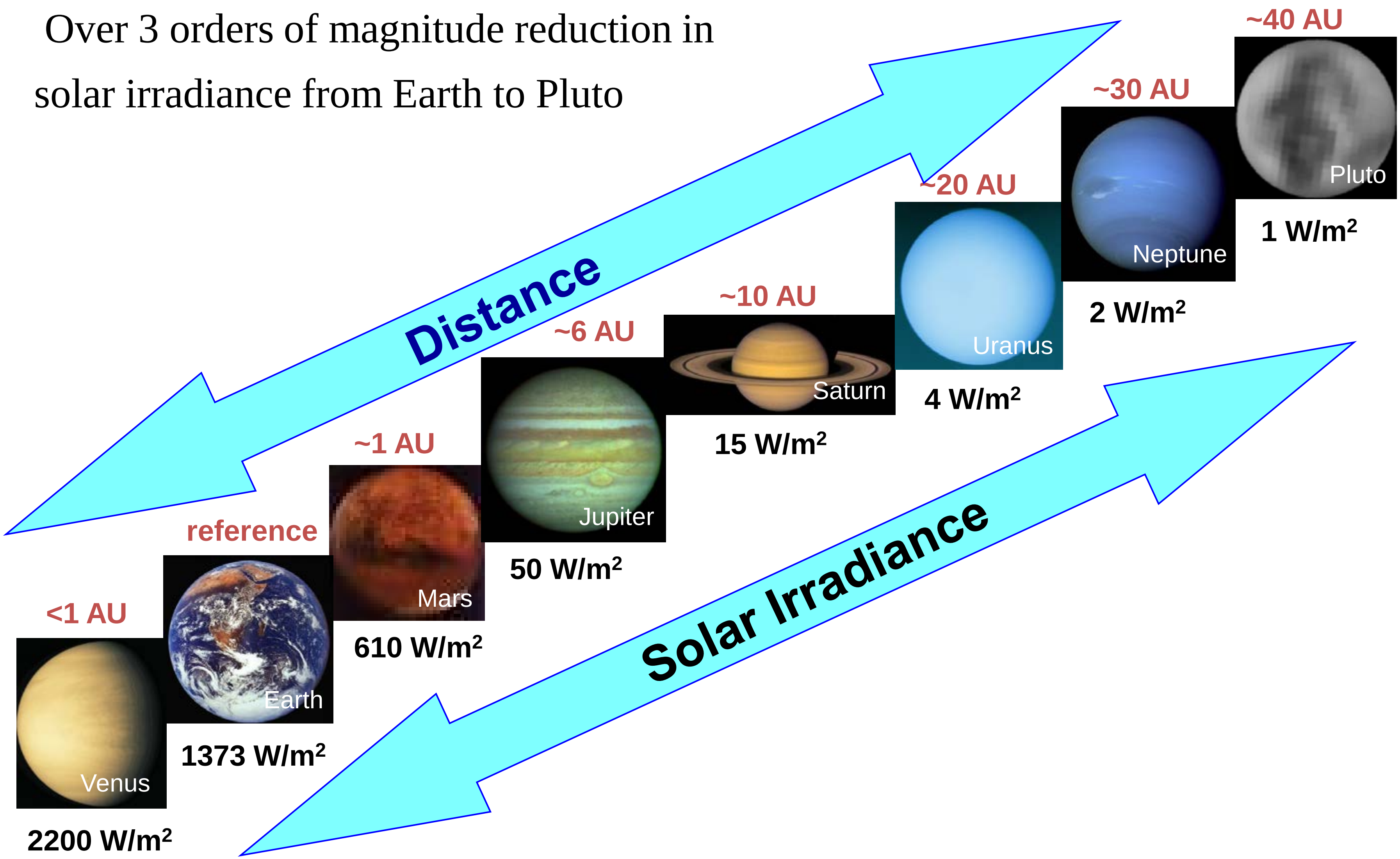
PV Technology Challenges for Outer Planet Missions

- Low Solar Intensities (< 40 W/m2)
- Low Temperatures (< -140 C)
- High Radiation (6e15 1MeV e-/cm2)
- Low Mass (~ 3X lower than SOP)
- Low Stowage Volume (~ 3X lower than SOP)
- Long Operational Life (> 15 years)
- High Reliability

Mission Destination & Power System Challenges

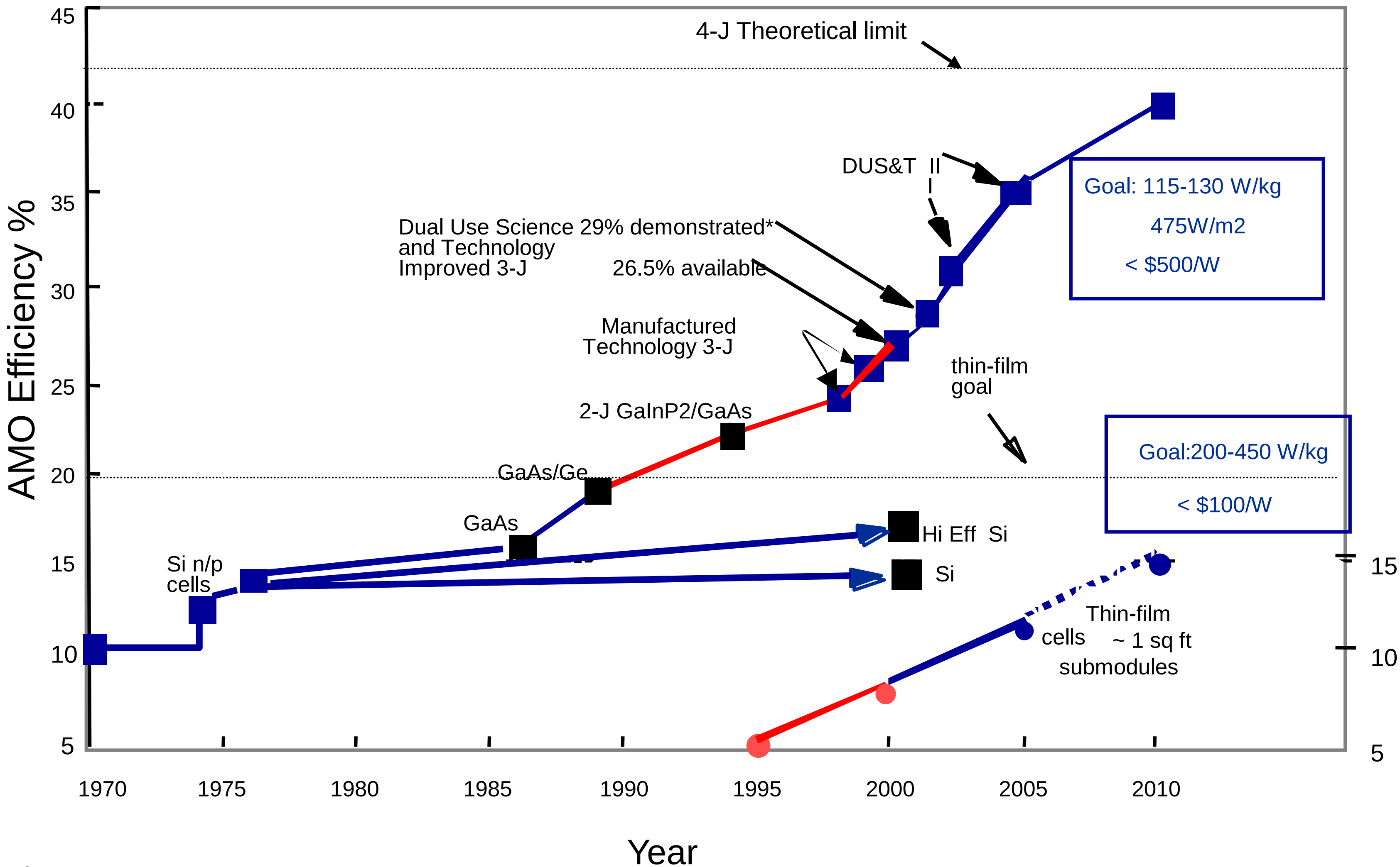
Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto



PV Capability Needs for Next Decadal Outer Planet Missions

Mission Type	Mission	Performance Capability Needs*	Benefits
Orbiters/Flyby	Jupiter Saturn Europa Titan Enceladus	• LILT Capability (> 38% at 10 AU & < -140 C) • Radiation Tolerance (6e15 1MeV e-/cm2) • High Voltage (>100V) • High Power (>50 kW@ 1AU) • Low Mass (3X lower than SOP/>250 W/kg) • Long Life (> 15 years) • High Reliability	Enhancing & Enabling

Solar Cell Efficiency Improvements



Overview of SOP Triple-Junction Solar Cells

Characteristic	Value/description		
Manufacturer	Azur Space	SolAero Technologies	Spectrolab
Manufacturer's designation	3G30C	ZTJ	XTJ-prime
Efficiency at 28 deg C, AM0[1]	29.8%	29.5%	30.7%
Voltage at maximum power, 28 deg C, AM0 (V)	2.41	2.41	2.39
Typical areal mass density (mg/cm^2)	86	84	84
Temperature coefficient at 28 deg C, un-irradiated (% Pmax/deg C)	-0.23%	-0.22%	-0.22%
Typical cell thickness[2] (μm)	150	140	140
Normalized maximum power degradation at 1E15 1 MeV e/cm^2 per AIAA-S111	Not reported	0.85	0.85
Normalized maximum power degradation at 1E15 1 MeV e/cm^2 per ECSS-ET-20-08C[3]	0.9	Not reported	0.87
Solar absorptance	0.91	0.92	0.88

Source data: www.azurspace.com, www.solaerotech.com, www.spectrolab.com, September 7, 2016

[1]Reported efficiencies assume a solar intensity of 135.3 mW/cm^2.

[2]Values represent Ge wafer thickness. Azur Space and Spectrolab have offered cell thickness down to 80 mm; 140-150 mm has been the standard in flight production.

[3]The ECSS test standard includes photon and temperature annealing subsequent to irradiation.

- Current cells provide ~30% efficiency at beginning-of-life, AM0
- Minor variations in voltage, current, radiation degradation and thermal properties between different manufacturers (Temperature annealing not practicable for cells under LILT conditions.)

Overview of State-of-Practice Solar Arrays

- Body mounted array – installed directly on body of spacecraft or platform
  - No sun-tracking mechanisms
- Deployable rigid array – rigid panels stowed for launch and unfolded on orbit
  - Panel structure is typically honeycomb sandwich with composite face-sheets
  - Sun-tracking in one or two axes
- Deployable flexible array – flexible blanket deployed by an extensible structure
  - Flexible fold-out array: blanket is folded when stowed
  - Flexible roll-out array: blanket is rolled on a mandrel when stowed
- Combination of body mounted and deployable, ex. SMAP, MER Rovers
- Specialized versions of all three types include
  - Electrostatically clean arrays – prevent accumulation of electric charge on array surfaces
  - High temperature arrays – survive high irradiance for missions close to the sun

Summary of Current Array State-of-Practice

Array technology	Maximum power at 1 AU (current state-of-practice), approximate*	Specific power at 1 AU, BOL (W/kg)**	Areal power density (W/m2)**	TRL
Body-mounted array	2 kW	N/A	314	9
Deployable rigid array	25 kW	80	330	9
Flexible fold-out array	120 kW	150	338	9
Flexible roll-out array	25 kW	150	338	7

*Based on demonstrated capability

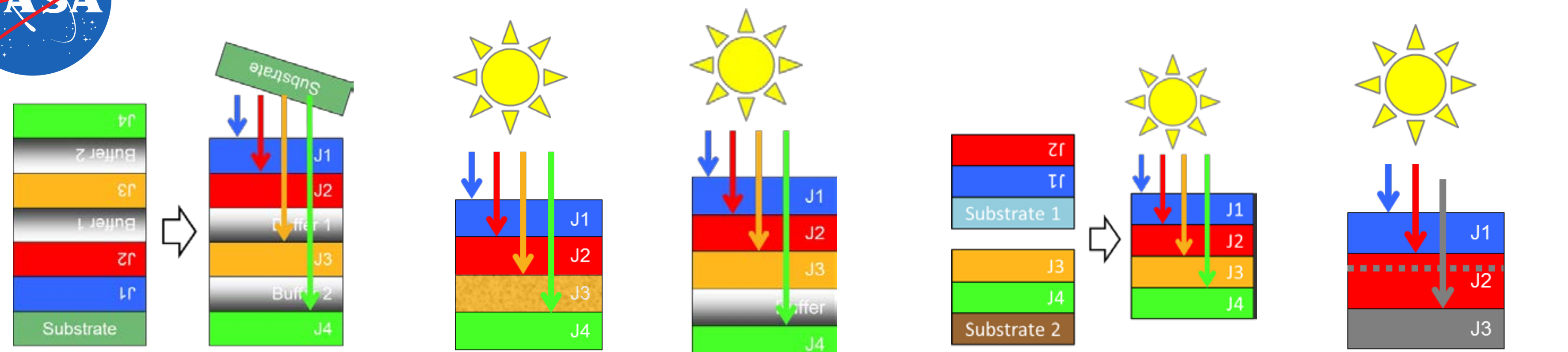
**Assuming all arrays have SoP triple junction cells

Future PSD Mission Needs vs SOP Capabilities

Type of PSD Missions	Future Mission Needs	SOP Capability
	Mission General Needs	
All Missions	High Efficiency Solar Cells (~38%)	30%
	Low Mass Arrays (> 250 W/kg)	150 W/kg
	Mission Specific Needs	
Outer Planet Missions	LILT Capability up to 10 AU	LILT capability up to 5.5 AU
Solar Electric Propulsion Missions	High Voltage, High Power Arrays (300V, 100 kW)	100 V & < 30 kW

- Future planetary science missions require PV power systems that are mass and volume efficient have long life and operate under extreme environments.
- SOP PV systems are heavy and have limited operational capabilities at extreme environments.

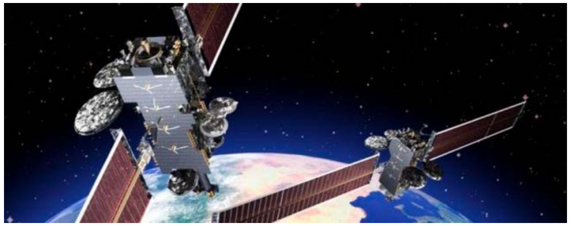
Advanced Cell Technology Table



Inverted metamorphic | Dilute nitride | Upright metamorphic | Semiconductor Wafer bonding | Near-IR absorbers

Cell technology	Potential Capability	Status	Issues
Inverted metamorphic	36-37%	34-35% demonstrated in lab cells	Achieving cost parity
Dilute nitride	36-37%	30-31% demonstrated in lab cells	Volume manufacturability
Upright metamorphic	36-37%	29-30% demonstrated in lab cells	Material quality in high bandgap subcells
Wafer bonding	36-37%	34-35% demonstrated in lab cells	Achieving cost parity
Near-IR absorbers	36-37%	26-27% demonstrated in lab cells	Performance improvement over SoP

Developing Solar Array Technology
Flexible arrays

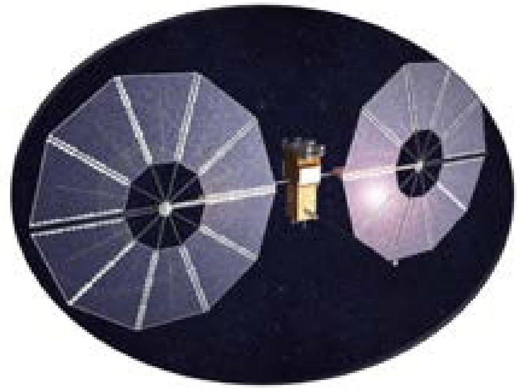

Source:lockheedmartin.com/us/ssc/commspace.html

A2100 spacecraft
Manufacturer: Lockheed Martin
Description: Flexible fold-out
Key features: Based on heritage ISS solar arrays
Status: In development for flight programs

Composite Beam Roll-Up Solar Array (COBRA)


Source:solaerotech.com/products

Manufacturer: SolAero Technologies
Description: Flexible roll-out
Key features: Compact stowage for cubesats and smallsats


Source:nasa.gov/offices/oct/home/feature_sas.html#.WAmcEzKZOqA

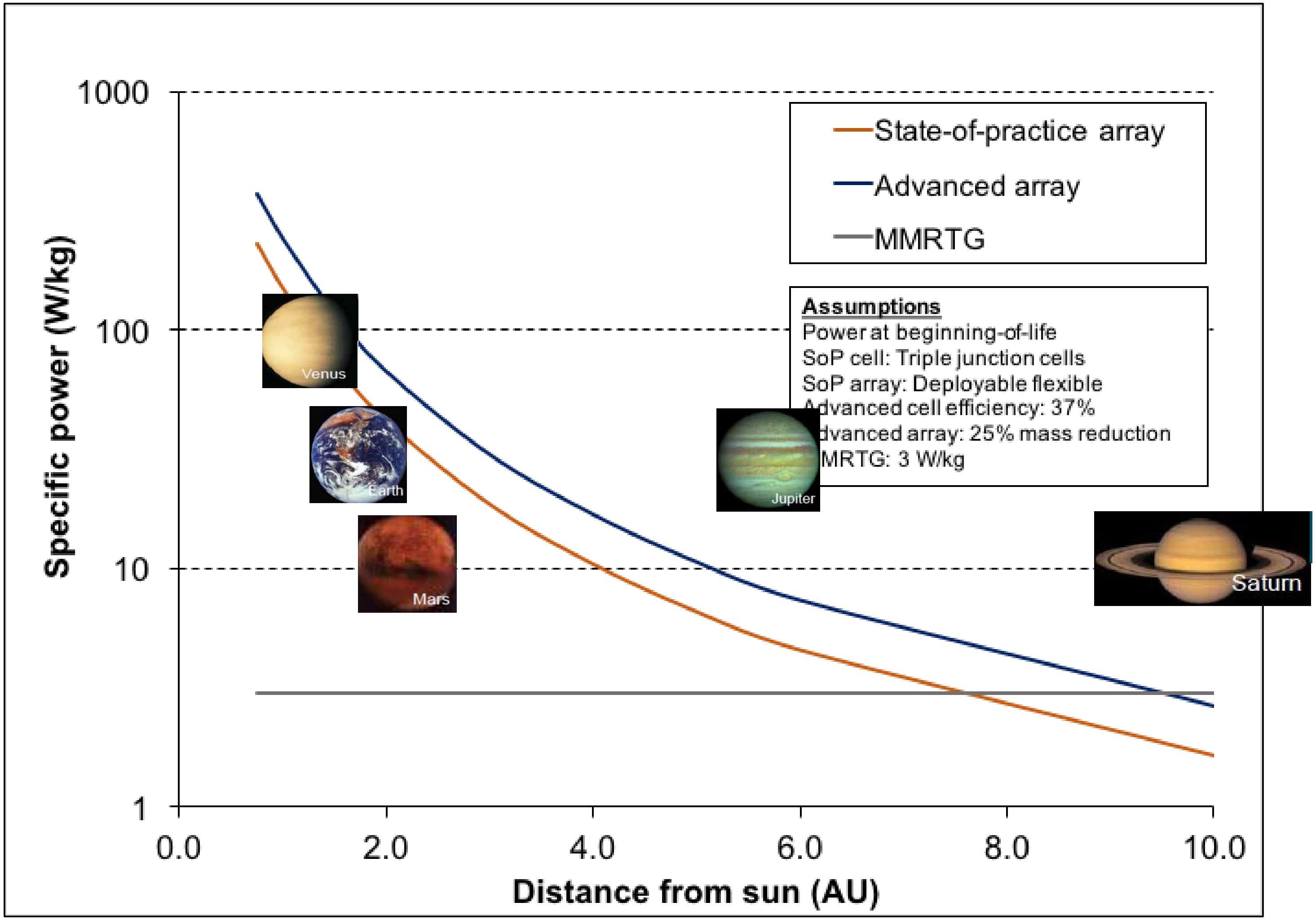
Megaflex
Manufacturer: Orbital ATK
Type: Flexible fold-out, circular
Key features: Extends diameter beyond Ultraflex design. Intended to reach >100 kW capability.
Status: Demonstrated deployment >10 m diameter in ground test.

Source:nasa.gov/offices/oct/home/feature_sas.html#.WAmcEzKZOqA

Mega-ROSA
Manufacturer: Deployable Space Systems (DSS)
Type: Flexible roll-out
Key features: Deployment of multiple ROSAs from a central spine. Intended to reach >100 kW capability.
Status: Deployment mechanism concept demonstrated in ground test.

- Flexible array development is continuing, focused on lower mass and higher power
- Goals are 500 W/kg specific power and 80 kW/m3 stowage at BOL, 1 AU

Specific Power vs Distance from Sun



- SoP arrays provide higher specific power than MMRTGs at Jupiter
- Advanced arrays are could reach the specific power of MMRTGs at Saturn

Key Findings

- Solar power systems have been used to power a wide range of planetary science missions
  - 0.3 AU to 5.5 AU
  - Mars surface, Jupiter, Mercury, Asteroid
- Future planetary science missions have unique solar power system needs
  - High Power Solar Arrays (>100 kW) for solar electric propulsion missions (outer planet & asteroid)
  - High Efficiency Solar Cells (> 37%) for small spacecraft planetary missions
  - High Specific Power (> 4 W/kg at 10 AU) & LILT capable (4-10 AU) Solar Arrays for outer planetary missions
- SOP PV systems have limited operational capabilities at extreme environments.
  - Low solar intensities and low temperature environments of outer planets
  - High temperature, high/low solar intensity and corrosive environments of Venus
  - Dusty Mars environments
- Advanced solar cells and arrays are under development at several companies and universities with support from DOD and private funding
  - Cell Technologies (32-36%): 4-5 J cells, Inverted metamorphic , Dilute nitride, Upright metamorphic, Wafer bonding
  - Array Technologies (150-300 W/kg): Flexible fold-out, Flexible roll-out and Concentrator
- No NASA significant investments in the area of advanced space solar cells and arrays
  - Some limited investments are in the area high power arrays and LILT solar cells.

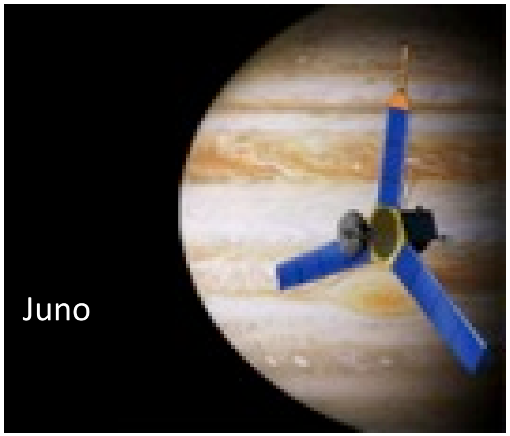
General Recomendations

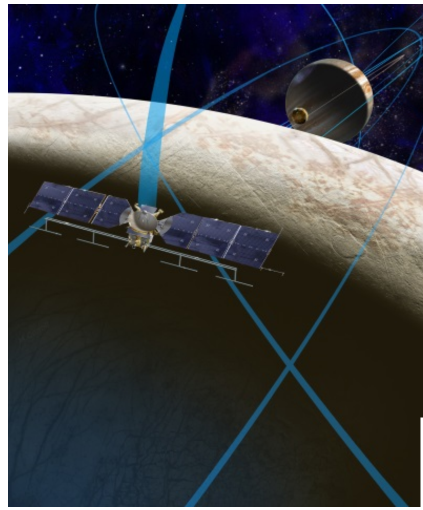
- Targeted investments should be made in the specific solar cell and array technologies needed to withstand the unique planetary environments.
- Partnerships with HEOMD and STMD and/or other government agencies such as DoE and DoD (AFRL, Aerospace Corporation, NRL, and ARL) should be established and maintained to leverage/tailor the development of advanced cell and array technologies to meet future planetary science mission needs.
- Existing infrastructure for PV technology development, testing and qualification at various NASA Centers should be upgraded to support future planetary science missions, as needed.

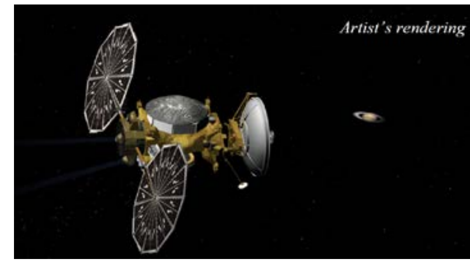
Specific Recommendations

- Develop high power (>100 kW) and low mass (200–250 W/kg) solar arrays for future solar electric propulsion missions operable up to 10 AU (for outer planet missions).
- Develop higher efficiency LILT solar cells and low mass, radiation resistant arrays for orbital missions to Jupiter, Saturn, and Ocean Worlds (Europa, Titan, etc.).
- Develop LIHT cells and arrays tolerant of the sulfurous environment required for Venus aerial and surface missions.
- Develop solar cells tuned to the Mars solar spectrum and solar arrays with dust mitigation capability for future Mars surface missions.
- Leverage the DoD investment in higher efficiency solar cells (~38%) and array technologies to enhance next decadal planetary space science missions.

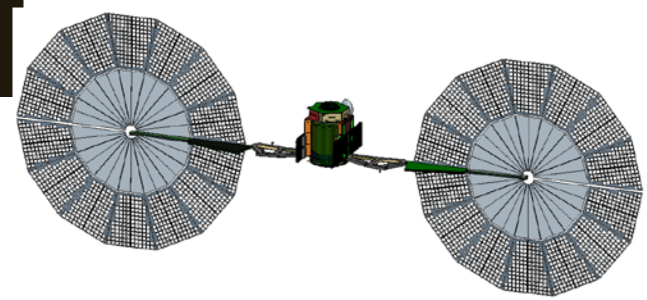
Solar Powered PSD Missions







Titan Saturn System Mission Concept (2011)



Ongoing

Near Future

SEP stage for Uranus/Neptune missions

Mission Concepts

Acknowledgements

This work pres[illegible]e was carried [illegible] at the Jet Propulsion Laboratory, California Institute of Technology under a contract with National Aeronautics and Space Administration.

Backup

Solar Arrays on NASA Planetary Science Missions

Launches since FY2000

Mission class	Mission	Destination	Launch date	Solar cell technology	Solar array technology	Power capability at 1 AU (W)
Outer planets	Juno	Jupiter	5-Aug-11	Triple junction	Deployable rigid	14000
Inner planets	Messenger	Mercury	3-Aug-04	Triple junction	Deployable rigid	450
	LCROSS	Moon	18-Jun-09	Triple junction	Body-mounted	600
	Lunar Reconnaissance Orbiter	Moon	18-Jun-09	Triple junction	Deployable rigid	1850
	Grail	Moon	10-Sep-11	Triple junction	Deployable rigid	763
	LADEE	Moon	6-Sep-13	Triple junction	Body-mounted	295
Mars	Mars Odyssey	Mars	7-Apr-01	GaAs/Ge	Deployable rigid	2092
	Mars Exploration Rover (2)	Mars surface	10-Jun-03 7-Jul-03	Triple junction	Body-mounted	390
	Mars Reconnaisance Orbiter	Mars	12-Aug-05	Triple junction	Deployable rigid	6000
	Phoenix	Mars surface	4-Aug-07	Triple junction	Ultraflex	1255
	MAVEN	Mars	18-Nov-13	Triple junction	Deployable rigid	3165
Asteroids/comets	Deep impact/EPOXI	Tempel-1 Hartley-2	12-Jan-05		Body-mounted	620
	Dawn (with solar electric propulsion)	Vesta Ceres	27-Sep-07	Triple junction	Deployable rigid	10300
	OSIRIX-REx	Bennu	8-Sep-16	Triple junction	Deployable rigid	3000

- Vast majority of missions since FY2000 utilized triple junction solar cells on deployable, rigid arrays

Advanced Solar Cell Technology

Overview

Bandgap optimization for high AM0 efficiency

- Inverted metamorphic
- Dilute nitride
- Upright metamorphic
- Wafer bonding
- Near-IR absorbers

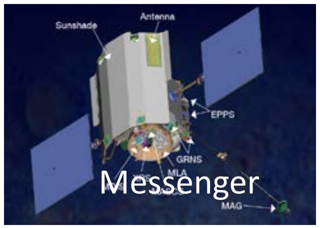
Improved operation in special environments

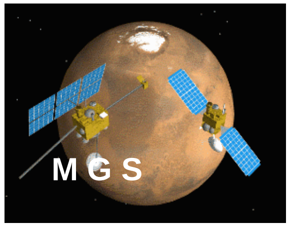
- Low irradiance low temperature
- High temperature
- Surface spectra
- Corrosive atmosphere
- Lightweight flexible
- High radiation

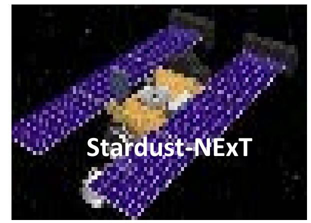
PV Technology Needs of Next Decadal Solar Electric Propulsion Missions

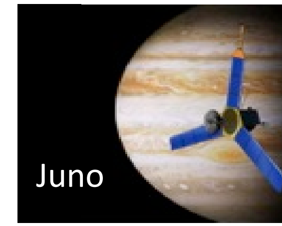
Solar Cell & Array Characteristics	Past	Present	Next Decadal Needs
High voltage			**300V**
Power (kW)	2.5	10-20	50-200
Specific Power (W/kg)	50-70	80-110	>150
Stowage Volume (kW/m^3)	~3-10	>30	>40
LILT Performance	Uncertain behavior under LILT conditions	Uncertain behavior under LILT conditions	LILT Capability needed (> 2.5 AU)
Cost $M/ kW	1-2	1.0	0.3-0.5
Other factors:	Complex deployment system	Simpler and reliable deployment system	Simplest and most reliable deployment system

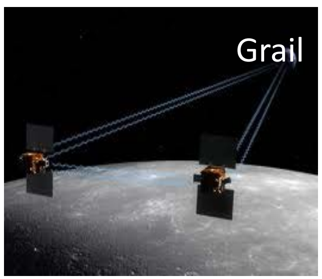
Solar Powered PSD Missions

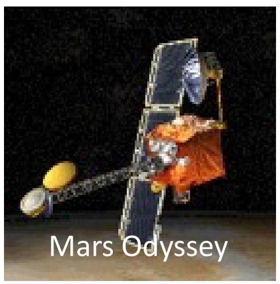


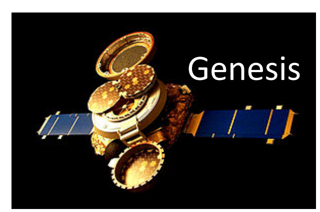






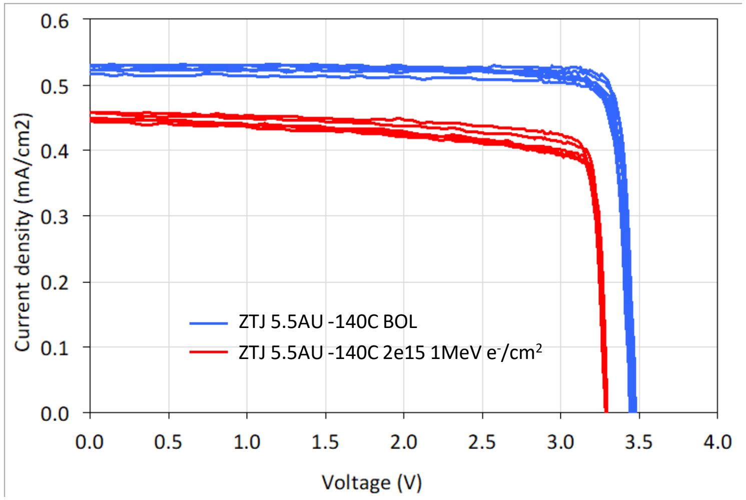


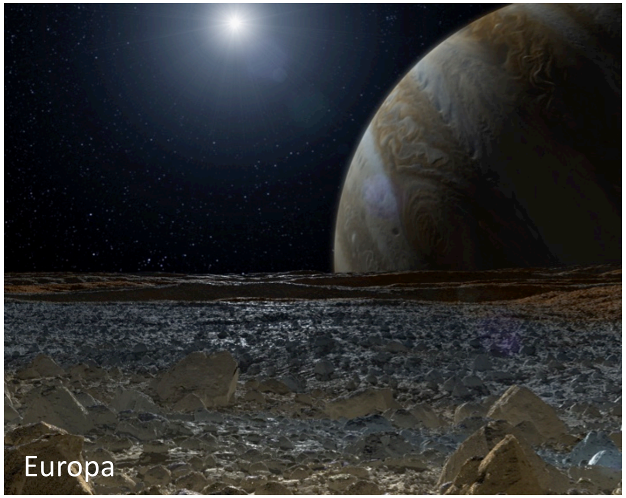




Improved Operation in Special Environments

Low Irradiance Low Temperature (LILT) Conditions





LILT = low irradiance low temperature (e.g. Jupiter 5.5AU -140°C, Saturn 9.5AU -165°C)

LIRT = low irradiance room temperature, current practice for screening and binning SoP cells intended for LILT applications

- Device modifications needed to eliminate mechanisms that limit LILT performance, using 1 AU-optimized SoP or advanced cells as starting point
- Also, screening yield improvements for qualitative cell-build cost reductions
- TRL = 4 for SoP-based, 2 for advanced cells
- Remaining challenge = statistical significance, advanced cells

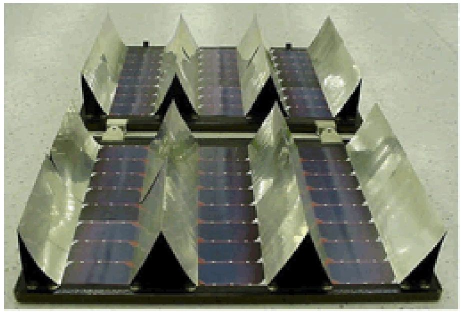
Summary of Findings

- Several types of advanced solar cells are under development at several companies and universities with support from DOD and private funding
  - 4-5 J cells, Inverted metamorphic , Dilute nitride, Upright metamorphic, Wafer bonding
- Significant improvement in solar cell performance is envisioned
  - Near-term: > 33% efficient
  - Mid– to Far-Term : > 37% efficient
- Several types of advanced solar arrays are under development with support from DOD and private funding
  - Flexible fold-out, Flexible roll-out, Concentrator
- Major advances in Solar Array Performance are envisioned
  - Near-term: 150-200 W/kg
  - Mid- to Far-term: 200-250 W/kg
- The biggest technology investments are mostly from DOD
  - Currently there is limited NASA funding in high power arrays and LILT solar cells
- NASA needs to work with DOD to advance and tailor advanced PV technologies for future planetary science missions

Developing Solar Array Technology

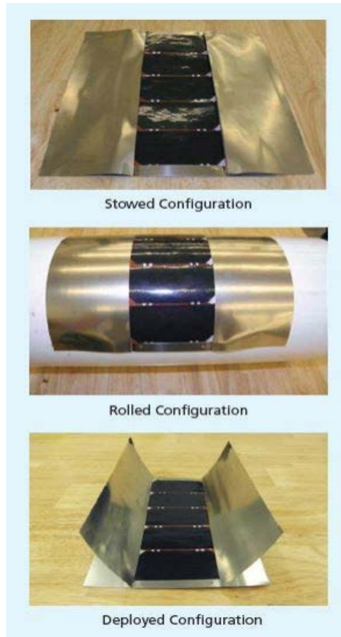
Concentrator arrays

Reflective Concentrators



Source:spaceflightsystems.grc.nasa.gov/PlanetaryScience/documents

Cell Saver Solar Array
Manufacturer: Orbital ATK
Description: reflective ~2X concentrator
Key features: Focused on cost reduction
Status: Flight experiment in orbit



Source:techbriefs.com/component/content/article/ntb/tech-briefs/manufacturing-and-prototyping/15070

Flexible Array Concentrator Technology (FACT)
Manufacturer: DSS
Description: Incorporates reflective concentrator into ROSA

Refractive Concentrators

Source:spinoff.nasa.gov/spinoff2002/er_7.html

Stretched Lens Array (SLA)
Manufacturer: Entech/Orbital ATK
Description: Fresnel lens ~7-10X concentrator
Key features: Based on Deep Space 1 array, but uses flexible lens instead of glass

Source:dss-space.com/products

SOLAROSA
Manufacturer: DSS
Description: Stretched lens on flexible blanket
Key features: Incorporates Fresnel lens into ROSA

- Research and development has been performed on multiple technologies that utilize concentrated sunlight.