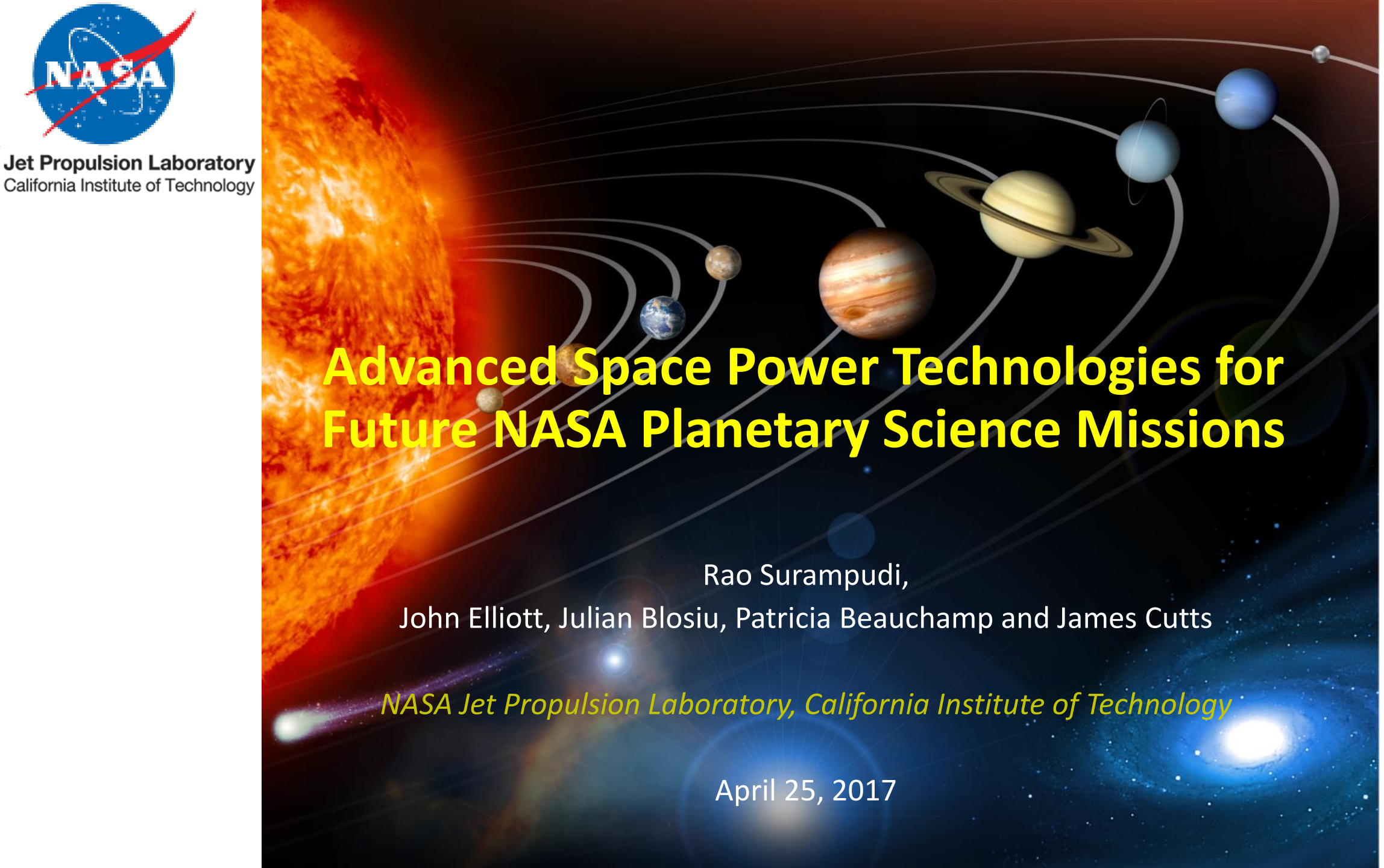

Jet Propulsion Laboratory
California Institute of Technology

Advanced Space Power Technologies for Future NASA Planetary Science Missions

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John Elliott, Julian Blosiu, Patricia Beauchamp and James Cutts

NASA Jet Propulsion Laboratory, California Institute of Technology

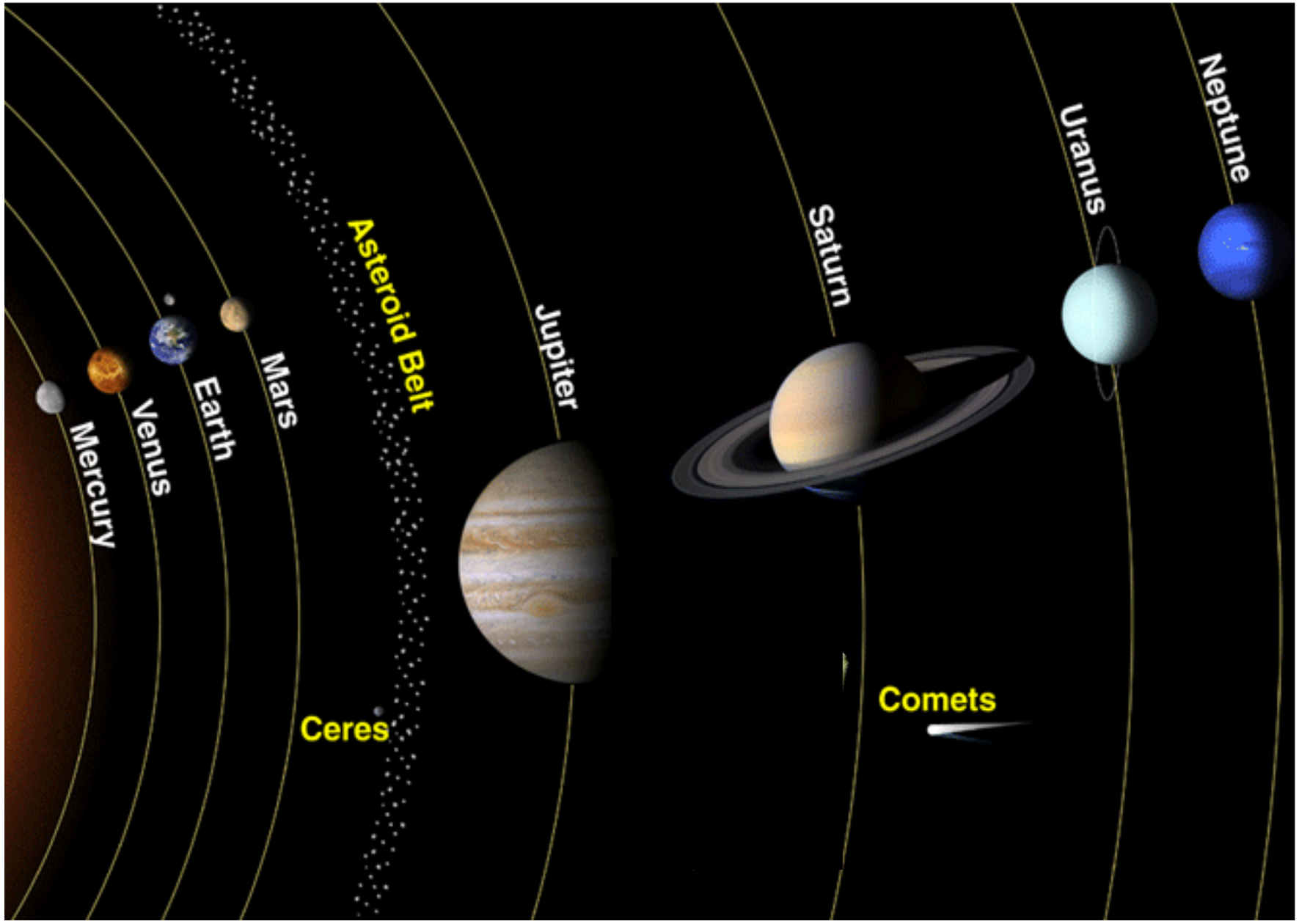
April 25, 2017

Outline

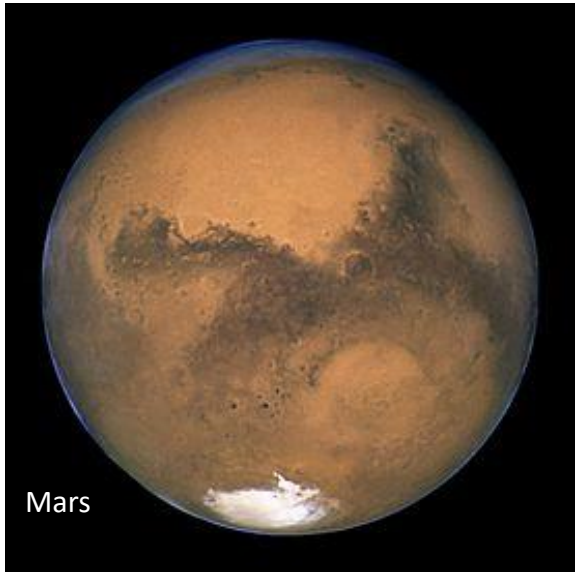
- Background
- Outer Planetary Missions & Needs
- Inner Planetary Missions & Needs
- Mars Missions & Needs
- Small Body Missions & Needs
- Summary & Conclusions

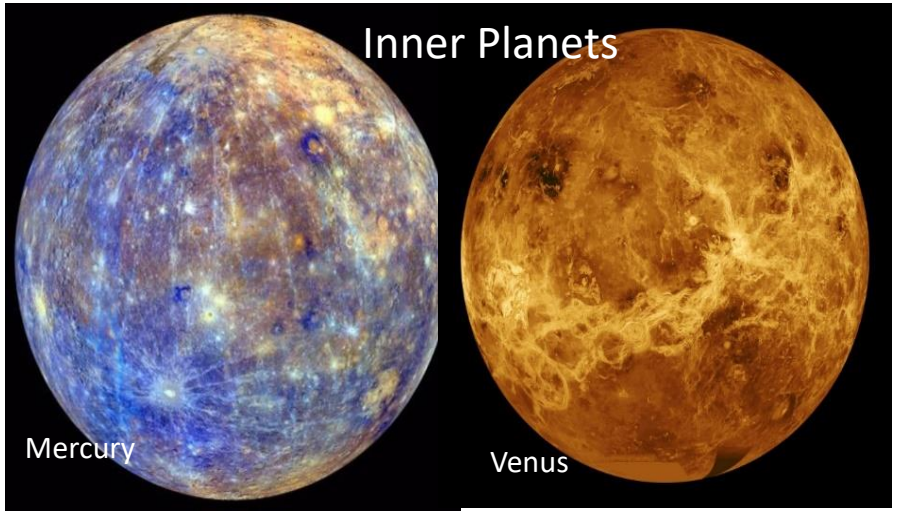
Background

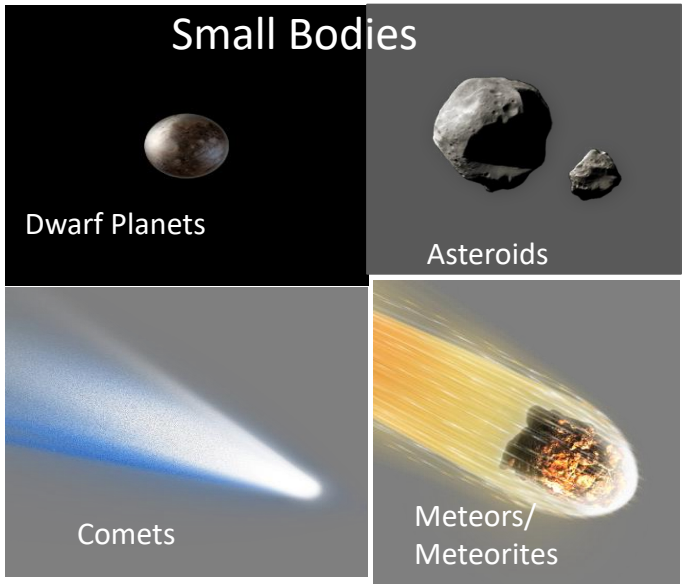
Planetary Science Mission Destinations



Planetary Science Mission Destinations







Classification of Planetary Science Missions Based on Mission Type

Flyby (RPS/PV)

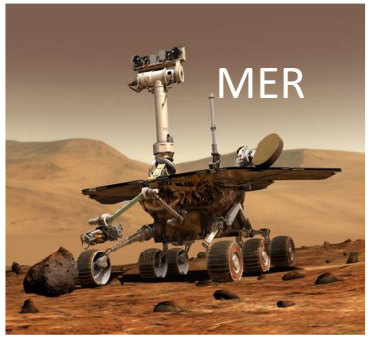
Orbiter (RPS/PV & chemical)

Electric Propulsion (PV/NEP& Chemical)

Cubesat (PV & Chemical)

Probes (Chemical)

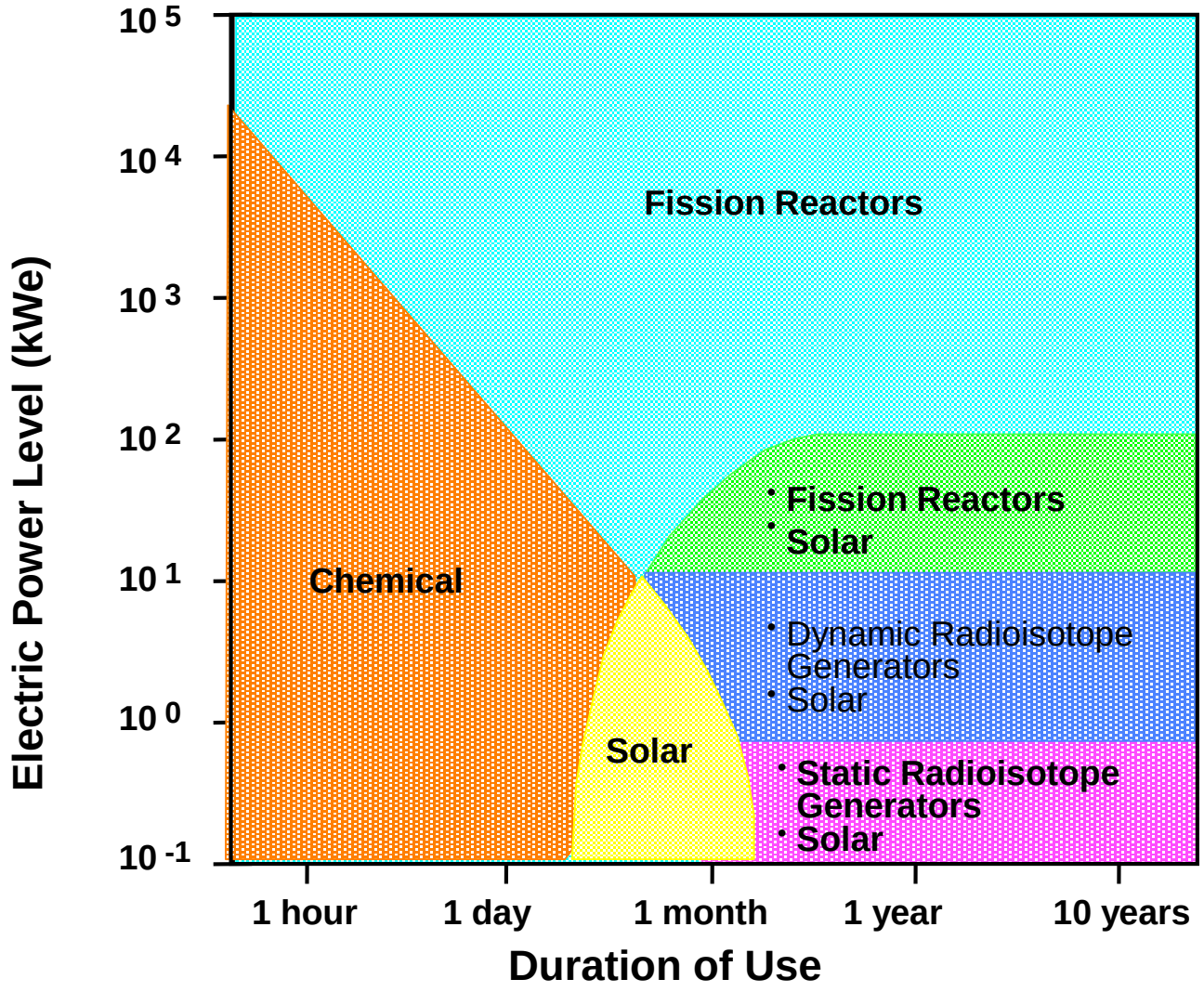
Lander (RPS/PV & Chemical)



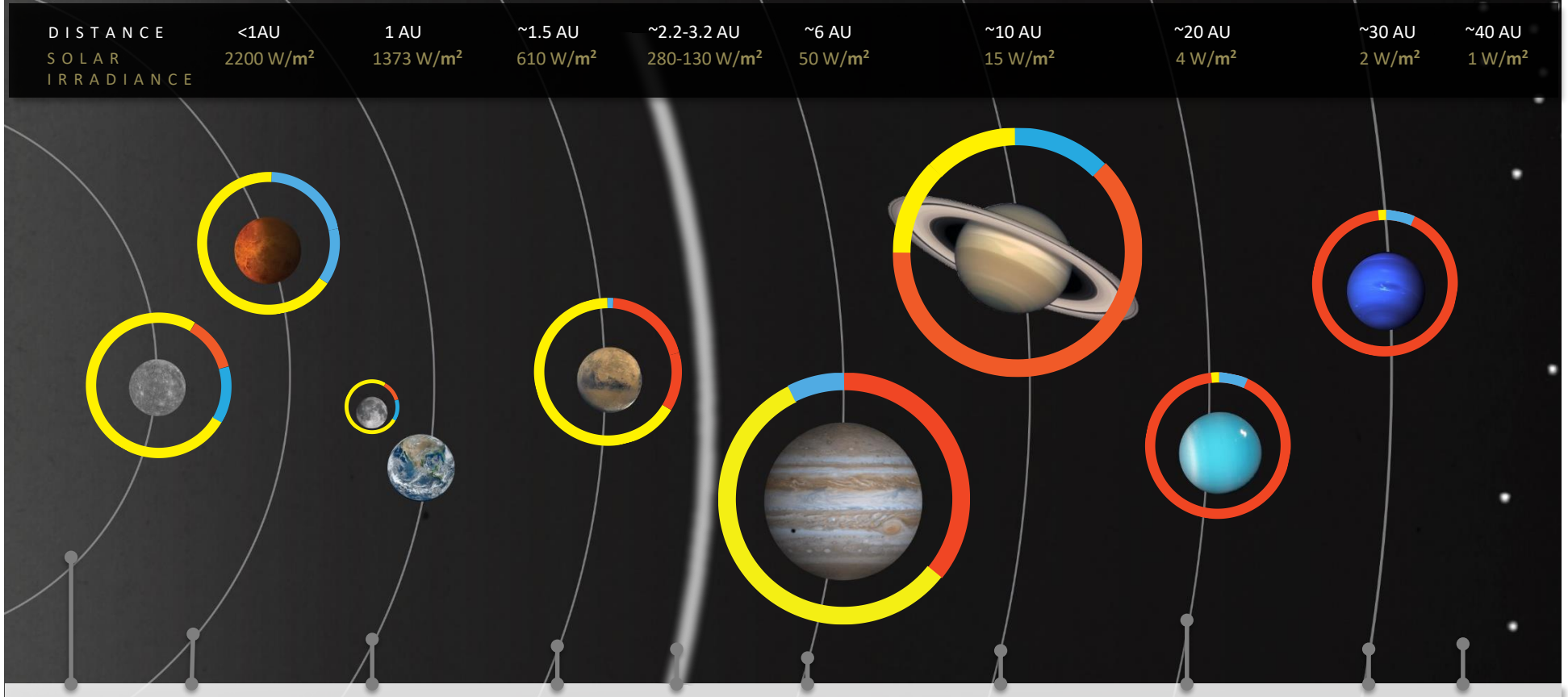
Rover (RPS/PV & Chemical)

Aerial (PV & Chemical)

Operational Envelope of Power Technologies



Spacecraft Power needs and service life dictates the choice of power technologies (solar cells, radioisotope power systems, nuclear reactor, batteries)



MERCURY

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

VENUS

SOLAR
- Orbiters
- Upper Atmosphere Probes*
- Surface Probes**

RPS
- Current RPS not operable in Venus surface environment

BATTERIES
- Atmospheric probes
- Surface Missions

MOON

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

MARS

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Long-lived Polar Lander
- Long-lived, high capability rovers

BATTERIES
- Short-lived surface missions

ASTEROIDS

SOLAR
- Sample Return
- Flybys/Tours
- Orbiters
- Landers

RPS
- May be necessary for Trojan asteroids

BATTERIES
- Short-lived surface missions

JUPITER

SOLAR
- Orbiters
- Flybys

RPS
- High capability
- orbiters
- Long-lived moon landers

BATTERIES
- Atmospheric Probes
- Short-lived landers

SATURN

SOLAR
- Flyby s/c
- Orbiters

RPS
- High-capability orbiter
- Ring observer
- Titan Montgolfier (MMRTG)
- Long-lived surface mission

BATTERIES
- Atmospheric probes
- Short-lived surface missions

URANUS

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys

BATTERIES
- Atmospheric probes

NEPTUNE

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Long-lived Triton Lander

BATTERIES
- Atmospheric probes

KUIPER BELT

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Landers

BATTERIES
- Short-Lived landers

*requires tech dev for solar cells in corrosive environment
**requires tech dev for high temperature

POWER TECHNOLOGY OPTIONS APPLICABLE TO SOLAR SYSTEM EXPLORATION MISSION CONCEPTS AS OF 2015(1)

(1) Notional mission applicability based on expert opinion developed in JPL A-Team study in August, 2015

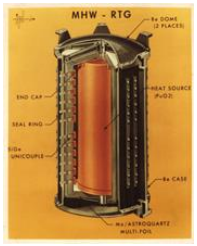
Solar
RPS
Battery

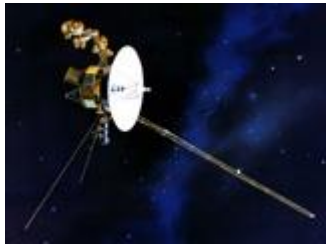
Approximate relative applicability of power technologies to target body missions

RTG Powered Planetary Science Missions

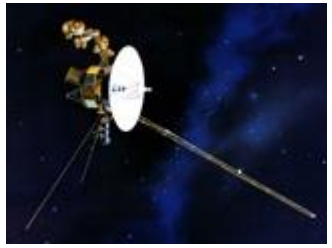
Pioneer 11&12

Viking 1&2

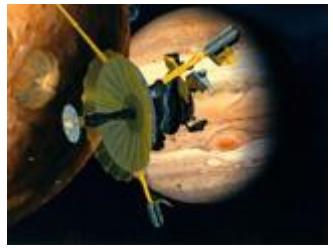




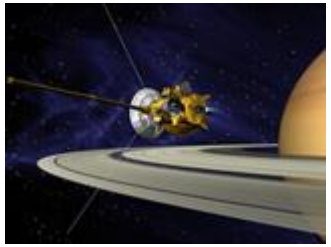
Voyager-1



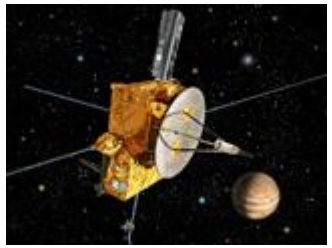
Voyager-2



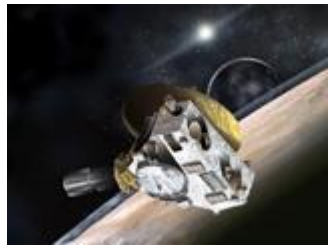
Galileo



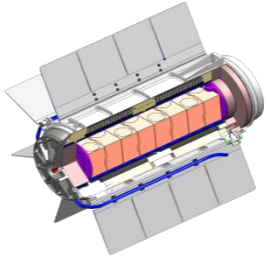
Cassini



Ulysses



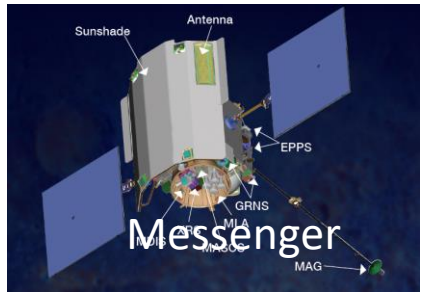
New horizons

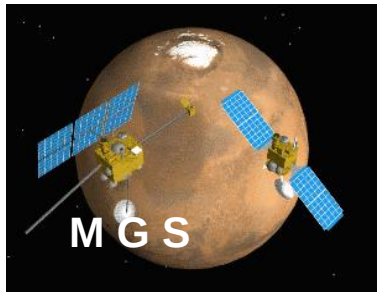


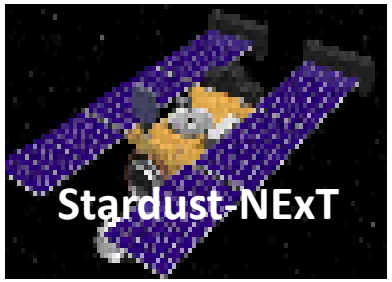
Curiosity

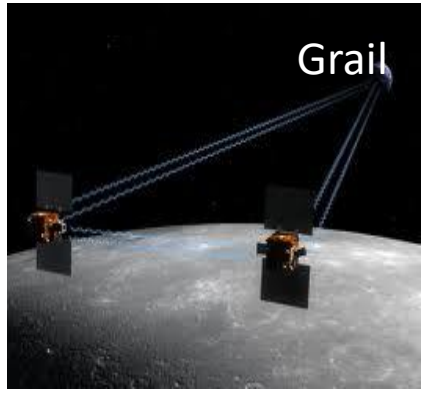
Mars 2020

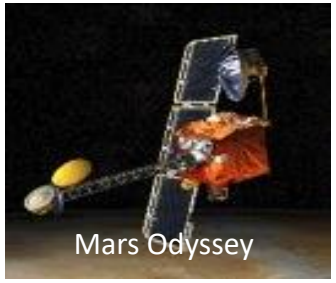
Solar Powered Planetary Science Missions

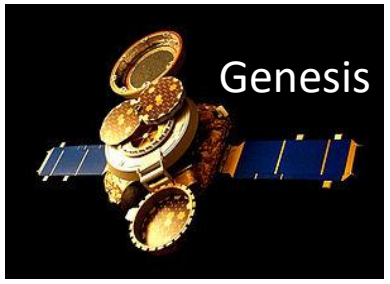


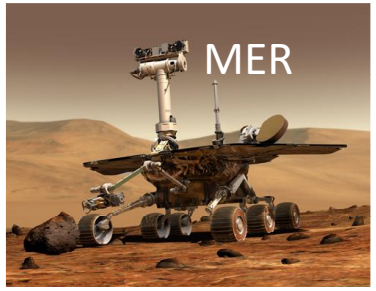


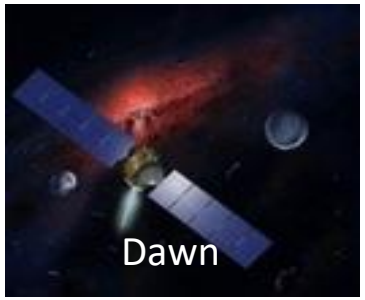




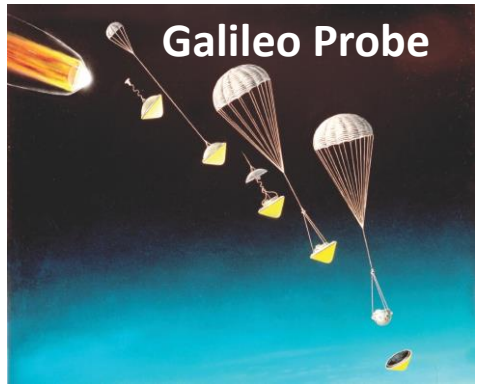


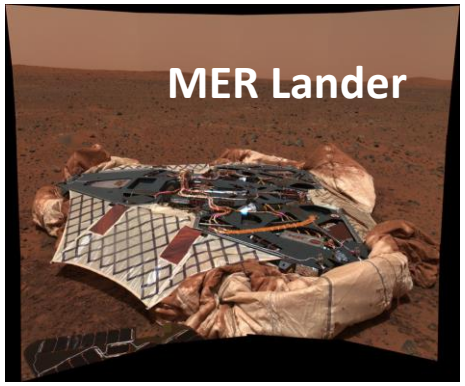


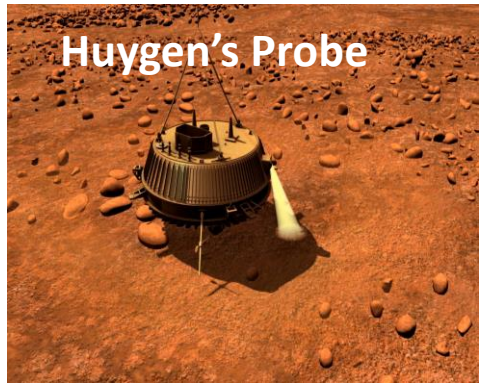




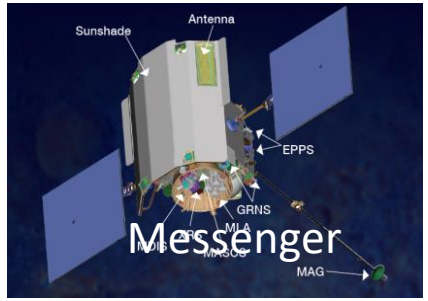
PSD Missions Powered by Primary Batteries

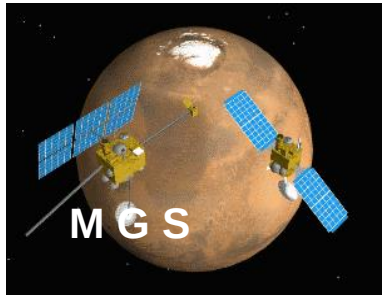


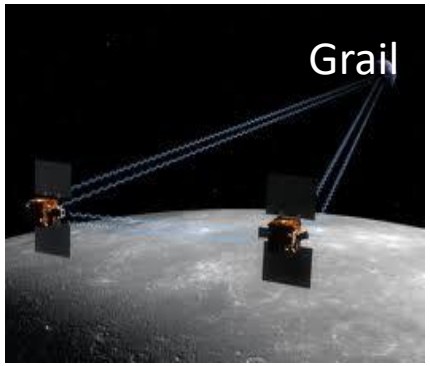


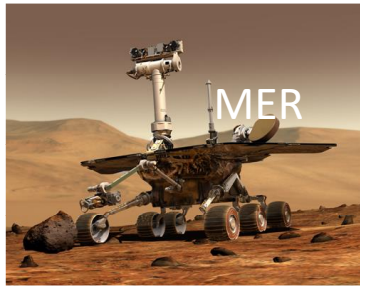


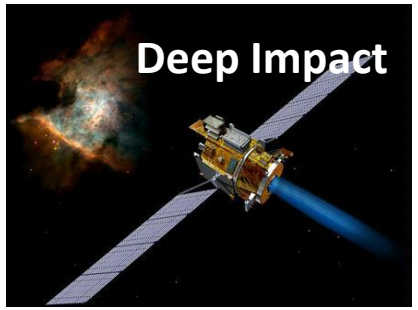
PSD Missions that used Rechargeable Batteries

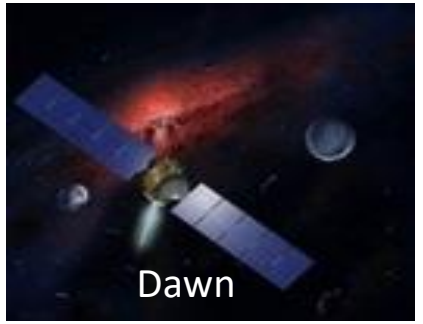


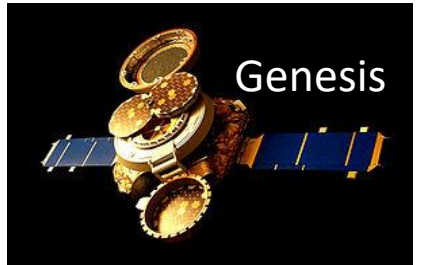




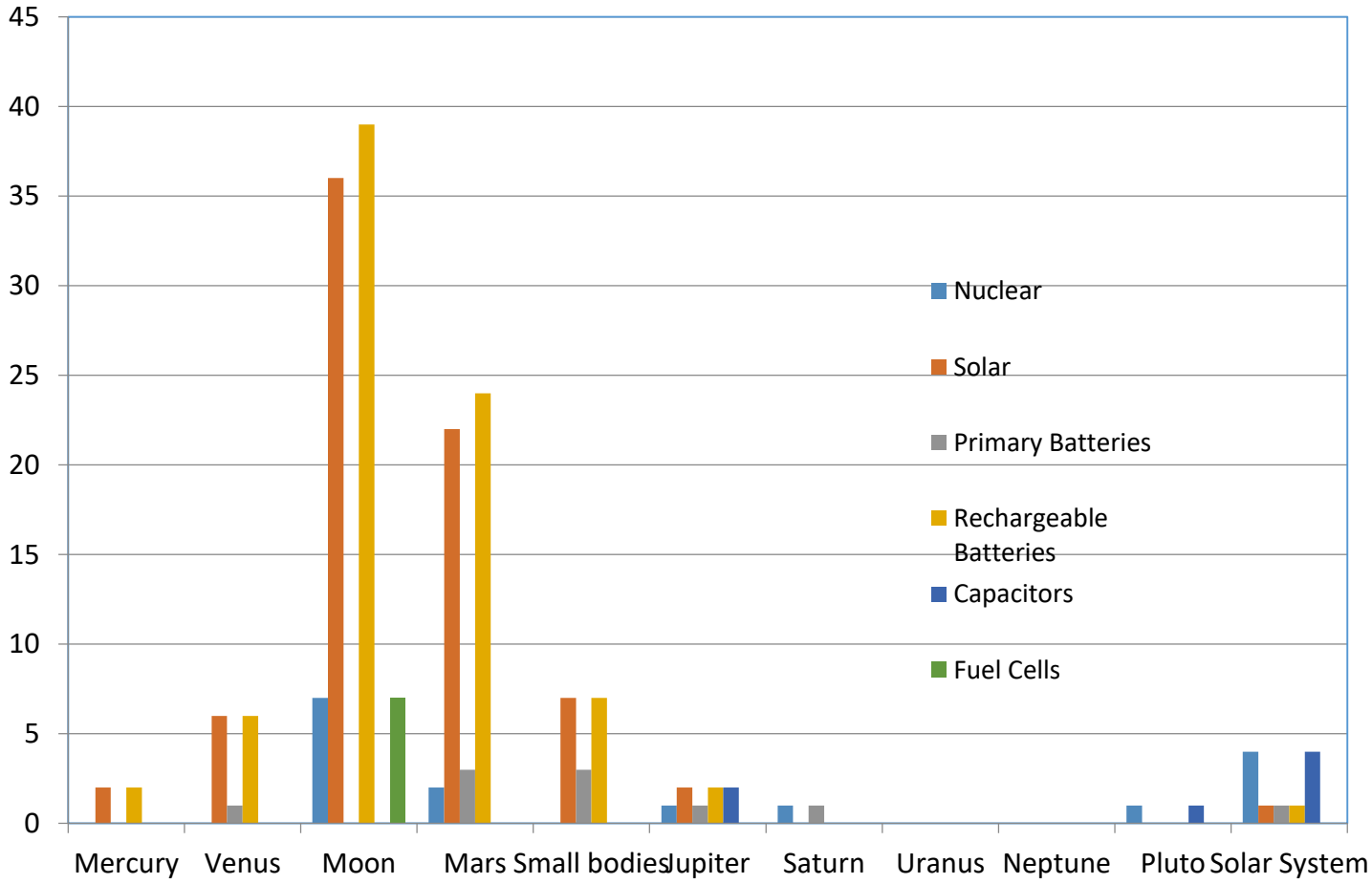




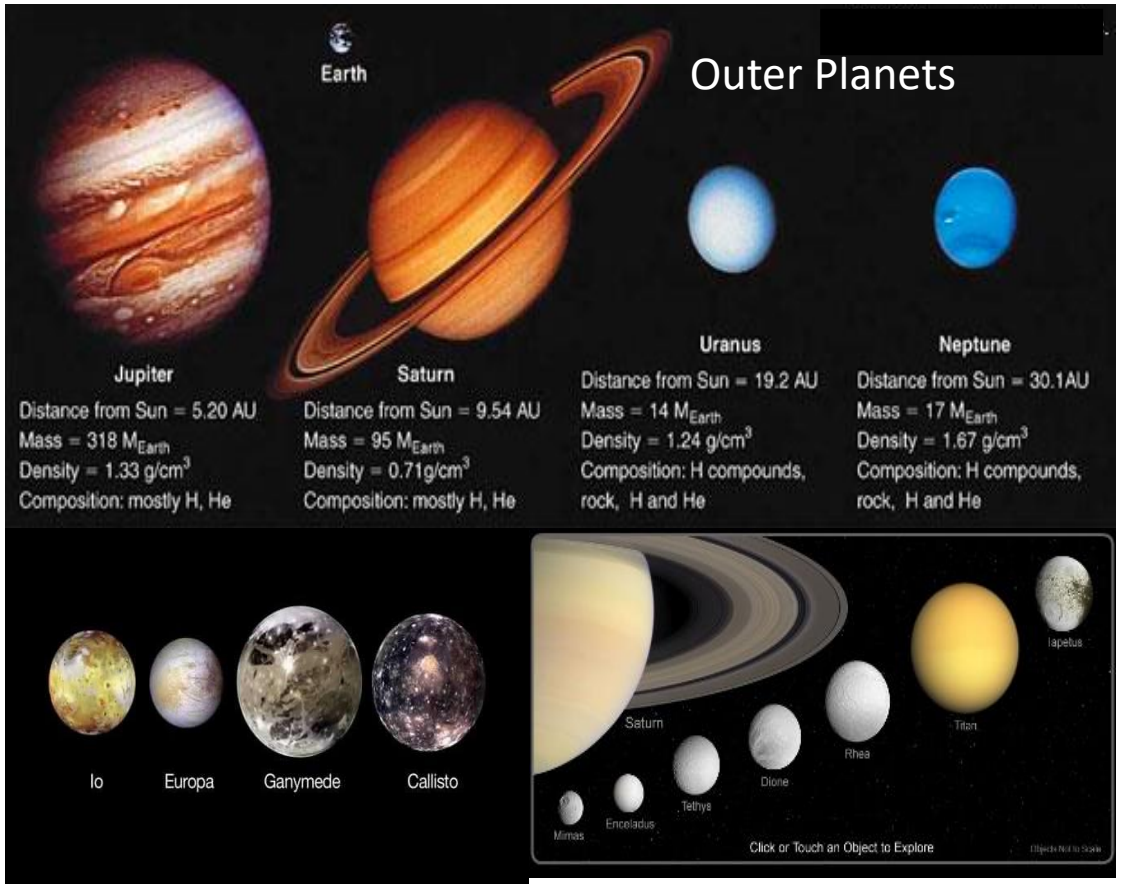




Power Systems used in Various Solar System Missions

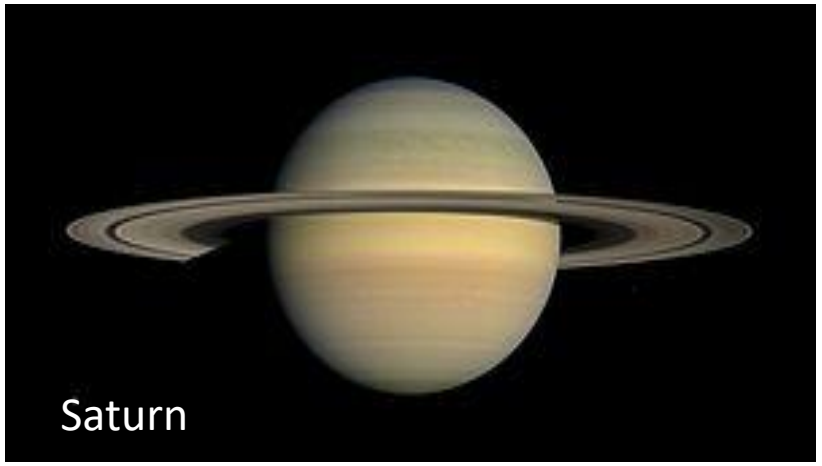


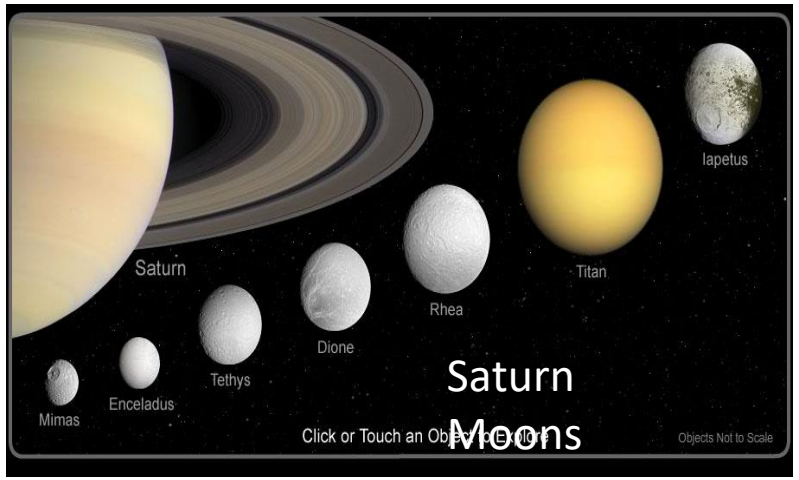
1) Most of the inner planet, Moon and Mars missions are solar powered, 2) Most of the outer planet Flyby missions are nuclear (radioisotope) powered, 3) Some solar-powered Jovian missions, 4) Most of the solar-powered and some radioisotope missions used rechargeable batteries for load levelling and powering during eclipse periods and 5) Fuel cells were used only in Human missions

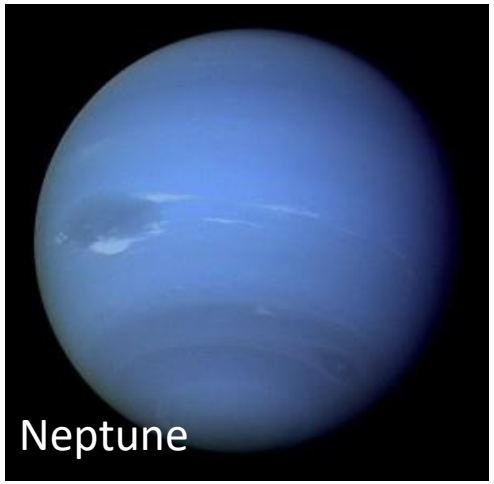


Outer Planetary Missions & Power Technology Needs

Outer Planet Mission Destinations

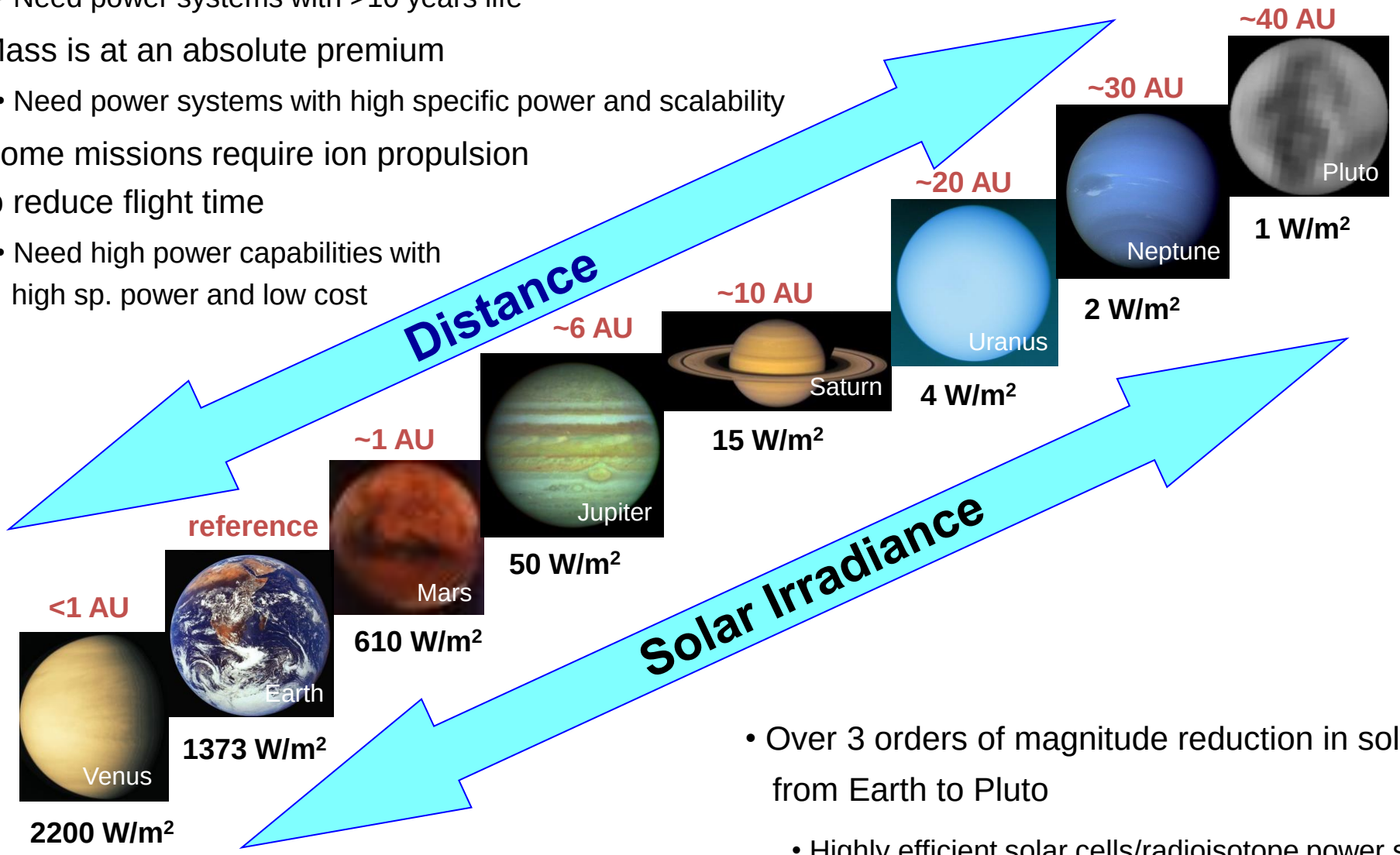






Major Power Challenges of Solar System Missions

- Flight times are long
  - Need power systems with >10 years life
- Mass is at an absolute premium
  - Need power systems with high specific power and scalability
- Some missions require ion propulsion to reduce flight time
  - Need high power capabilities with high sp. power and low cost

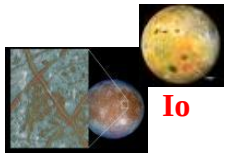


- Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
  - Highly efficient solar cells/radioisotope power systems

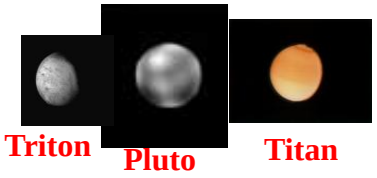
Major Challenges of Solar System Missions

Extreme Environments in Planetary Missions

- Some missions require high radiation resistant power systems
- Outer planetary surface missions require low temperature power systems

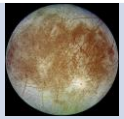
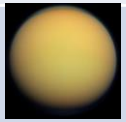


- Some outer planetary missions require power systems that can operate in deep space and in dense or tenuous atmospheres



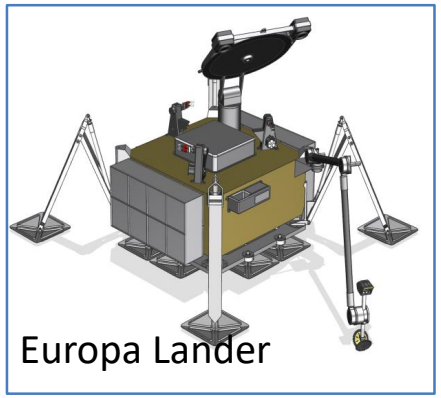
Inner planetary missions require power systems that can operate in very high temperature environments

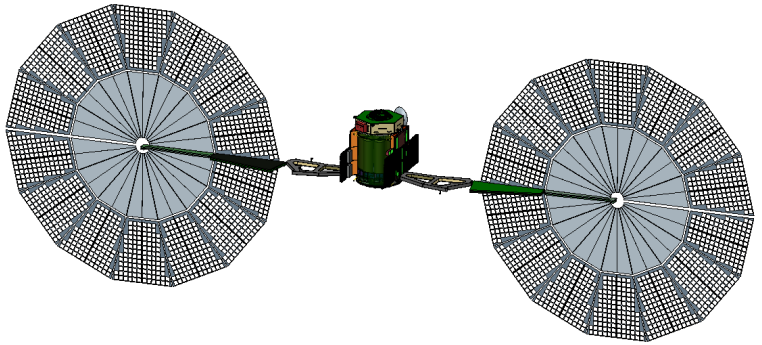
Ocean World Surface Environment

	World	Temperature °C	Gravity	Radiation	Atmosphere	Composition
	Europa	-223 to -140	1.314m/s2	5400 mSv / day	10^{-11}atm	
	Ganymede	-203 to -120	1.428m/s2		Trace	O2
	Callisto	-198 to -103	1.235m/s2	0.1mSv/day	7.10^{-12} atm	CO2/O2
	Enceladus	-240 to -128	0.113 m/s2		trace	H2O(91%)/N2/ CO2/CH4
	Titan	-179	1.352m/s2		1.45atm	N2/CH4
	Mimas	-200	0.064m/s2			
	Pluto	-240 to -218	0.620m/s2		10^{-5}atm	N2 /CH4/CO
	Earth	-90 to +57	9.807m/s2	0.02 mSv/Day	1atm	N2/O2

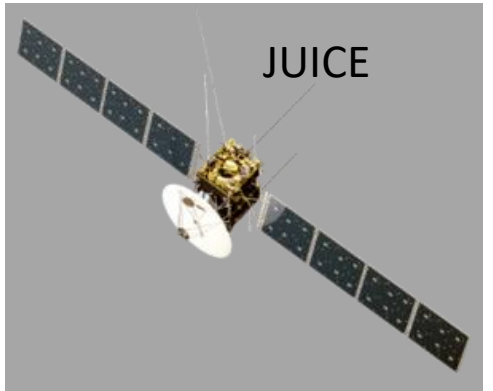
Potential Next Decadal Outer Planet Missions

- Ocean Worlds
  - Europa
  - Enceladus
  - Titan
- Icy Giants
  - Uranus
  - Neptune
- Giant Planets
  - JUICE
  - Saturn





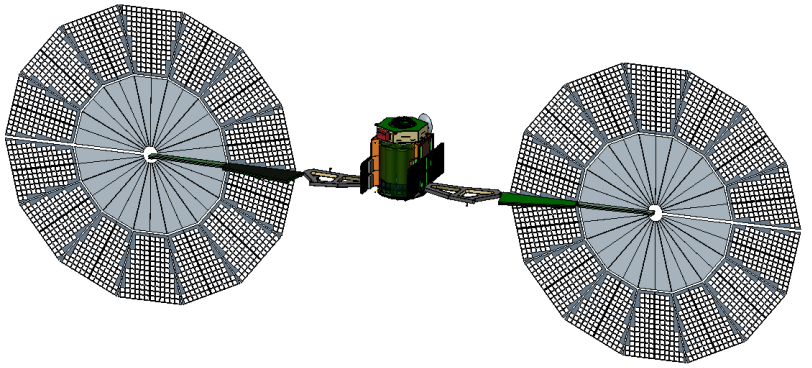
SEP stage for Uranus/Neptune missions



Artist's Concepts

Power System Needs for Future Outer Planetary Missions

- Radioisotope Power Systems(100-300 W): High Specific Power and Long Life

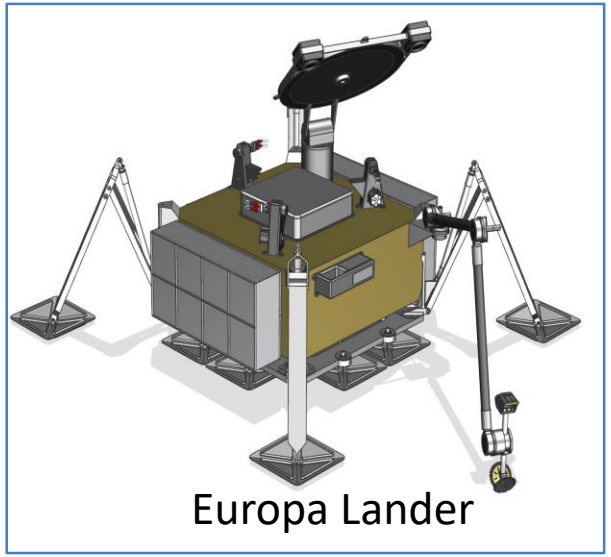


SEP stage for Uranus/Neptune missions

- Photovoltaic Power Systems: High Power, Low Mass & Radiation Tolerance, & LILT Capability

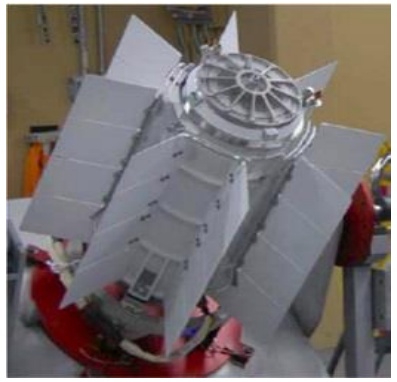
- Primary & Rechargeable Batteries: High Specific Energy, Long Life Low Temperature Performance, Radiation Tolerance & Sterilizable by heat or radiation

Artist's Concepts

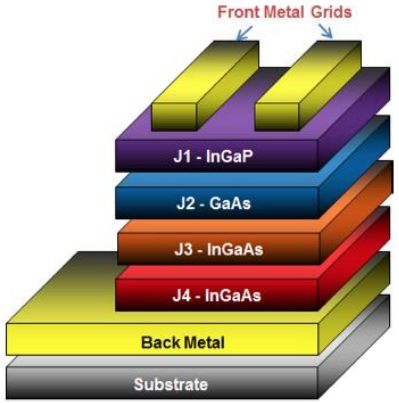


Europa Lander

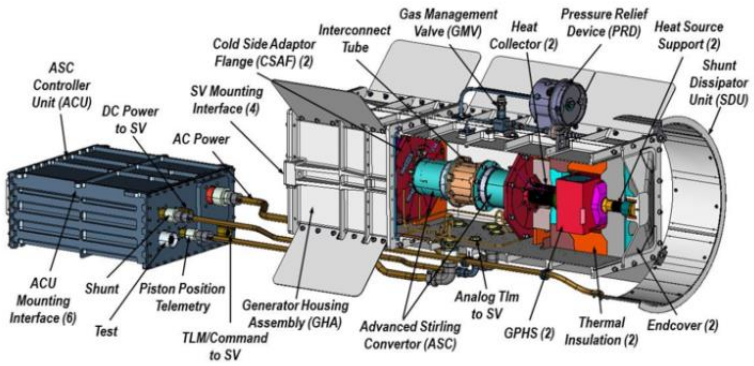
Advanced Power System Technologies Under Development



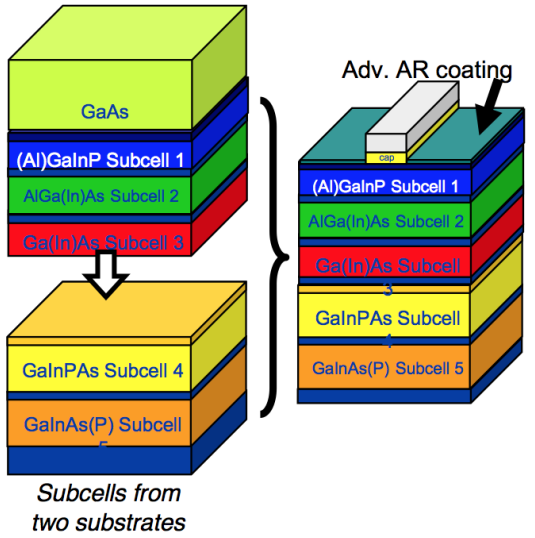
eMMRTG (potential)



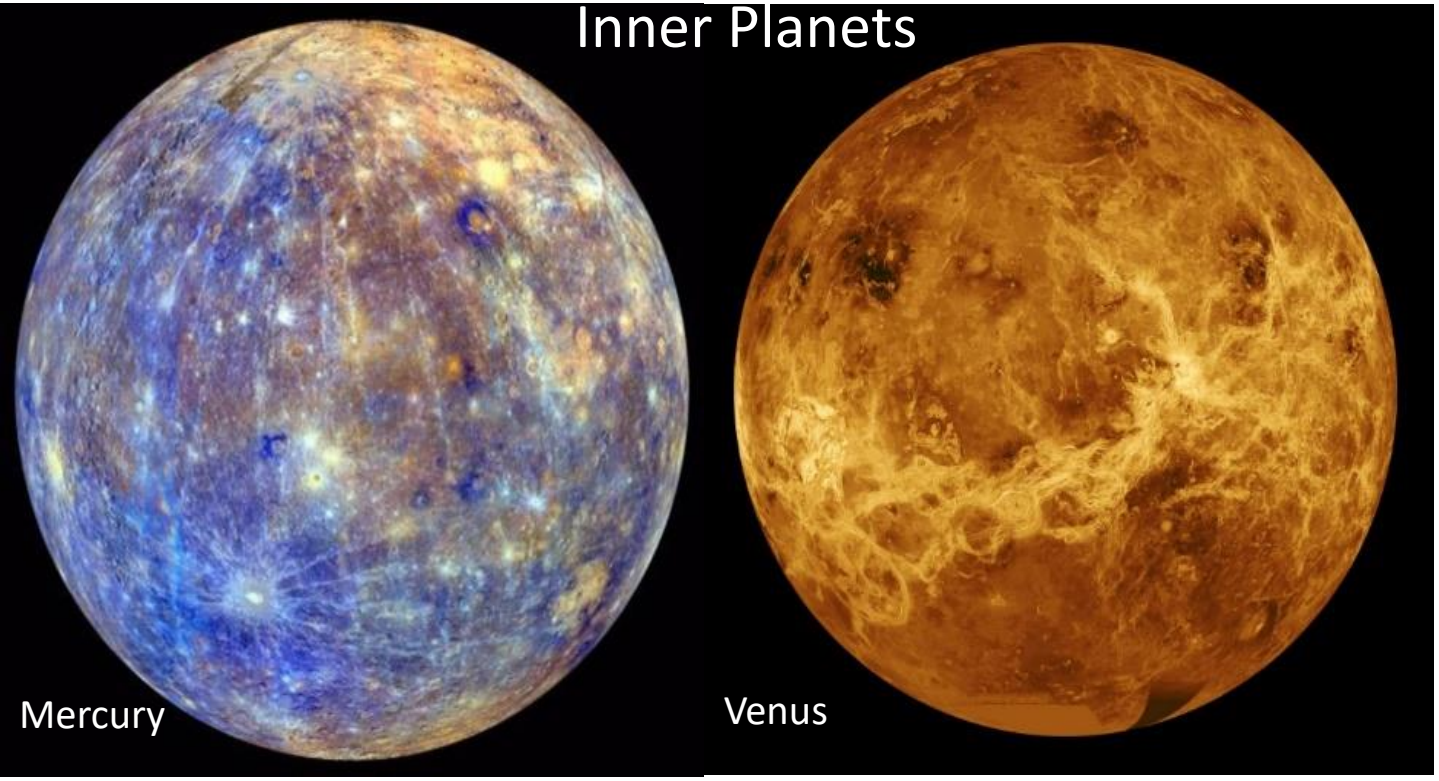
SolAero IMM-4J



Stirling RPS

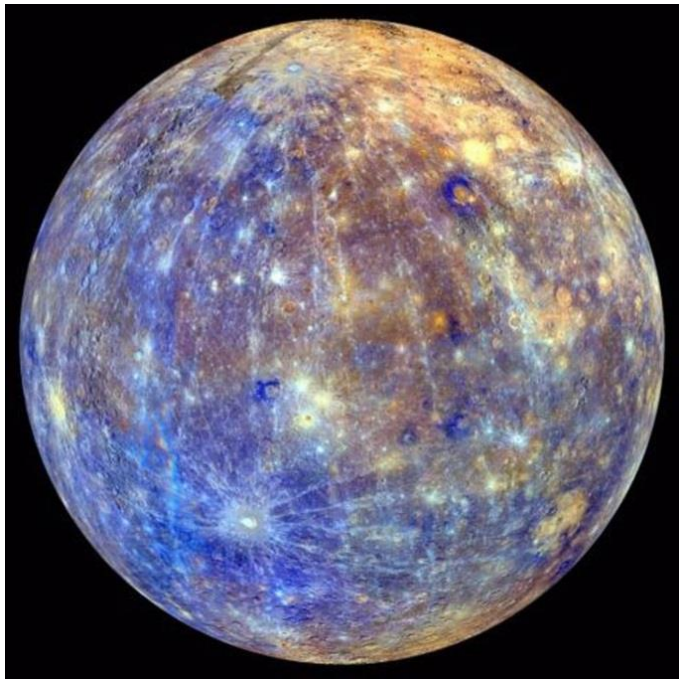


Spectrolab SBT-5J



Inner Planetary Missions & Power Technology Needs

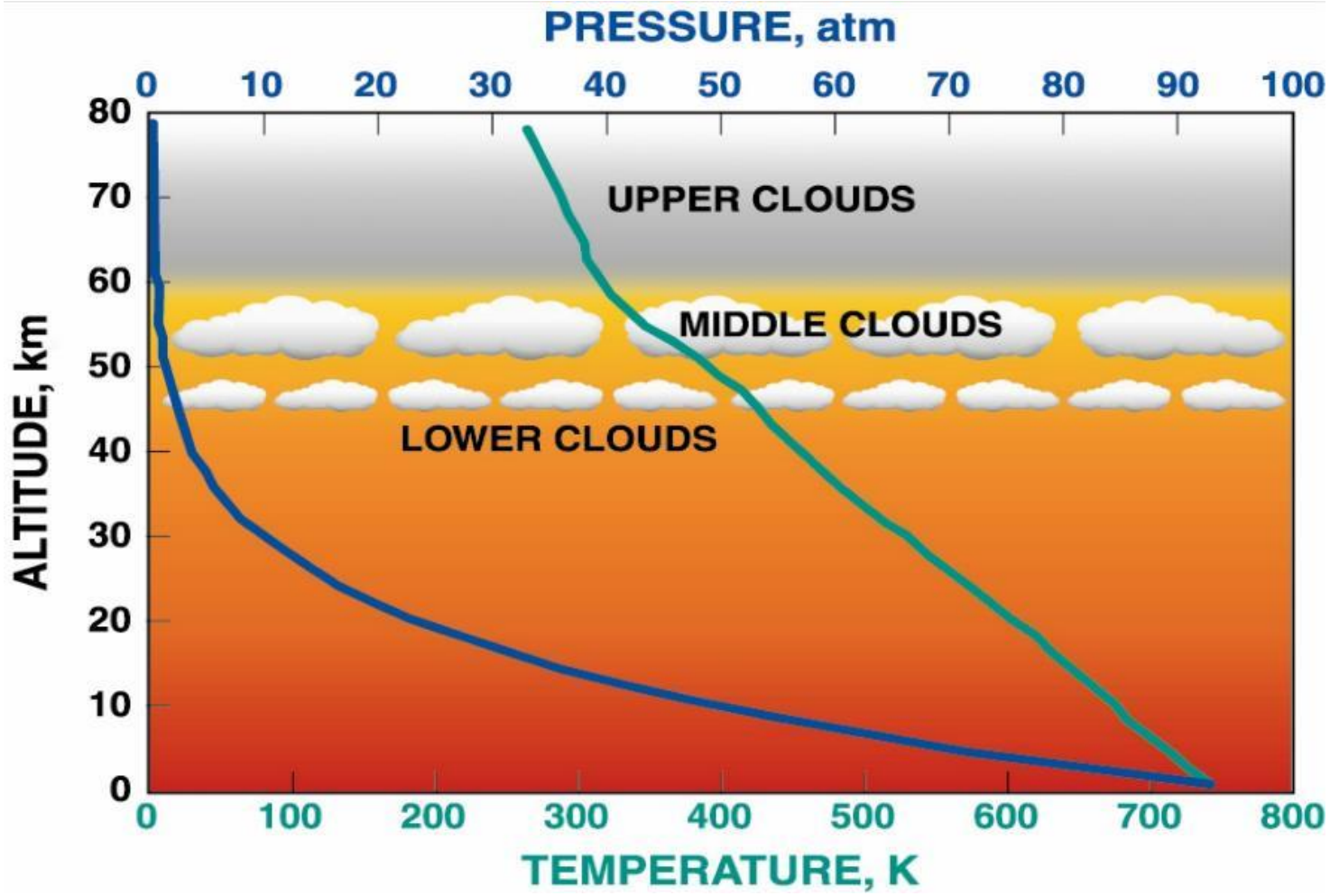
Inner Planetary Mission Destinations



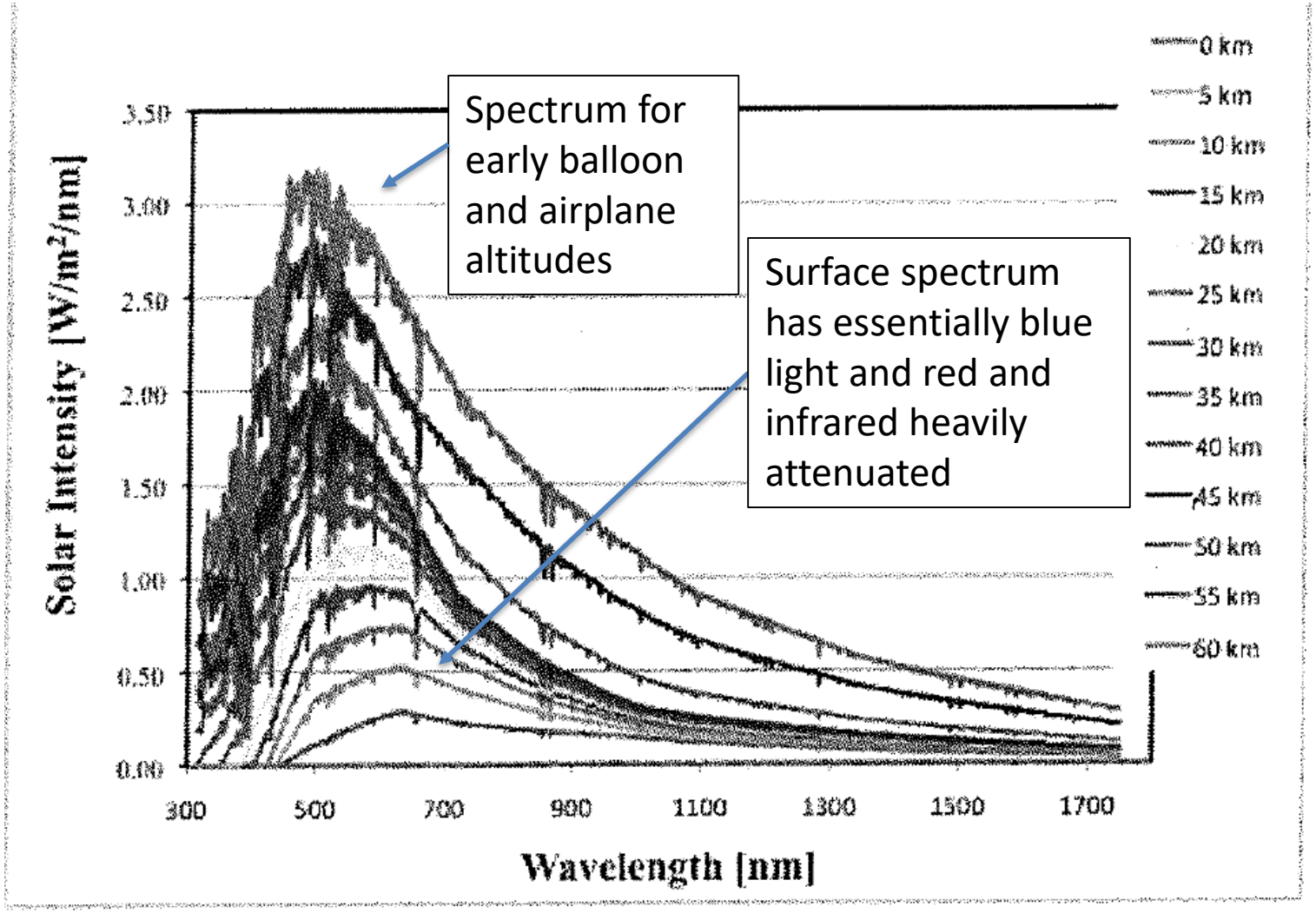
Mercury Solar day 176 Earth days

Venus Solar day 116 Earth days

Venus Environment

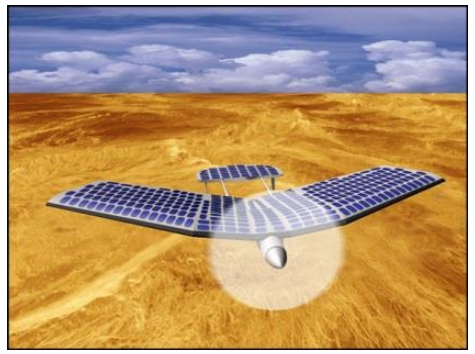


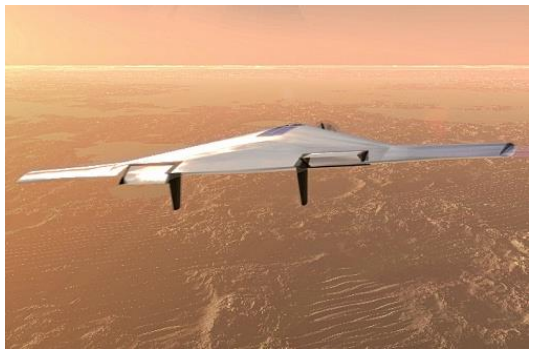
Solar Spectrum In Venus Atmosphere



Potential Venus Mission Concepts

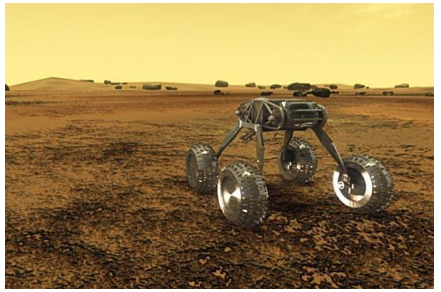
Upper Atmosphere 50 to 70 Km





Mid and Lower Atmosphere 50 to 10 Km

Surface



Near Term

Mid Term

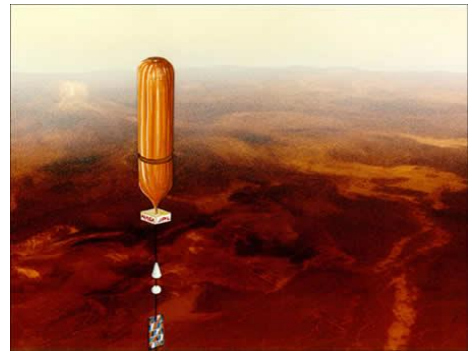
Long Term

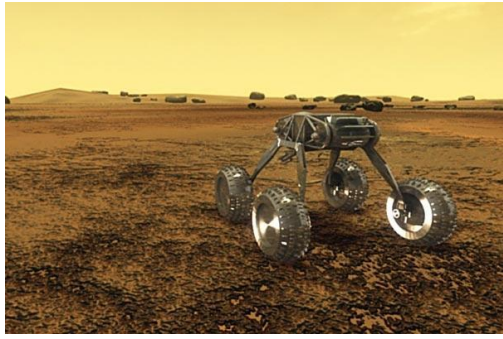
Power System Needs for Inner Planetary Missions

Photovoltaic Power Systems for Aerial Platforms & Surface Probes:
High Temperature Operation (300- 450C), Cells with LIHT capability in Venus Solar Spectrum, Operation in Corrosive Environments

Primary Batteries/Fuel Cells for Surface Probes:
High Temperature Operation (> 450C), High Specific Energy (>500 Wh/kg), Operation in Corrosive Environments

Rechargeable Batteries for Aerial Platforms:
High Temperature Operation (300-450C), Operation in Corrosive Environments, Low-Medium Cycle Life, High Specific Energy (>250 Wh/kg), Operation in High Pressures





Advanced Power Technologies Under Development

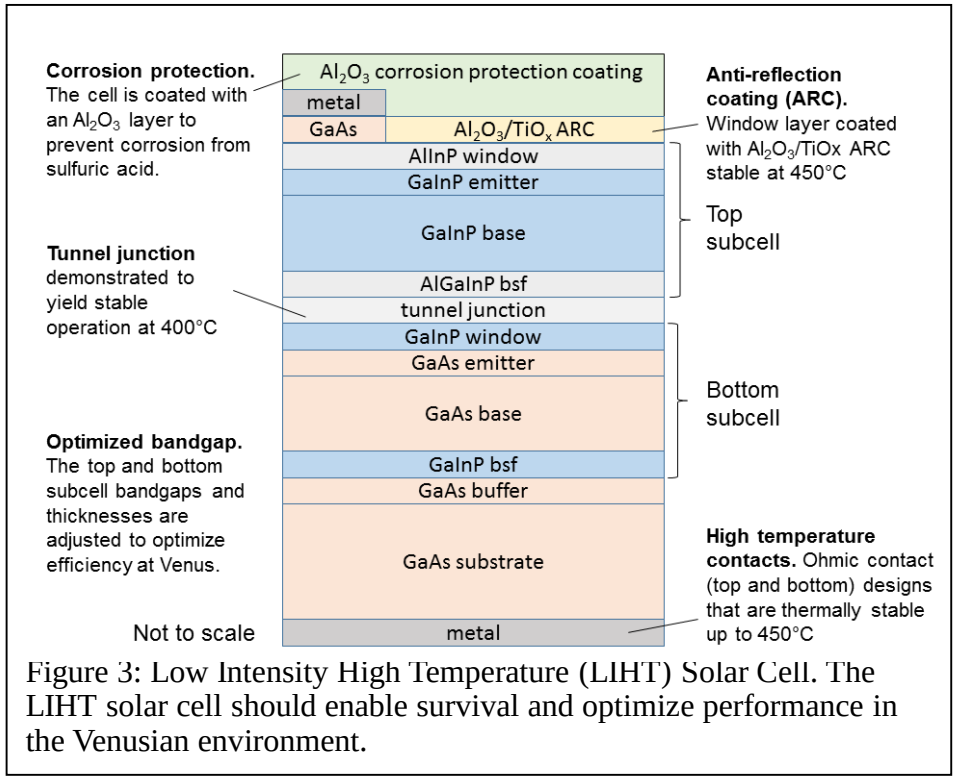


Figure 3: Low Intensity High Temperature (LIHT) Solar Cell. The LIHT solar cell should enable survival and optimize performance in the Venusian environment.

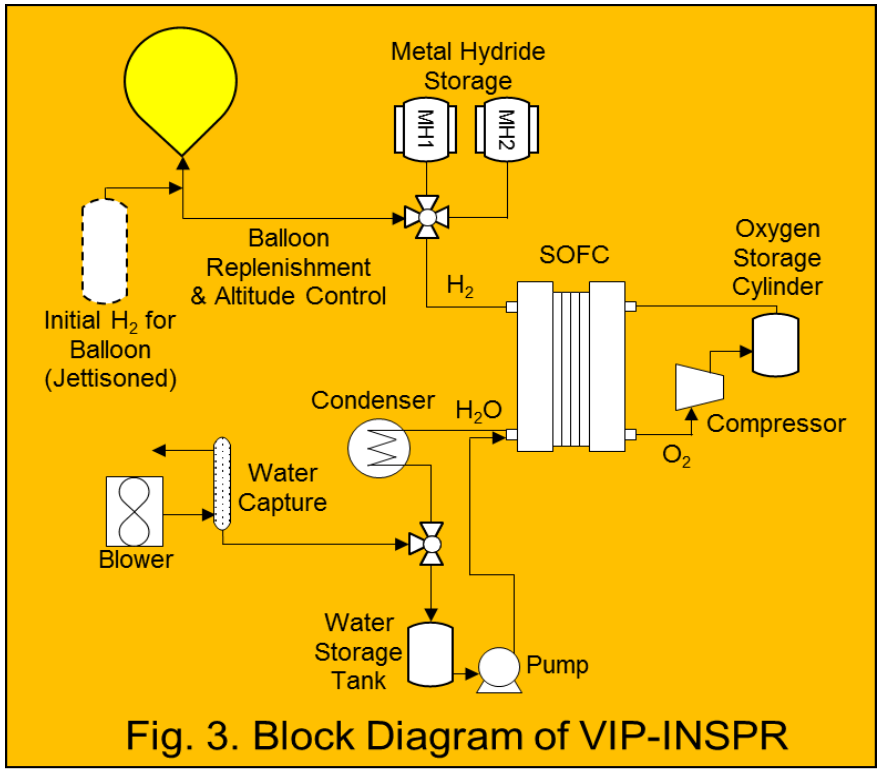
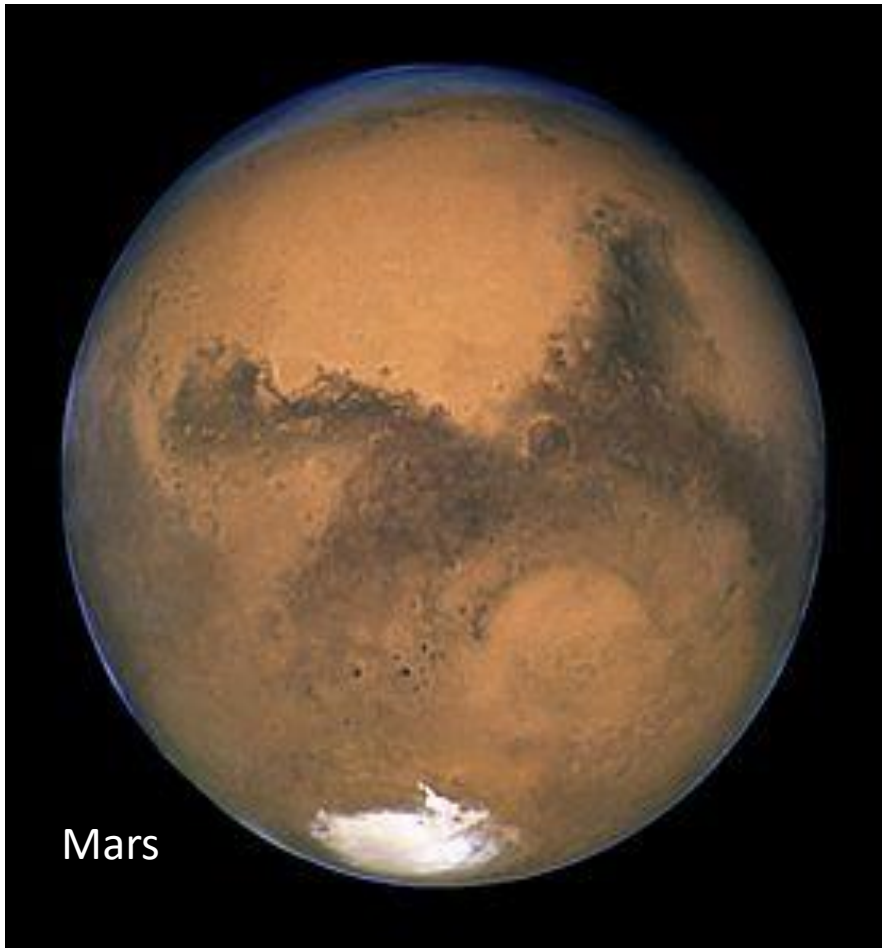
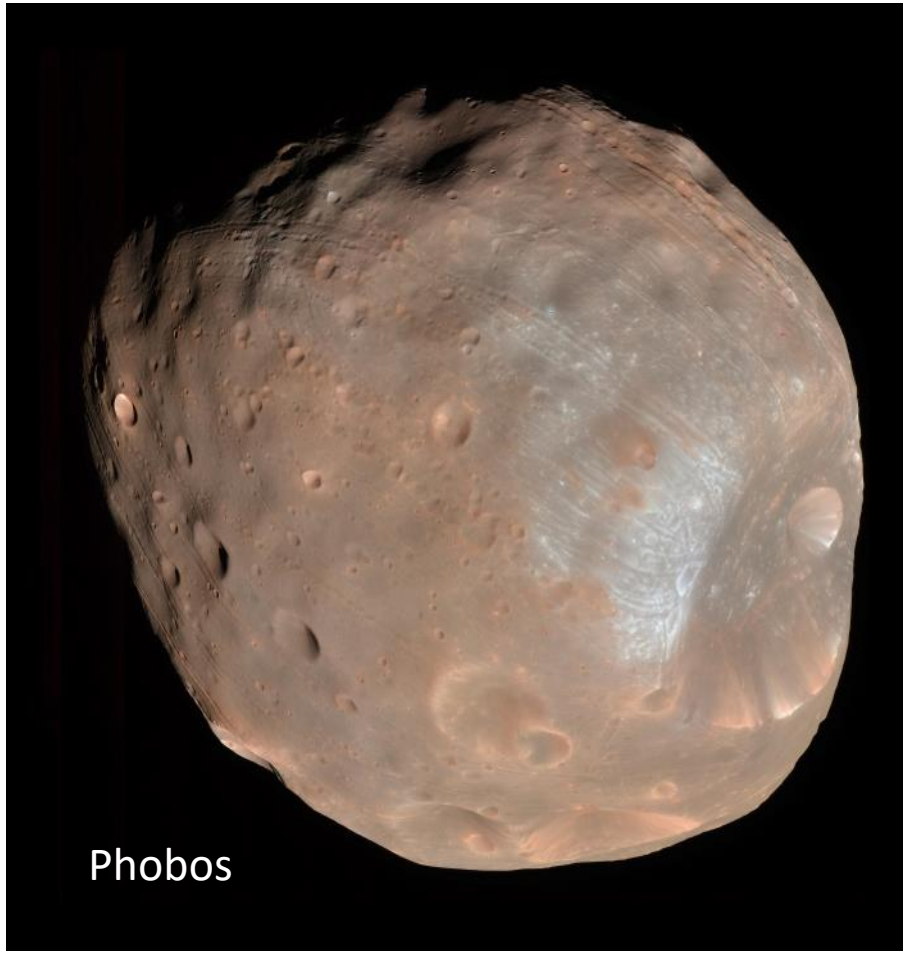


Fig. 3. Block Diagram of VIP-INSPR

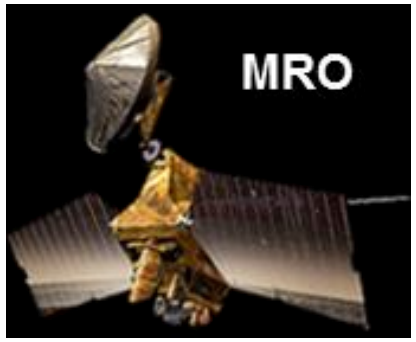
Mars Missions
&
Power Technology Needs

Mars Mission Destinations


Mars

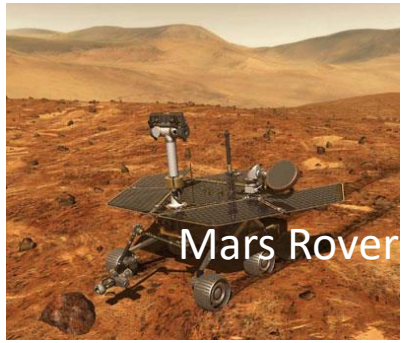

Phobos

Types of Mars Spacecraft



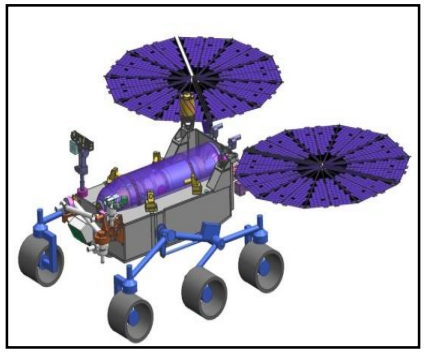
Orbiters

Landers

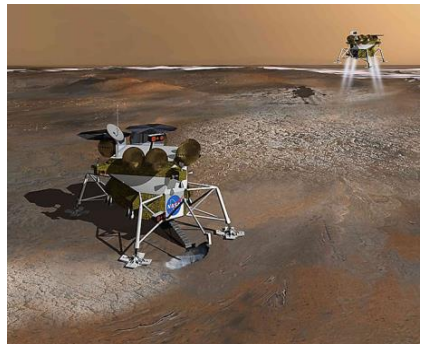


Rovers

Mars Aerial Vehicle



Potential Mars Sample Return

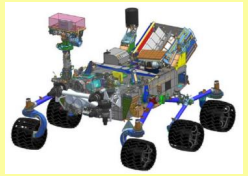


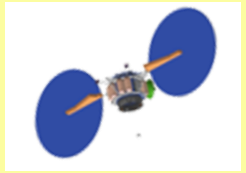
Robotic Precursor Missions

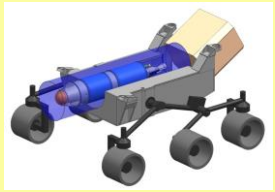
Mars Mission Concepts – 2020s and Beyond

Now through 2020	Decade of 2020's	Beyond

Potential Mars Sample Return



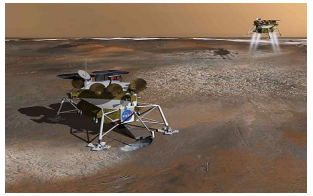




Mars 2020

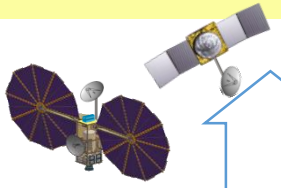
MSR Orbiter Concept (MSR, Comm, ComplimentaryScience)

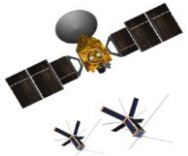
Sample Retrieval Concept (Landing, Retrieval Rover, Ascent Vehicle)

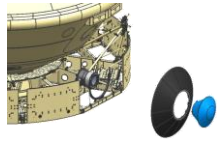


Robotic Precursor Missions

Human-Robotic Missions

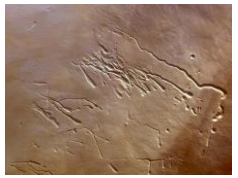


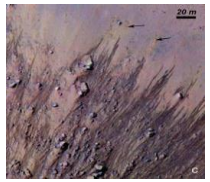




Contingency Orbiter Options

Secondary Vehicles (CubeSat, Aerocapture)





Other Scientific Priorities

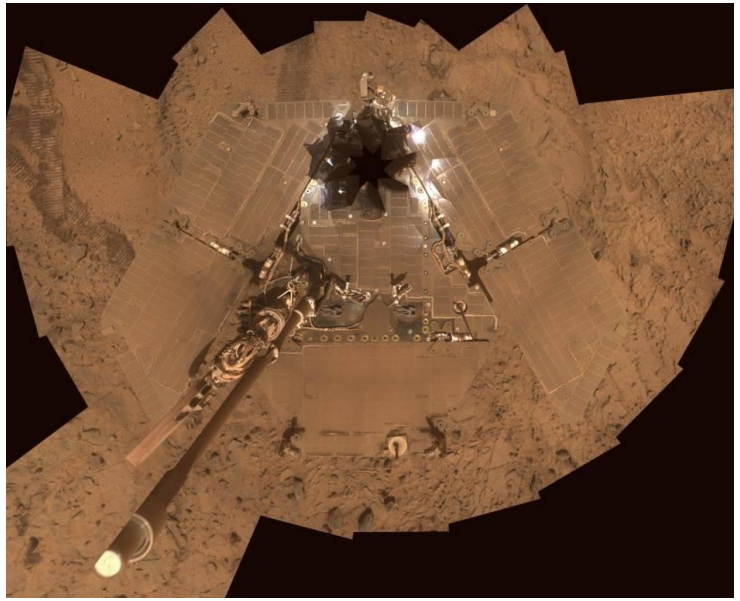
Other Complementary Science or Technology Objectives

Legend

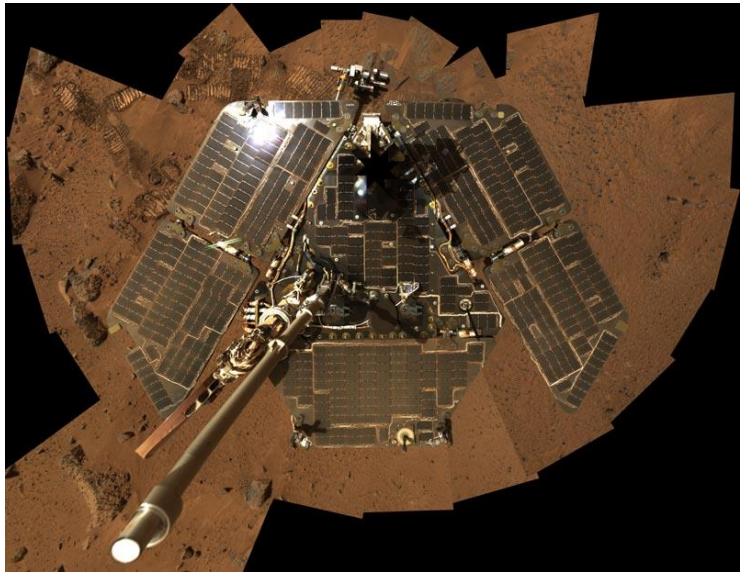
Primary Missions

Secondary Missions

Mars Surface Mission Challenges



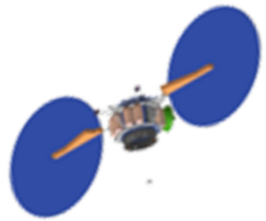
Dusty Array

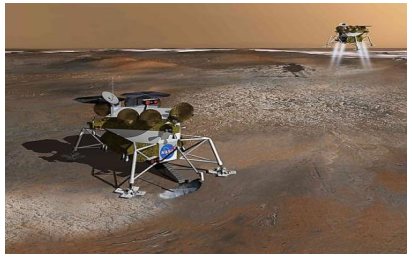


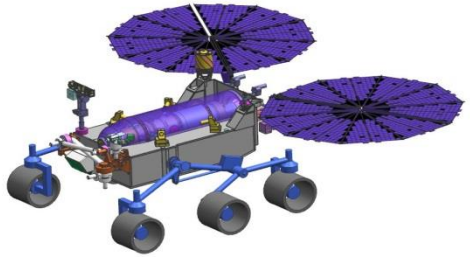
Array after natural wind cleaning

Next Decadal Mars Mission Concepts

- Mars Sample Return Missions
  - Mars 2020 Rover
  - MSR Orbiter
  - Sample Retrieval (Landing, Retrieval Rover, Ascent Vehicle)
- Mars Aerial Vehicles
- Human Precursor Missions







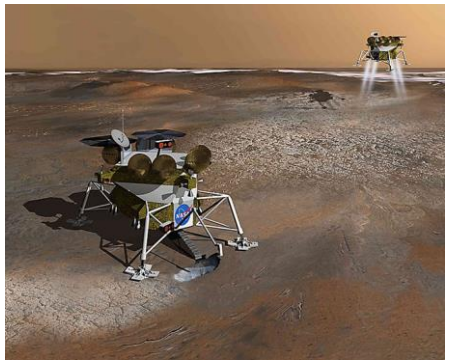
Power System Needs for Future Mars Missions

- **Photovoltaic Power Systems for Aerial & Surface Missions**: High efficiency Solar Cells to operate in Mars Solar Spectrum , Solar Arrays with Low Mass (>3 X lower than SOP) & Dust Removal capability

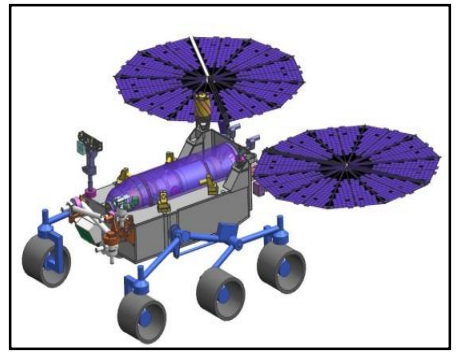
- **Rechargeable Batteries for Surface Missions:** High Specific Energy (>250 Wh/kg), Low Temperature Operation (-40 C), Long Cycle Life (>3000) , Sterilizable by heat or radiation

- **Rechargeable Batteries for Aerial Missions:** High Specific Energy (>250 Wh/kg), High Power Density (> 3kW/kg), Low Temperature Operation (-40 C)

- **Radioisotope Power Systems**: High Specific Power and Long Life

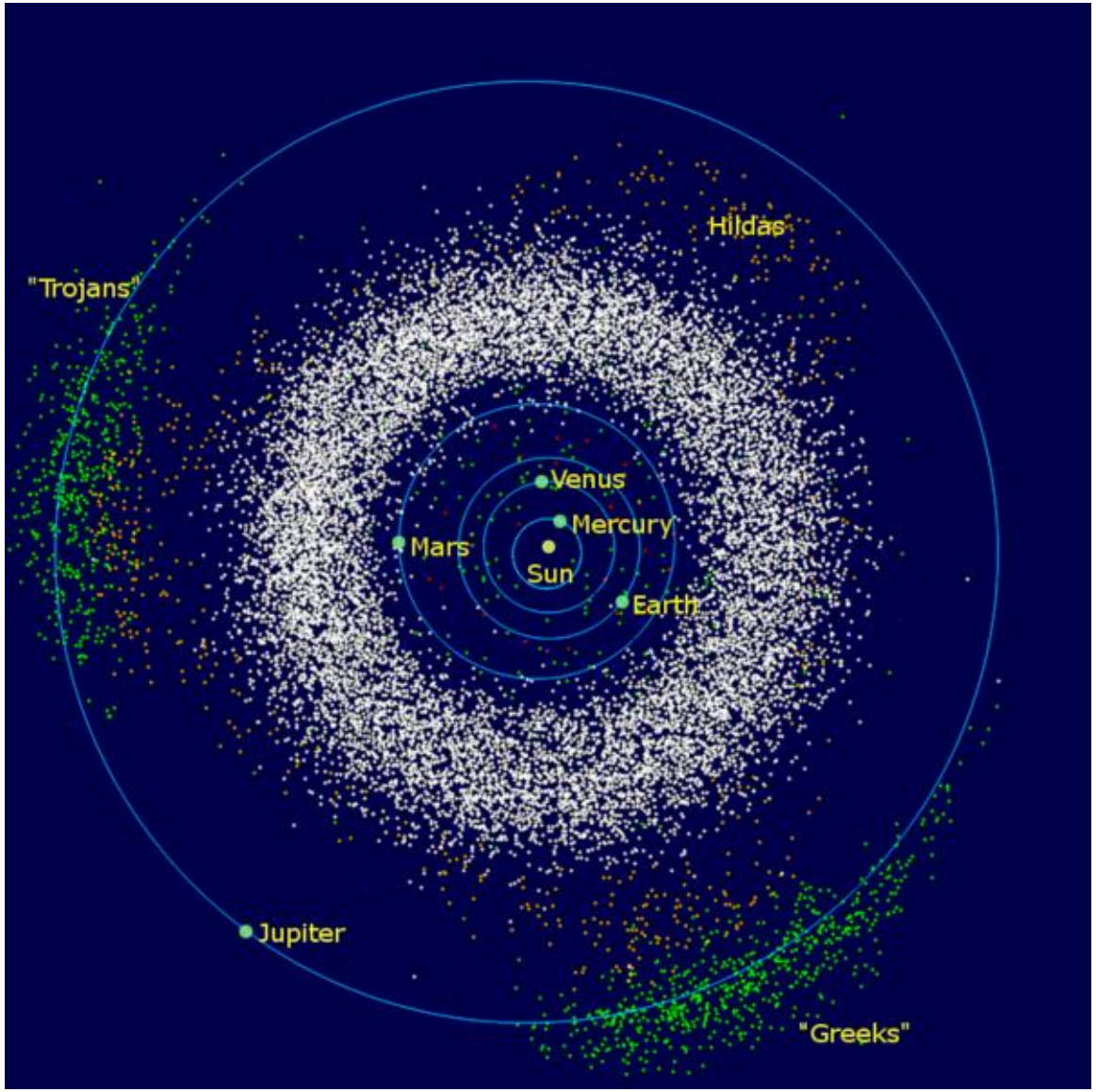


Robotic Precursor Missions



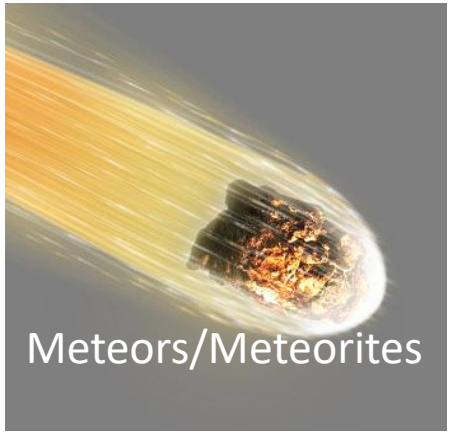
Mars Sample Return Concept

Mars Aerial Vehicle

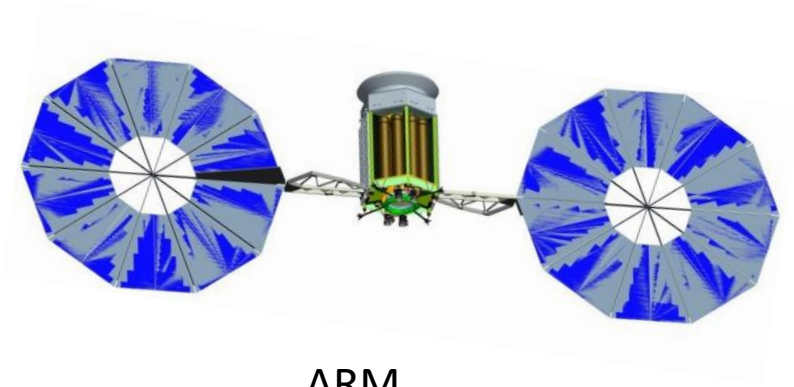


Small Body Missions & Power Technology Needs

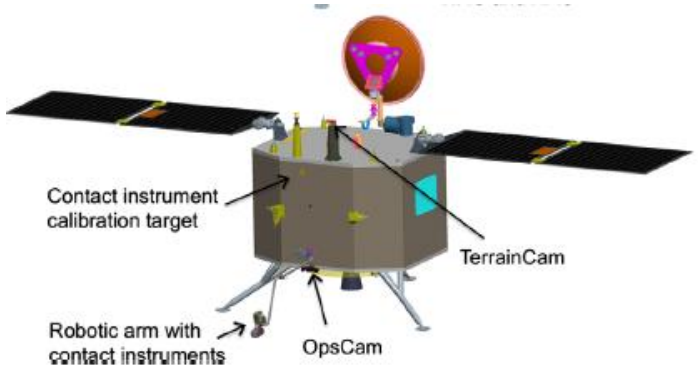
Small Bodies



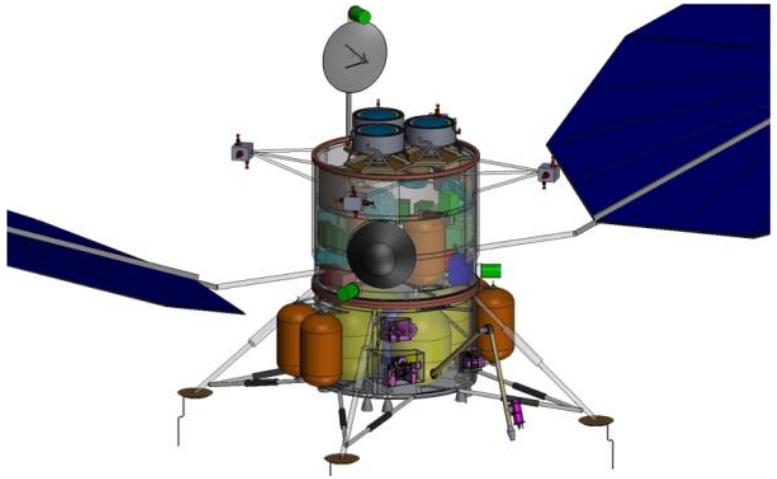
Types of Asteroid Mission Concepts



ARM



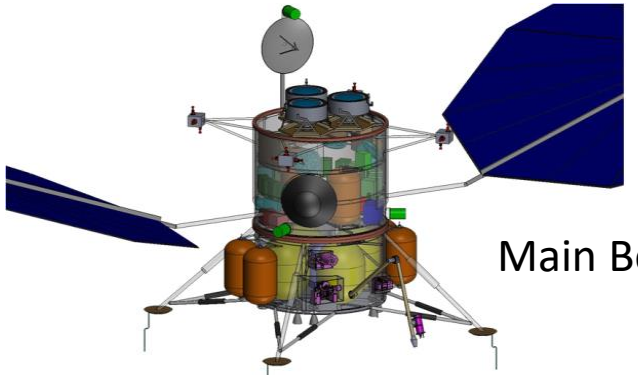
Phobos Lander



Main Belt Sample Return Mission

Potential Next Decadal Small Body Mission Concepts

- Flagship Mission:
  - Cryogenic Comet Nucleus Sample Return – explicitly stated in *Vision and Voyages*

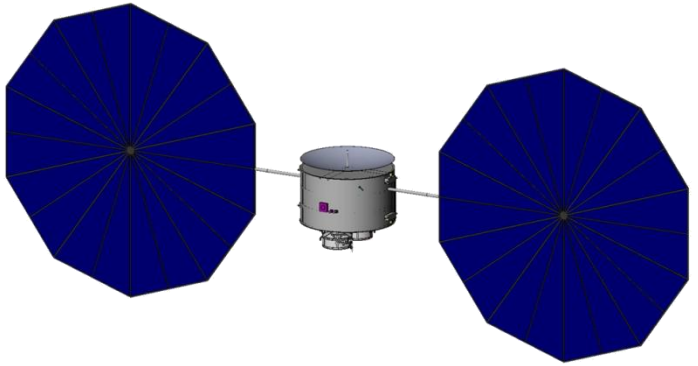


Main Belt Sample Return Mission

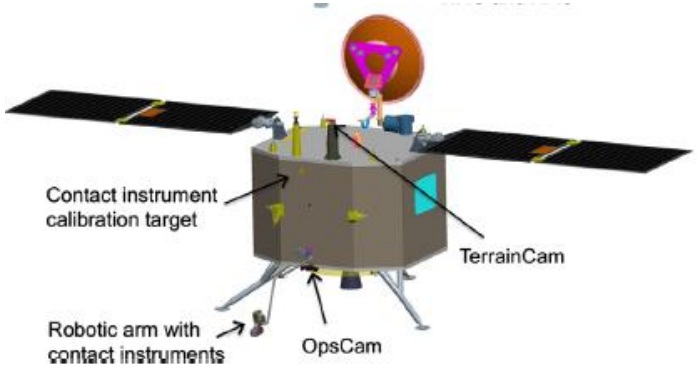
- Possible New Frontiers or Discovery
  - Trojan Tour and Rendezvous
  - Multi-asteroid rendezvous or flyby mission (depending on Discovery 14 selection, ESA M5 proposal)
  - Follow up to Dawn mission with Ceres **lander**
  - Themis, Hygiea, Pallas of interest after Dawn visiting Vesta and Ceres
  - *Follow-on mission to the Kuiper Belt?*

Power System Needs for Future Outer Planetary Missions

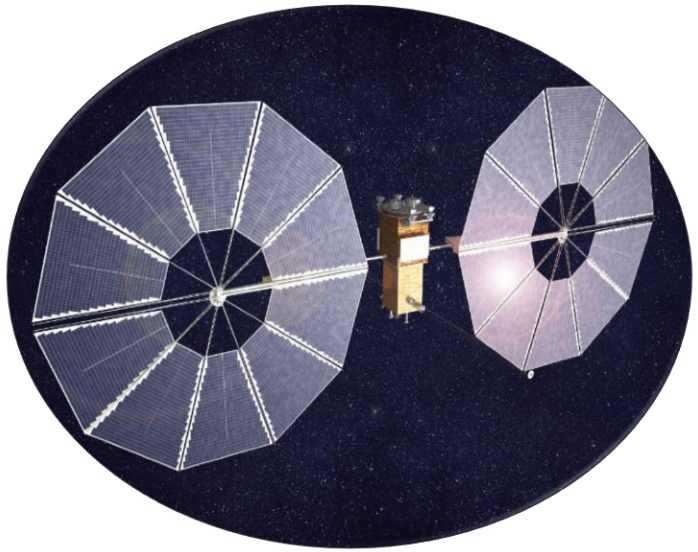
- Photovoltaic Power Systems:
  High Power, Low Mass & Radiation Tolerance, & LILT Capability



- Primary & Rechargeable Batteries:
  High Specific Energy, Long Life Low Temperature Performance, Radiation Tolerance & Sterilizable by heat or radiation



Advanced Solar Cell Technologies Under Development



MegaFlex Solar Array

Product Performance Targets:

- Power: 100-300 KW
- Effciency : > 35%
- Specific Power*: 200-500 W/kg
- Stowage volume*: 60-80 kW/m^3

Mega Roll-Out Solar Array

Product Performance Targets:

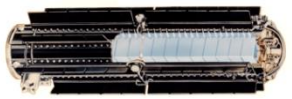
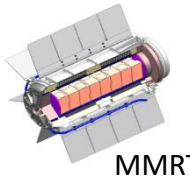
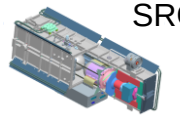
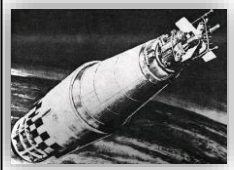
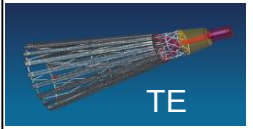
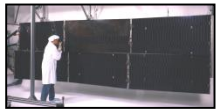
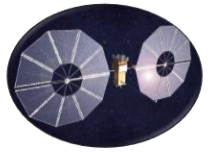
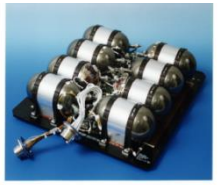
- Power: 100-300 KW
- Effciency : > 35%
- Specific Power*: 200-500 W/kg
- Stowage volume*: 60-80 kW/m^3

Summary of Findings & Recommendations

Power Technology Needs of Future Planetary Science Missions

- Advanced radioisotope power systems with high specific power (4-8 W/kg), high efficiency (> 10%) , and long life capability (>15 years) for outer planetary missions.
- High power (>50 kW) and low mass (> 200 W/kg) solar arrays and high efficiency solar cells (>38%) with LILT capability (4-10 A) for SEP and outer planetary missions
- High specific energy (> 500 Wh/kg) primary batteries and fuel cells (with sterilization capability for outer planetary surface missions
- High specific energy (>250 Wh/kg) and long cycle life rechargeable batteries for orbital and surface (with sterilization capability) missions.
- High temperature (300-450C) solar arrays and batteries for Venus aerial and surface missions

Space Power Source Technologies - Overview

	Past	Present	Future
Radioisotope Power Sources	 MHW RTG 5 W/kg 6.5 % eff	 MMRTG 3 W/kg 6.3 % eff	 eMMRTG ARTG  SRG 4-8W/kg 10-25 % eff
Fission Reactor Power Sources	 650W 1 W/kg 4 % eff		 Small FPS (1-5kW , 2-4 W/kg) 
Solar Cells	 Si Solar cells Rigid Panel Array 30-40 W/kg 9-15 % eff	 TJ Solar cells Flexible Panel Array 100W/kg 25% eff	 High eff. cells Low Mass Array  250 W/kg 35-39 % eff
Rechargeable Batteries	 Ni-H2 35 Wh/kg >30,000 Cycles	 Li-Ion 100 Wh/kg >30,000 Cycles	➢Adv. Li-Ion ➢Li-S ➢250 Wh/kg ➢30,000 Cycles

Acknowledgements

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