Solar System Exploration

Overview of NASA's 2006 Solar System Exploration Roadmap

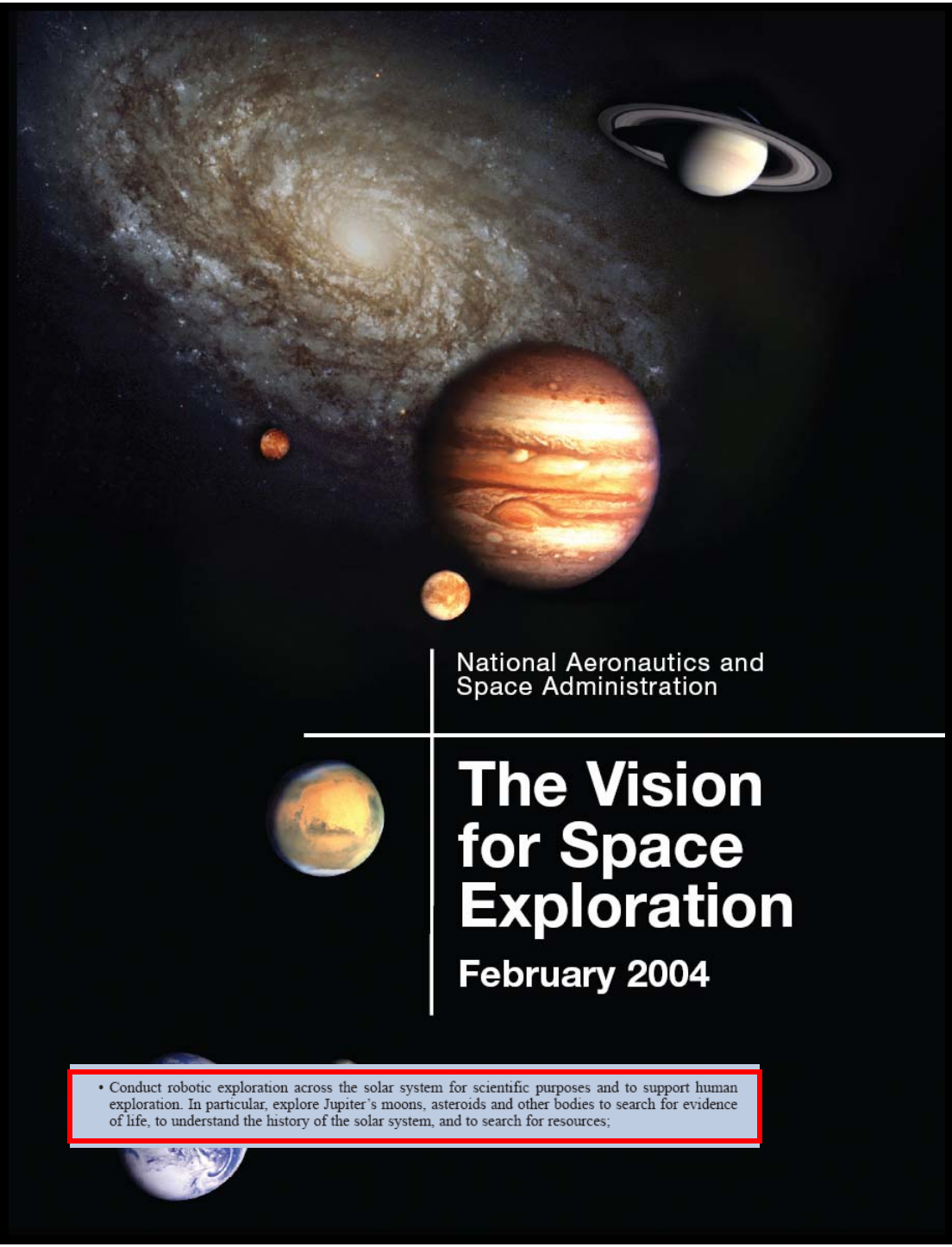
Based on the work of the

Solar System Exploration Roadmap Team

Presented by

Ellen Stofan and Jim Cutts

Jan 11, 2007



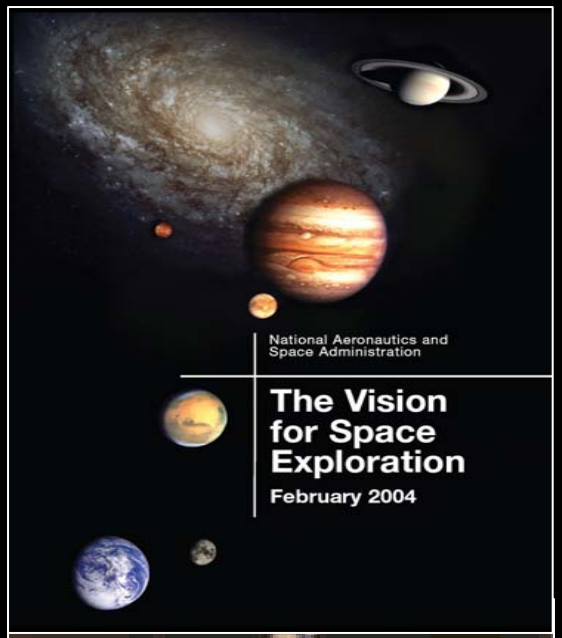
National Aeronautics and Space Administration

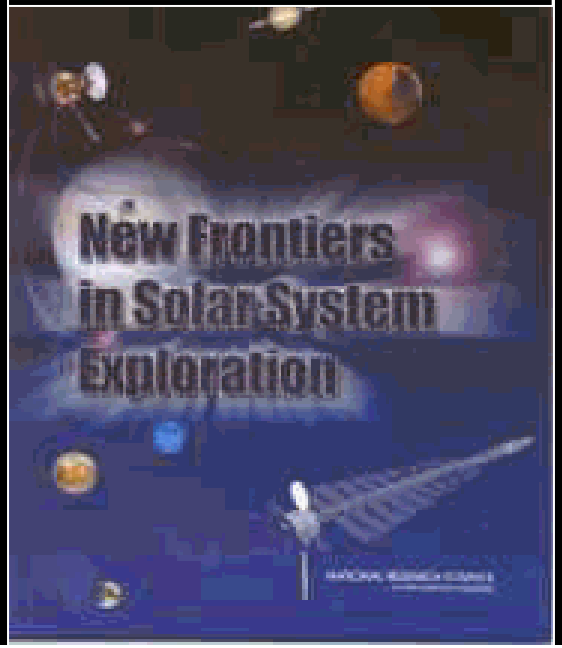
The Vision for Space Exploration

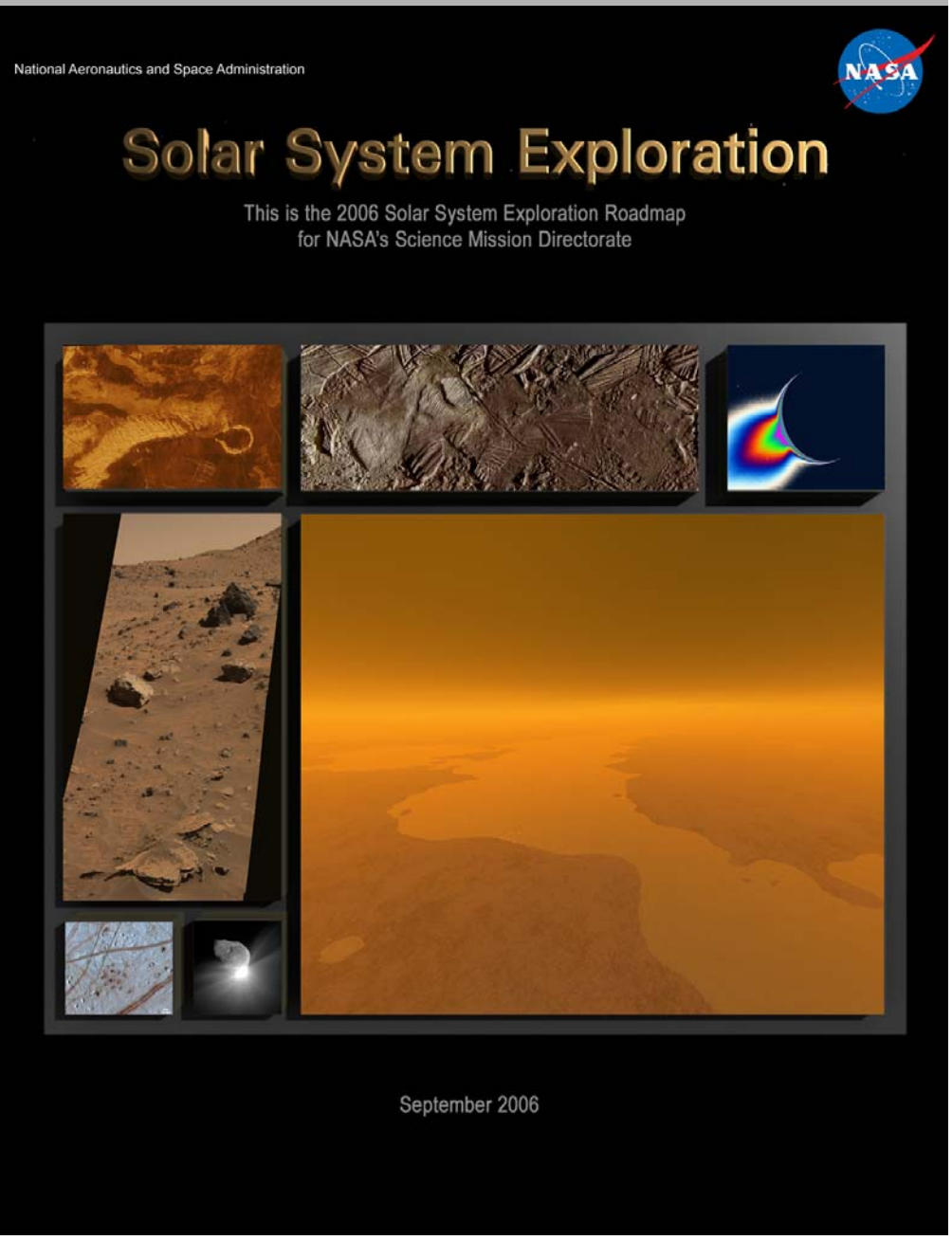
February 2004

- Conduct robotic exploration across the solar system for scientific purposes and to support human exploration. In particular, explore Jupiter's moons, asteroids and other bodies to search for evidence of life, to understand the history of the solar system, and to search for resources;

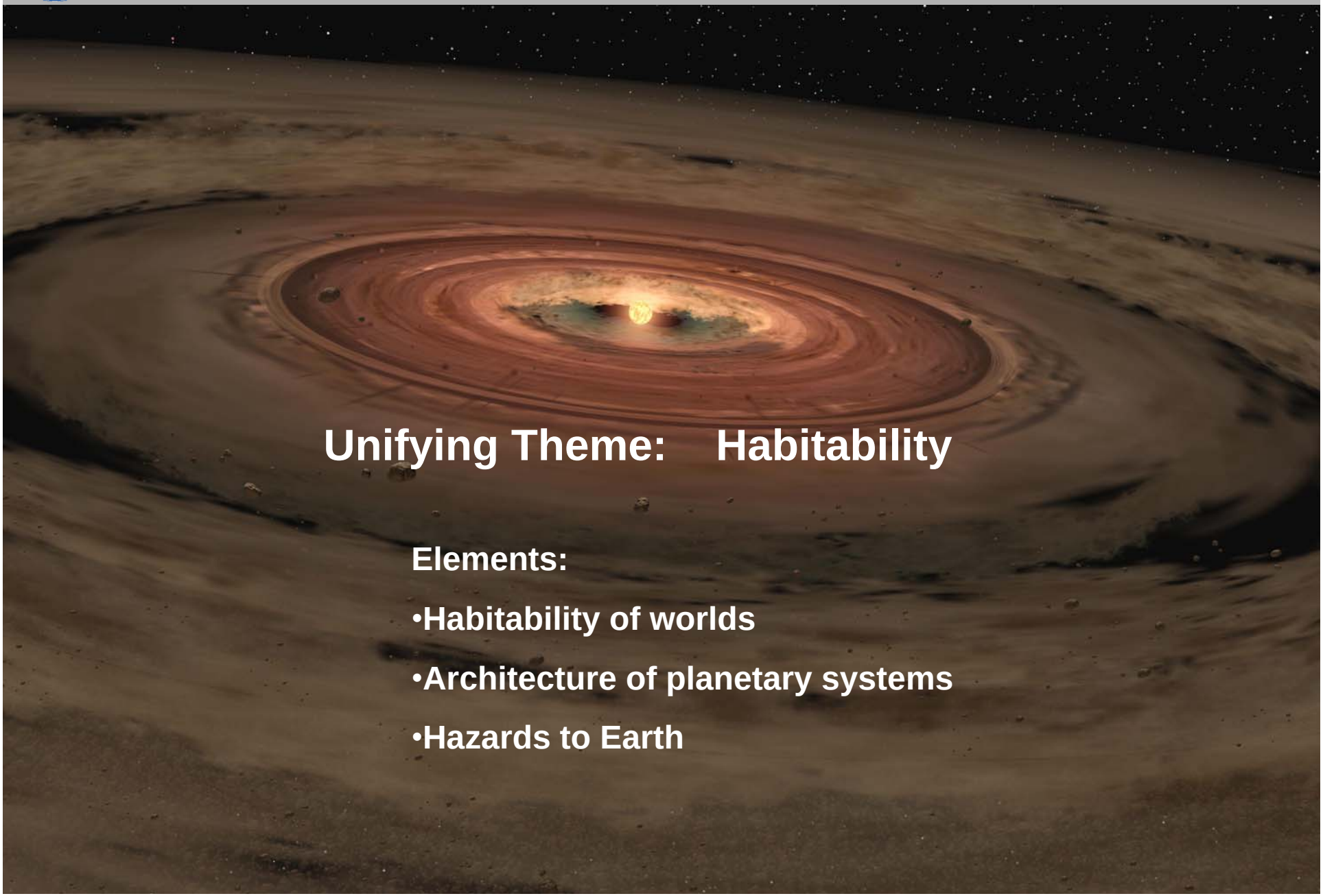
STRATEGIC ROADMAP PROCESS







SCIENCE OBJECTIVES

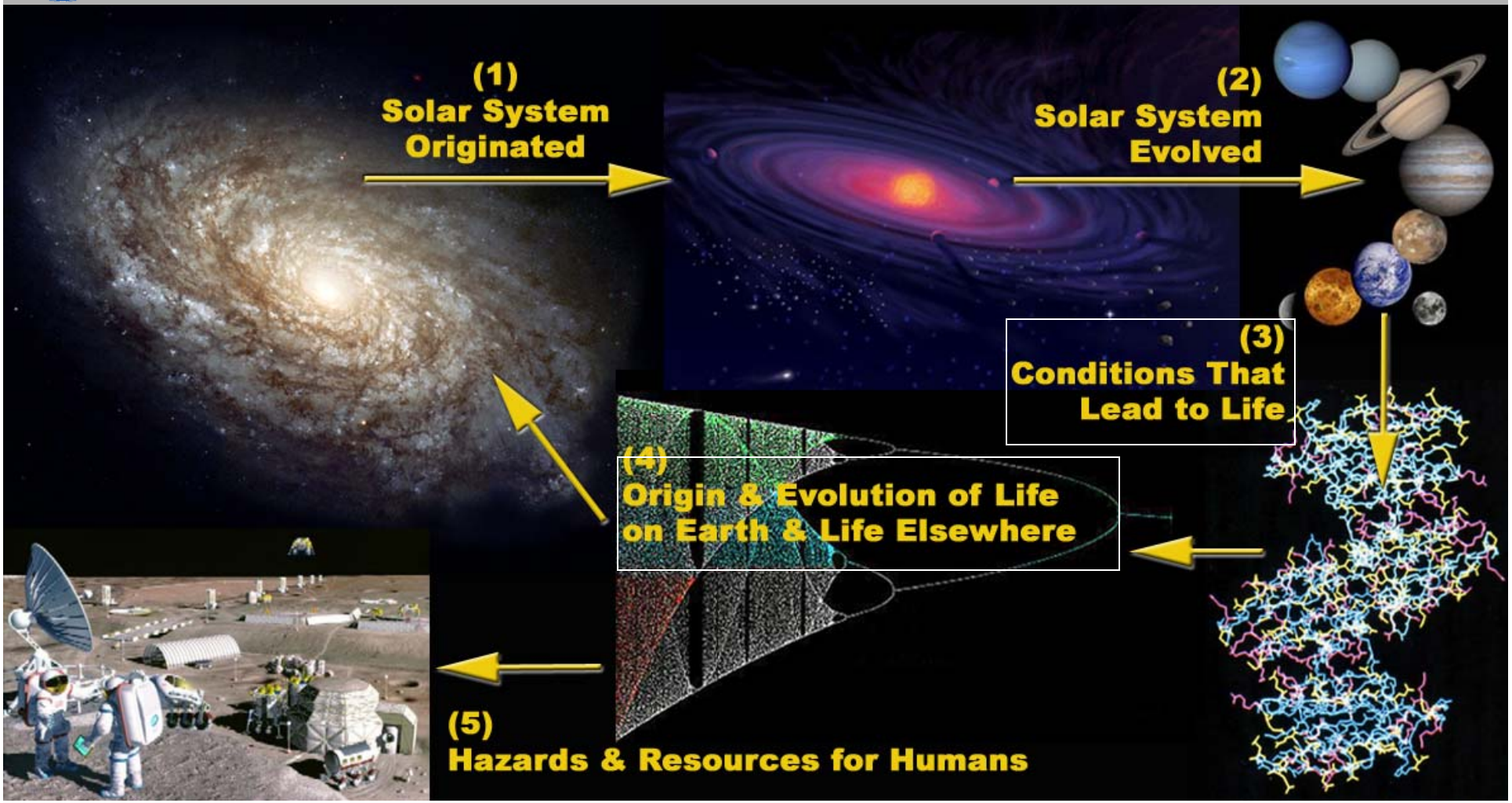


Unifying Theme: Habitability

Elements:

- **Habitability of worlds**
- **Architecture of planetary systems**
- **Hazards to Earth**

Solar System Roadmap Investigation Pathways



Underlying Theme: Habitability	Scientific Questions
• **Habitability of worlds** • **Architecture of systems** • **Hazards to Earth**	• How did the Sun's family and minor bodies originate? • How did the Solar System evolve to its current diverse state? • What are the characteristics of the Solar System the lead to the origin of life? • How did life begin and evolve on Earth and has it evolve elsewhere in the SS? • What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?

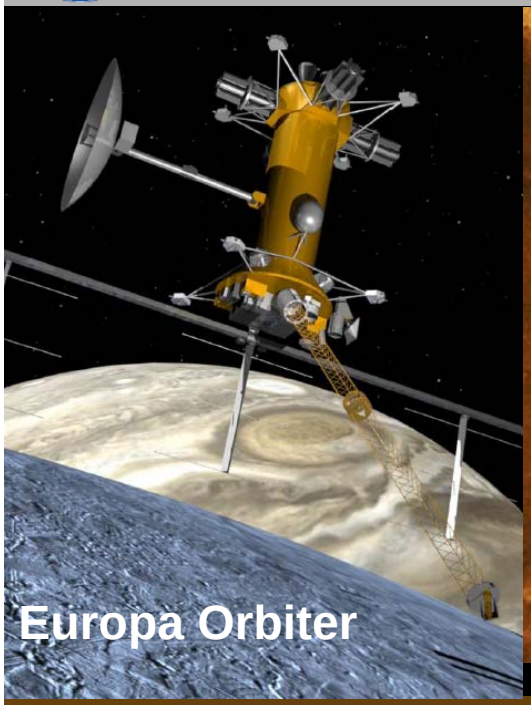
Missions to address these Science Goals

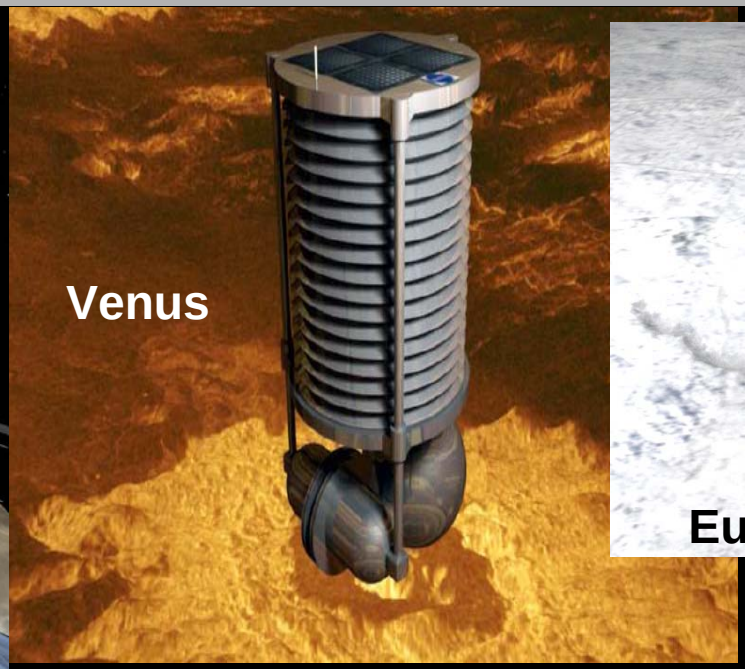
- Discovery
  - Competed missions
  - Cost cap of $425 (FY06)
  - Science objectives unconstrained

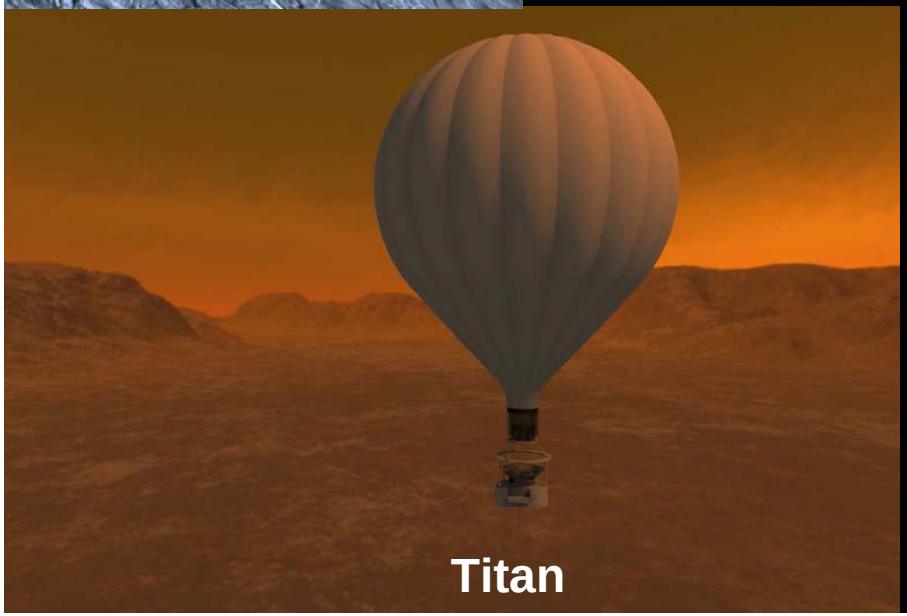
- New Frontiers Program
  - Competed missions
  - Cost cap of $700M (FY'03)
  - Targets and objectives specified by NASA

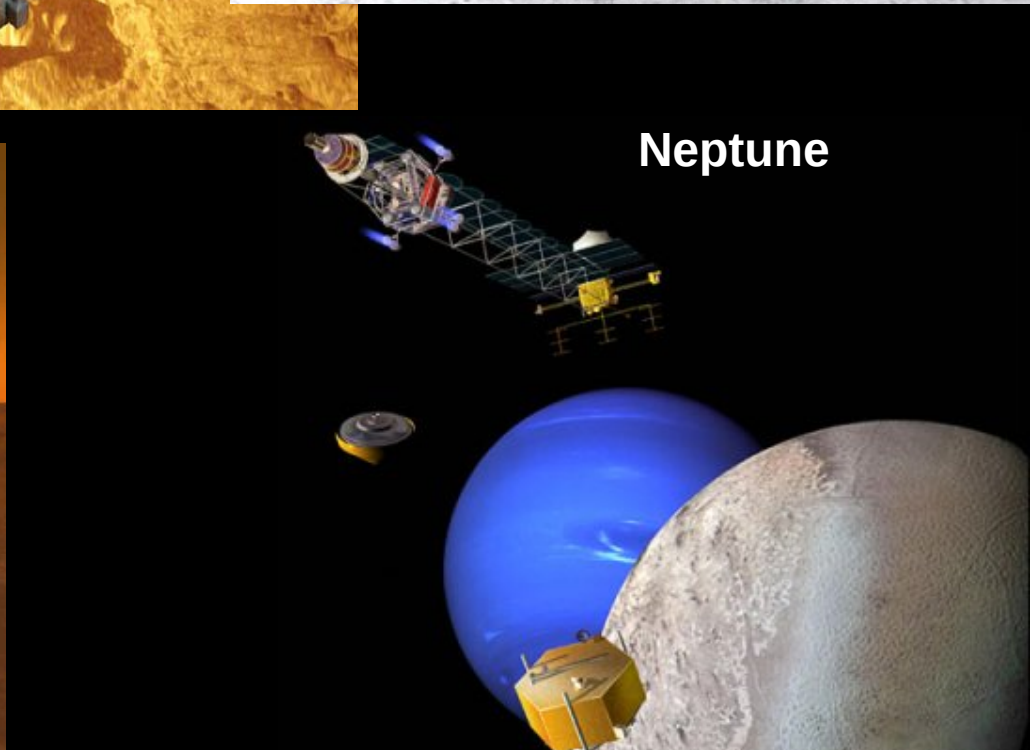
- Flagship or Strategic Missions
  - Assigned to a NASA Center
  - Two cost ranges recommended in the Roadmap
    - Small Flagship - $750 to $1.5B
    - Large Flagship - $1.5B to $3.0B

SOLAR SYSTEM ROADMAP: FLAGSHIP MISSION TARGETS









Science Traceability Matrix

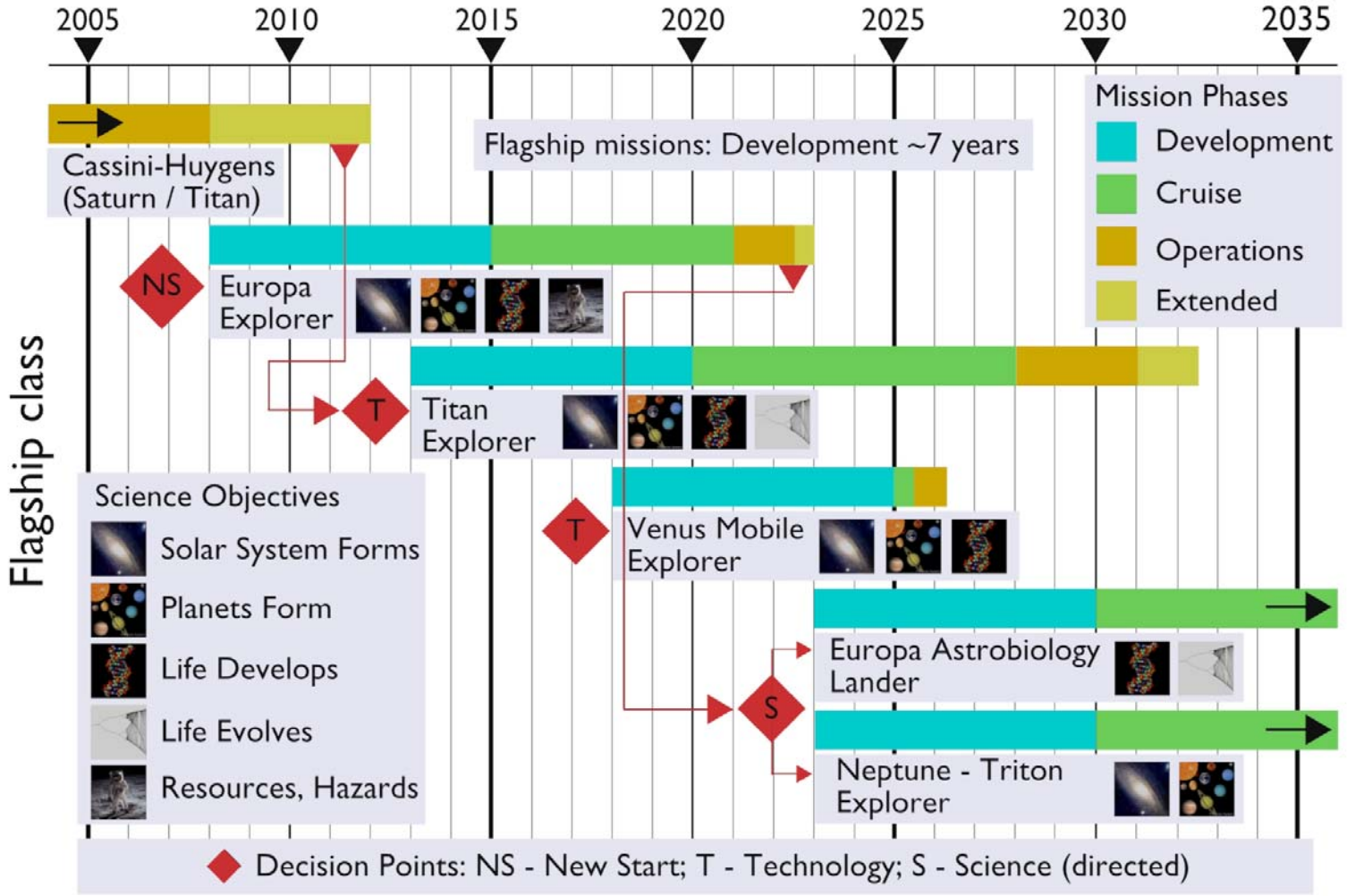
Major Questions	R&A		Discovery				New Frontiers						Flagship (Small/Large)							
Objectives	Expt.†	Theory	SB	Moon	Venus	Mercury	NH	Juno	SPABSR	VISE	CSSR	SP	C–H	EE	TE	VME	EAL	NTE	*CCSR**	*VSSR**
How did the Sun's family of planets and minor bodies originate?																				
Understand the initial stages of planetary and satellite formation	●	●	●	●	▲	▲	●	●	●		▲	●	▲	▲	▲	▲		●	●	●
Study the processes that determine the original characteristics of bodies in the Solar System	●	●	●	●		▲	▲	●	▲		●	●	▲	▲	▲			●	●	●
How did the Solar System evolve to its current diverse state?																				
Determine how the processes that shape planetary bodies operate and interact	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	●	●	●	●	●	●	●	●
Understand why the terrestrial planets are so different from one another	▲	▲			●	▲			▲	●						●				●
Learn what our Solar System can tell us about extrasolar planetary systems	▲	▲					▲	▲				▲	●	▲	▲	●		▲		●
What are the characteristics of the Solar System that led to the origin of life?																				
Determine the nature, history, and distribution of volatile and organic compounds in the Solar System	▲	▲	▲				●	●		▲	●	●	●	●	●	●	●	●	●	●
Determine evidence for a past ocean on the surface of Venus	▲	▲			▲					▲						●				●
Identify the habitable zones in the outer Solar System	▲	▲											●	●	●		●	●		
How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?																				
Identify the sources of simple													●	▲	●		●	▲	●	
													▲	▲	●		●			
																▲				●
ologic record to determine the historical relationship between Earth and its biosphere	●	▲																		
Identify environmental hazards and resources enabling human presence in space																				
Deter namic an in																				
Inven etary and protect human explorers																				

Convention: ● Major or Unique Contribution; ▲ Support Contribution

Flagship missions are required to address the MOST of the science objectives concerned with investigating the origin and evolution of life

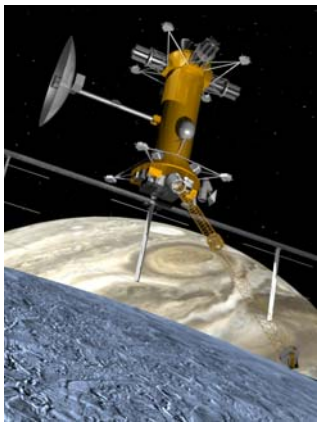
This requires a balanced program that includes Discovery, New Frontiers **AND Flagship class** missions

Recommended Sequence of Flagship Class Missions



Missions occur **twice per decade** with launches in **2015, 2020, 2025**, and **2030**. Red diamonds are decision points determining proceeding with the mission. Directed missions.

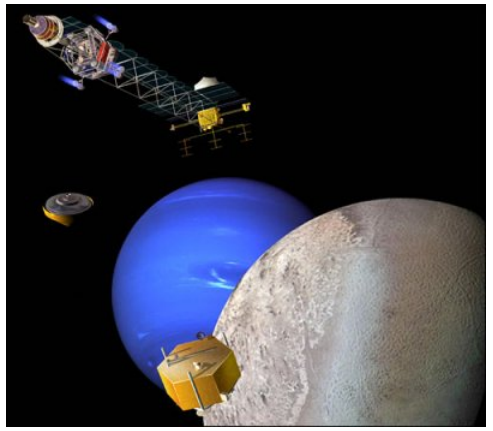
Solar System Strategic Roadmap
Flagship Missions – Nominal Mission Sequence



Europa Explorer

Titan – Enceladus Explorer

Venus Surface Explorer



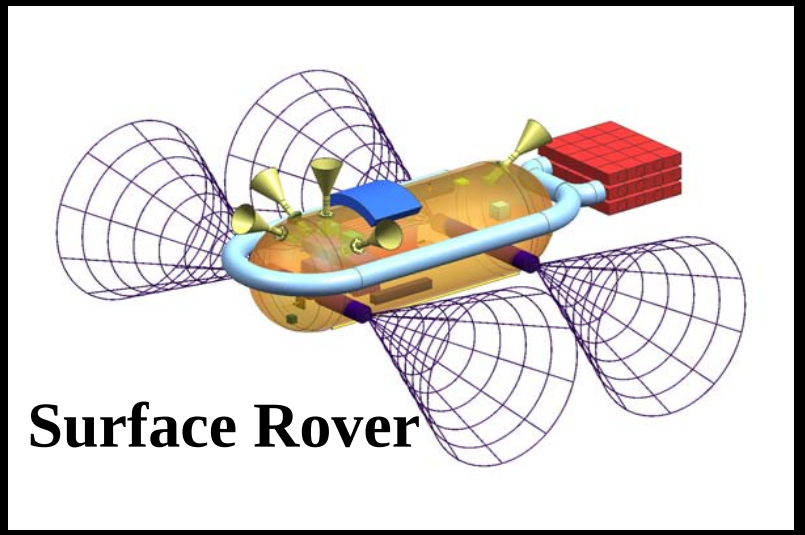
Neptune Triton Explorer

OR

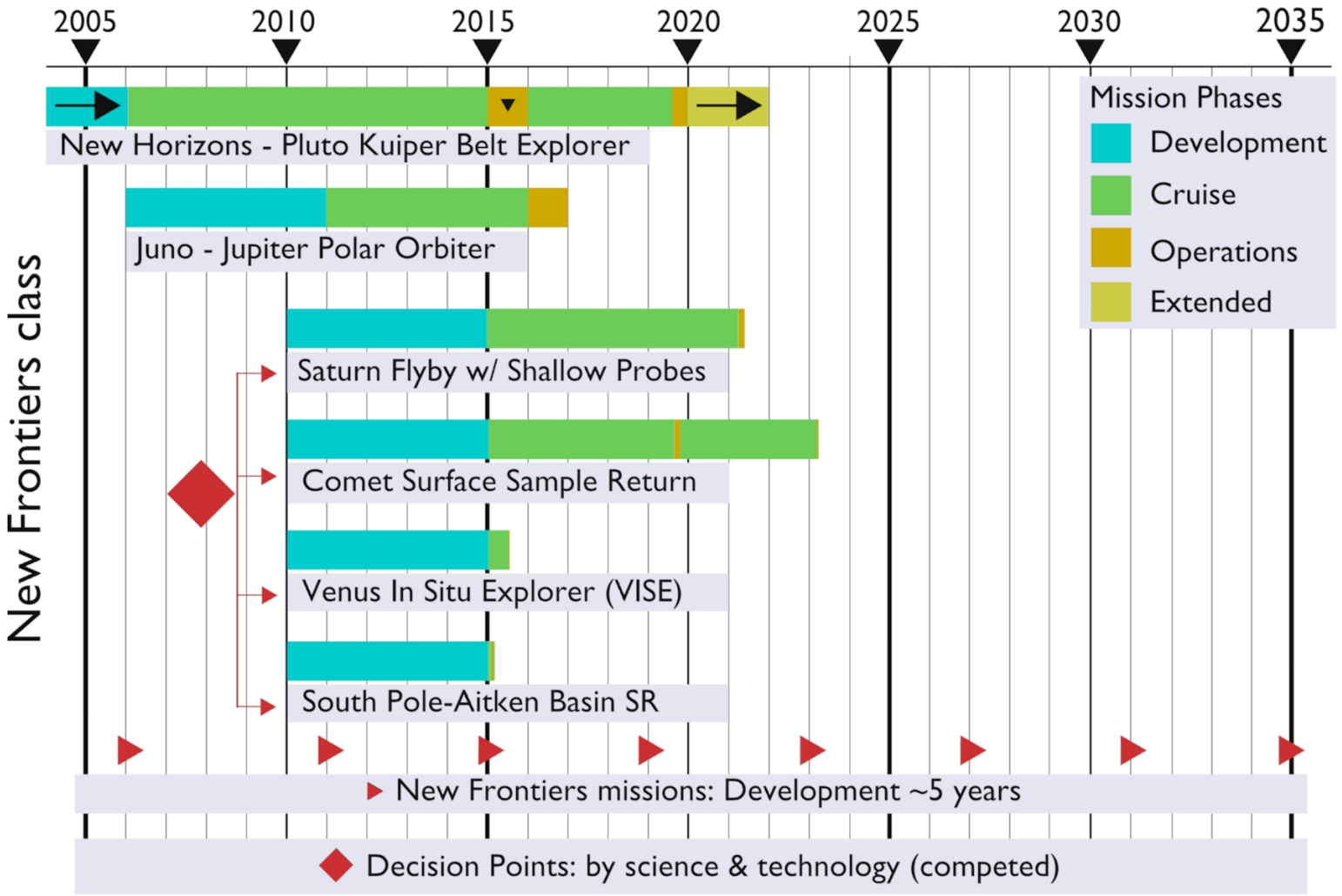
Europa Astrobiology Lander

Feasibility of accessing recent oceanic material (frozen or liquid)

Venus Mobile Explorer



Recommended Sequence of New Frontiers Missions



Missions occur ~3-4 times per decade. Competed missions.

The ▼ in the New Horizons – Pluto Kuiper Belt Explorer timeline represents the closest approach at Pluto on July 14, 2015

New Frontiers Program

1st NF mission
New Horizons:

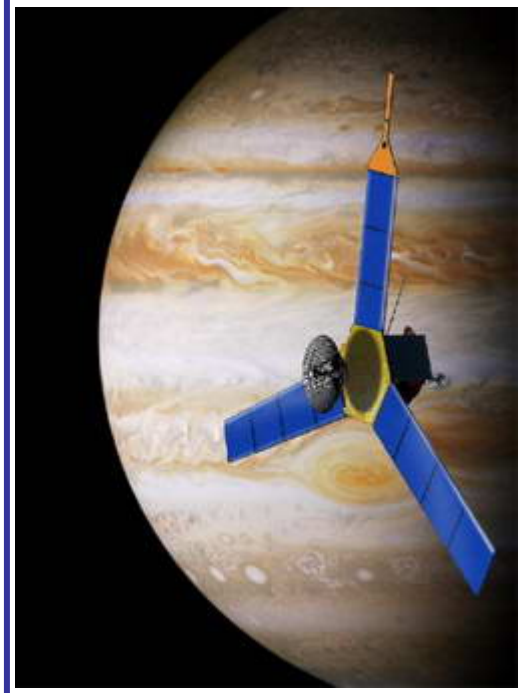
Pluto-Kuiper Belt Mission
(scheduled launch: Jan. 2006)

Pluto-KBO

NASA named New Horizons as the first mission in the series of New Frontiers missions for Solar System Exploration (2006 launch)

2nd NF mission
JUNO:

Jupiter Polar Orbiter Mission



2011 launch

3rd NF mission opportunity

Lunar South Pole – Aitken Basin Sample Return

Moon

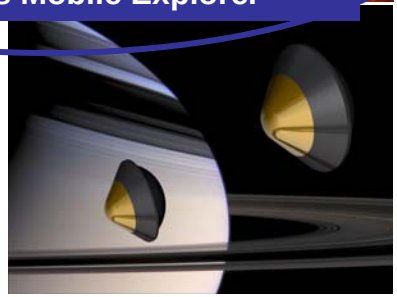
Comet Surface Sample Return (CSSR)

Comets

Venus In Situ Explorer (VISE)

Would precede Flagship Mission Venus Mobile Explorer

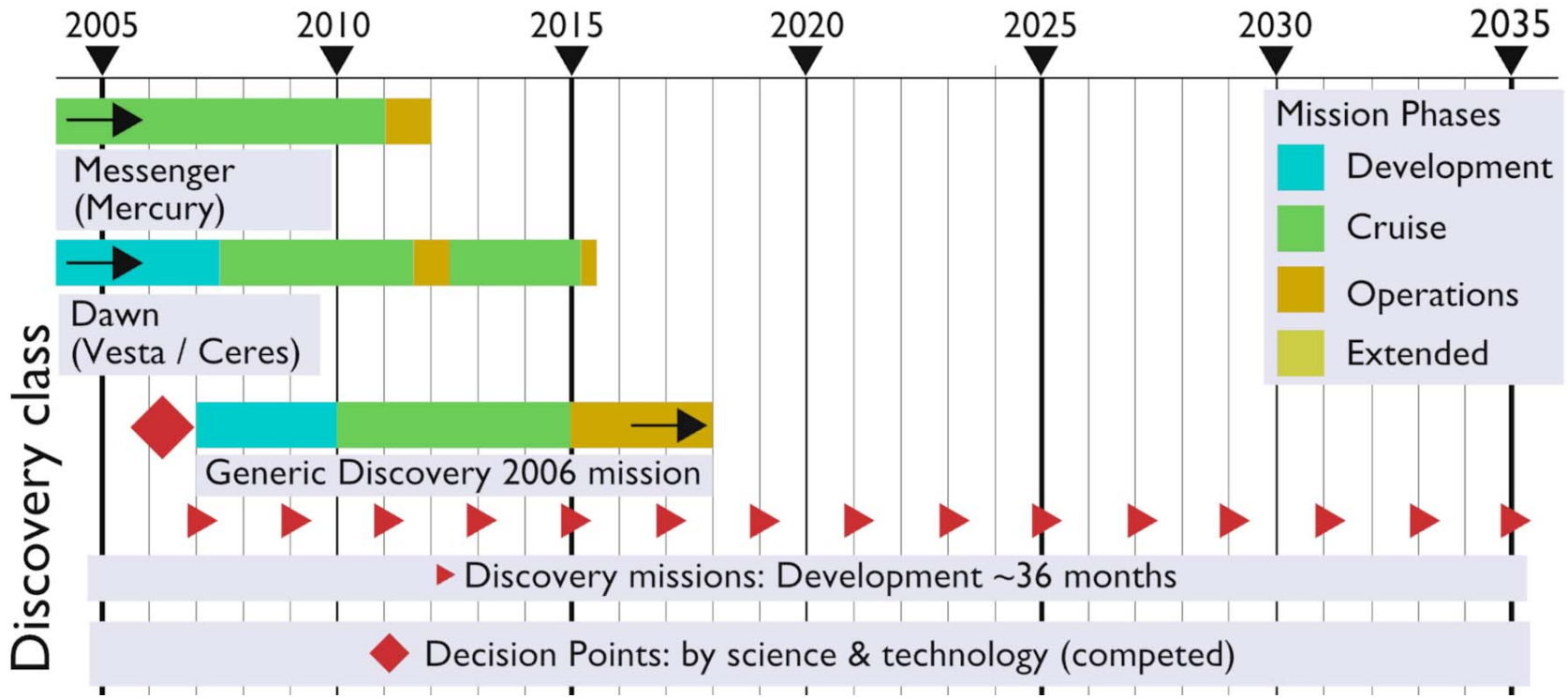
Saturn Flyby with Probes



Saturn

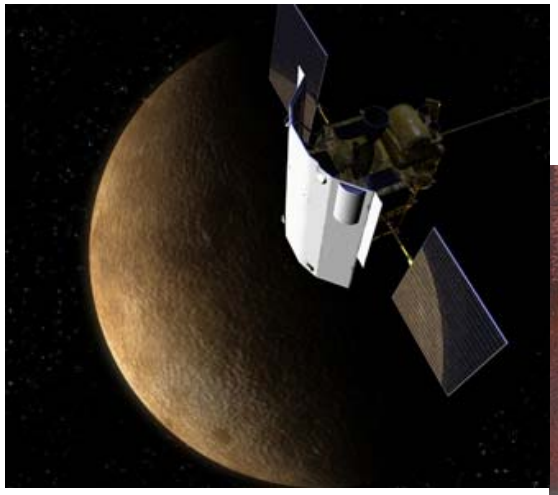
COMPLEX will now be reviewing these candidates and providing Guiding Principles to Planetary Science Division

Sequence of Discovery Class Missions



Missions occur ~4 to 7 times per decade.
Competed missions, missions are not pre-defined.

Discovery Class Missions



Messenger

Dawn

Origins Spectral Interpretation, Resource Identification and Security (OSIRIS) – *an asteroid sample return*

PI: Michael Drake of the University of Arizona, Tucson

Project Manager: NASA GSFC

Vesper - Venus chemistry and dynamics orbiter

PI: Gordon Chin of GSFC

Project Manager: NASA GSFC

Gravity Recovery and Interior Laboratory (GRAIL) - lunar orbiter

PI: Maria Zuber of MIT

Project Manager: JPL

Discovery 2006 selections

Status

- Solar System Roadmap is published in electronic form. It can be downloaded at http://solarsystem.jpl.nasa.gov
- NASA's Planetary Science Division recently decided to make print copies which will be distributed in January.
- Science Mission Directorate Strategic Plan, has already been influenced by the roadmap.
- NASA's Planetary Science Division recently announced their intent of initiating studies of strategic flagship missions to four outer planet satellite target: Europa, Titan, Enceladus and Ganymede.

Acknowledgements

Jonathan Lunine UA
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Andrea Belz
Craig Peterson

SSE ROADMAP TEAM

- Roadmap teams members for the
  - SRM3-2005, and
  - SRM3-2006
- Co-chairs:
  - SRM3-2005 Phase 1:
    Orlando Figueroa
    Scott Hubbard
    Jonathan Lunine
  - **SRM3-2006 Phase 2:**
    Jonathan Lunine
    James Cutts
    Melissa McGrath
- Team members from: NASA, Academia, Industry

2005	2006	Name	Affiliation
		Co–Chairs	
▲		Orlando Figueroa	NASA Science Mission Directorate
▲	●	G. Scott Hubbard	NASA Ames Research Center
▲	▲	Jonathan Lunine	University of Arizona Lunar & Planetary Laboratory
		Members	
●		Andrew Christensen	Northrop Grumman
●		Jerry Chodil	Ball Aerospace (retired)
●	●	Ben Clark	Lockheed Martin Astronautics
●		Greg Davidson	Northrop Grumman
●		David DesMarais	NASA Ames Research Center
●	●	Douglas Erwin	National Museum of Natural History
●		Wes Huntress	Carnegie Institution of Washington
●	●	Torrence V. Johnson	Jet Propulsion Laboratory
●		Thomas D. Jones	Consultant
●	▲	Melissa McGrath	NASA Marshall Space Flight Center
●	●	Karen Meech	University of Hawaii
●	●	John Niehoff	Science Applications International Corporation
●	●	Robert Pappalardo	University of Colorado; Jet Propulsion Laboratory
●	●	Ellen Stofan	Proxemy Research, Inc.
●	●	Meenakshi Wadhwa	The Field Museum
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●		Carl Pilcher	Directorate Coordinator, Designated Federal Official
●		Judith Robey	Advanced Planning and Integration Office Coordinator
		Ex Officio and Liaison	
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●		Chris Jones	Jet Propulsion Laboratory
●		Jason Jenkins	NASA Exploration Systems Mission Directorate
●		Gregg Vane	Jet Propulsion Laboratory
●		Charles Whetsel	Jet Propulsion Laboratory
		Planetary Program Support	
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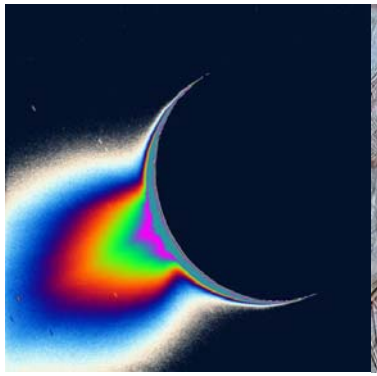
	●	Tibor Balint	Jet Propulsion Laboratory
	●	Andrea Belz	Jet Propulsion Laboratory
	●	Craig Peterson	Jet Propulsion Laboratory
	●	Philippe Crane	NASA HQ
	●	Curt Niebur	NASA HQ
▲ — co–chairs ; ● — team members			

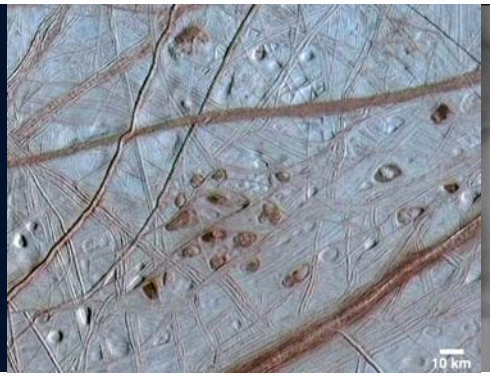
Backup Charts

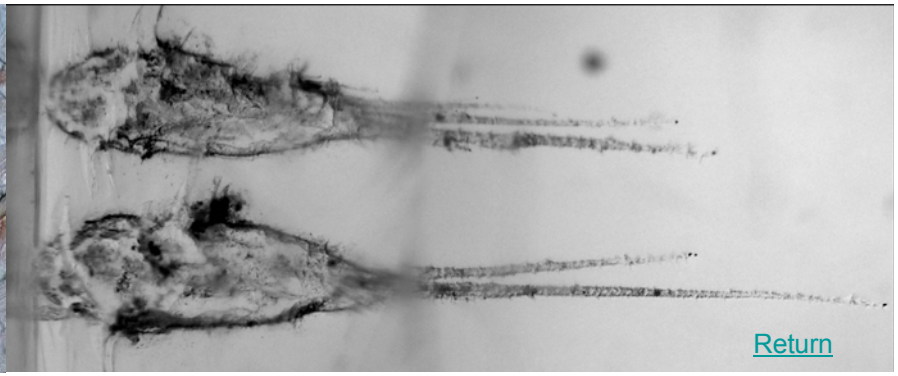
- Science Questions

Question Three: What are the characteristics of the Solar System that led to the origin of life?

Objectives	Investigations and Measurements
Determine the nature, history, and distribution of volatile and organic compounds in the Solar System	• Analyze the chemical and isotopic composition of comets. • Determine Jupiter's water abundance and deep atmospheric composition. • Determine the chemical and isotopic composition of Venus' surface and atmosphere. • Determine the distribution of organic material on Titan and Enceladus.
Determine the evidence for and age of an ocean on the surface of Venus	• Search for granitic and sedimentary rocks. • Analyze the mineral composition of hydrated silicates and oxidized iron. • Investigate the interplay of volcanic activity and climate change.
Identify the habitable zones in the outer Solar System	• Characterize the geothermal zones on Enceladus. • Search for volcanically–generated and impact–generated hydrothermal systems on Titan. • Confirm the presence and study the characteristics of Europa's subsurface ocean. • Conduct comparative studies of the Galilean satellites.



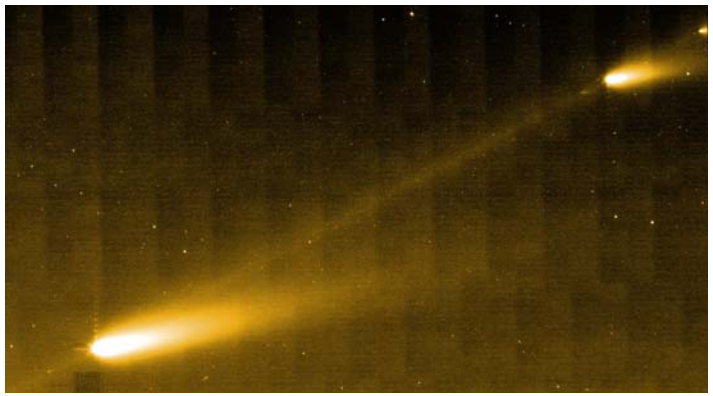


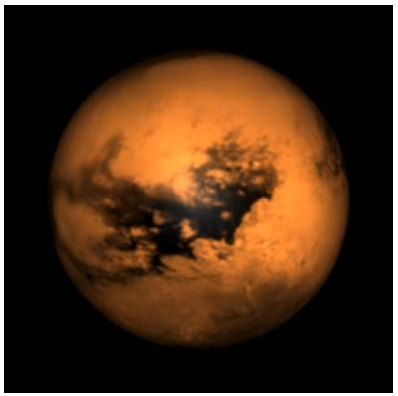


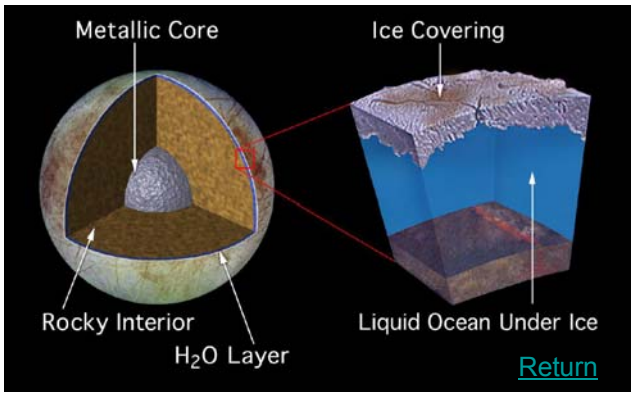
Return

Question Four: How did life begin and evolve and has it evolved elsewhere in the Solar System?

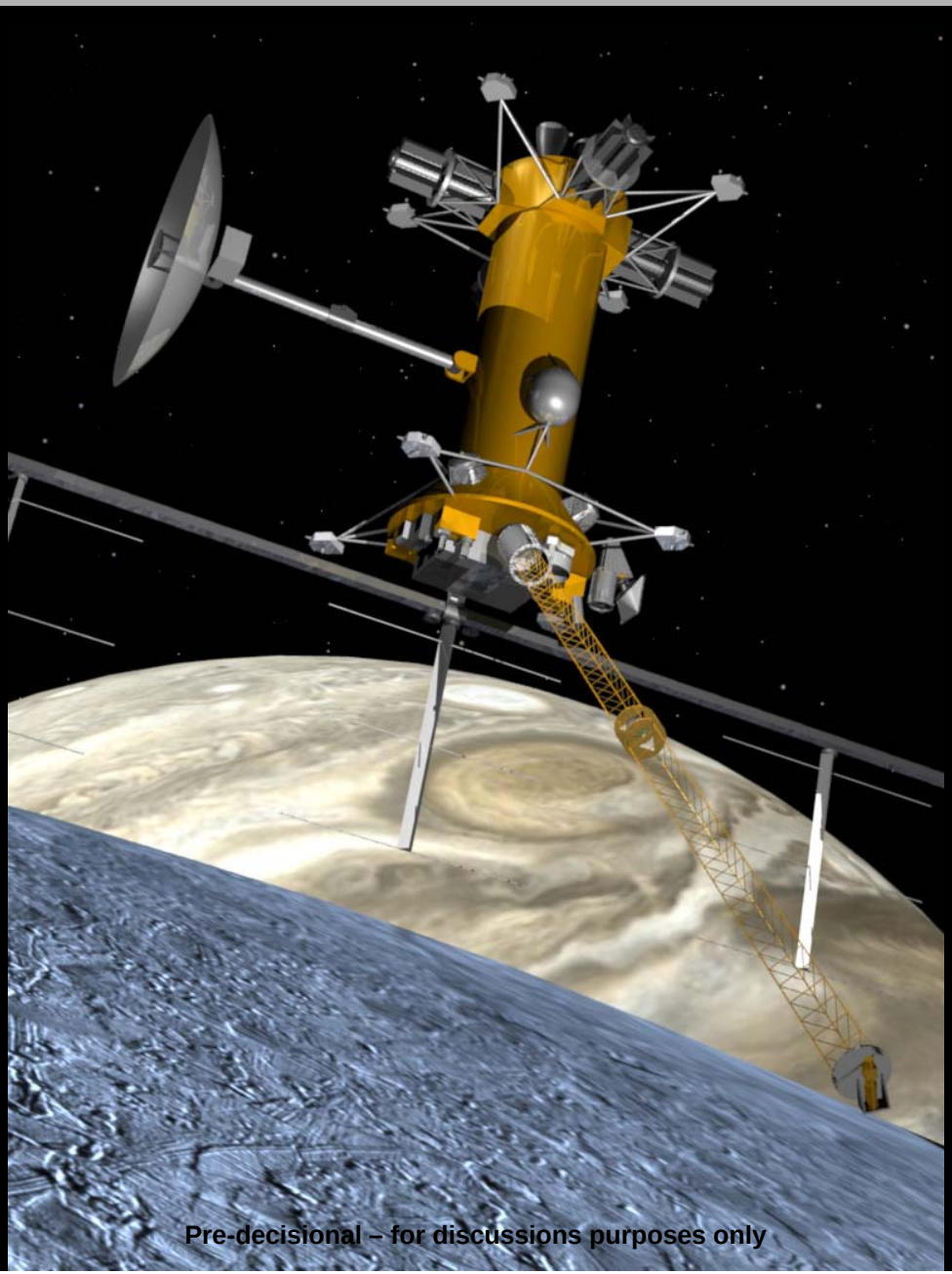
Objectives	Investigations and Measurements
Identify the sources of simple chemicals important to prebiotic evolution and the emergence of life	• Determine the chemical composition of comets and Kuiper Belt objects. • Study surface organic deposits on Titan, and interaction of surface with atmosphere.
Search for evidence for life on Europa, Enceladus, and Titan	• Identify and study organic deposits from the subsurface ocean on Europa. • Study biomarker signatures in surface organics in active/recently active areas on Titan. • Sample subvent fluids for biological activity.
Search for evidence for past life on Venus	• Search Venus samples for chemical and structural signatures of life.
Study Earth's geologic and biologic record to determine the historical relationship between Earth and its biosphere	• Investigate biological processes on the early Earth through multidisciplinary studies. • Examine the records of the response of Earth's biosphere to extraterrestrial events.





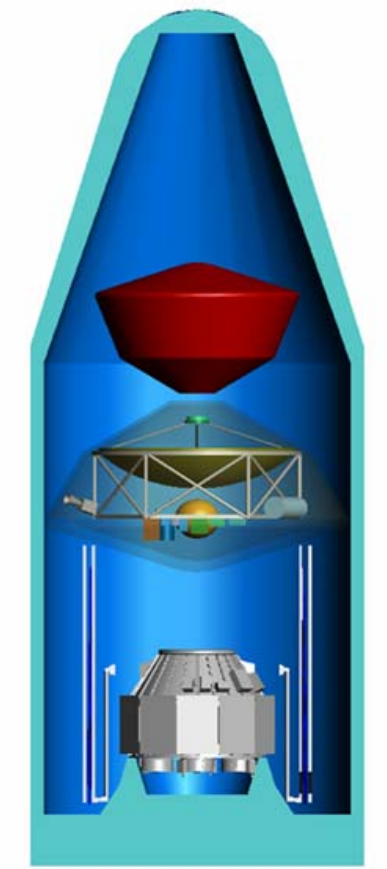


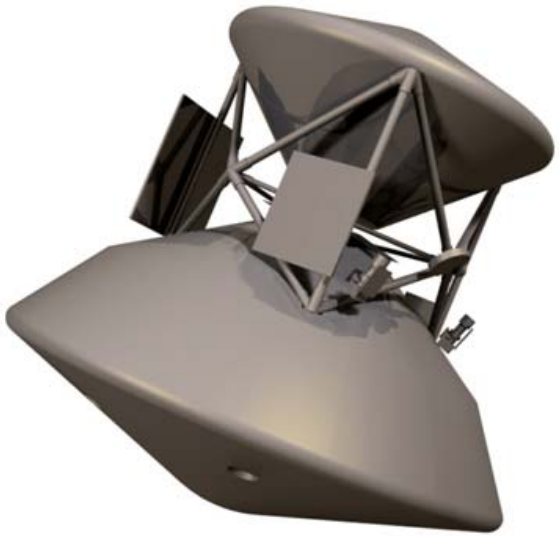
Europa Explorer

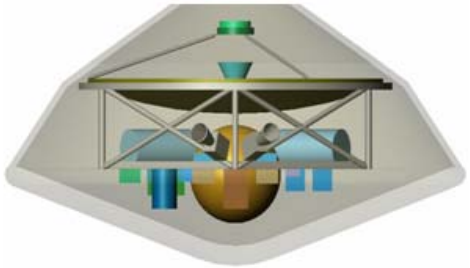


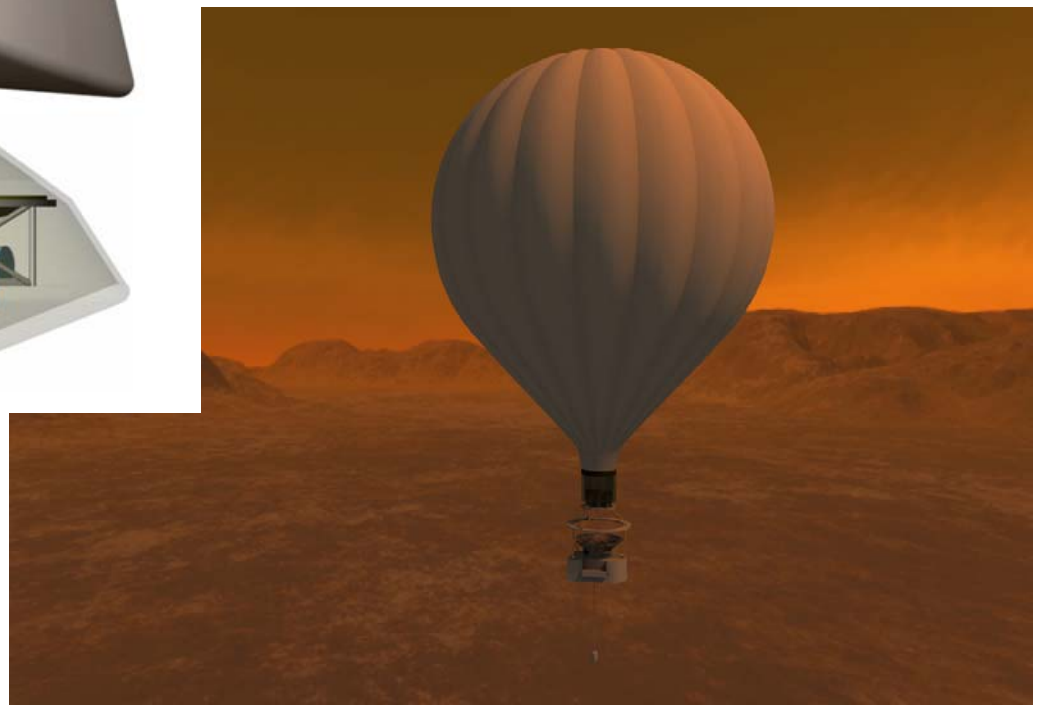
Pre-decisional – for discussions purposes only

Titan Enceladus Explorer

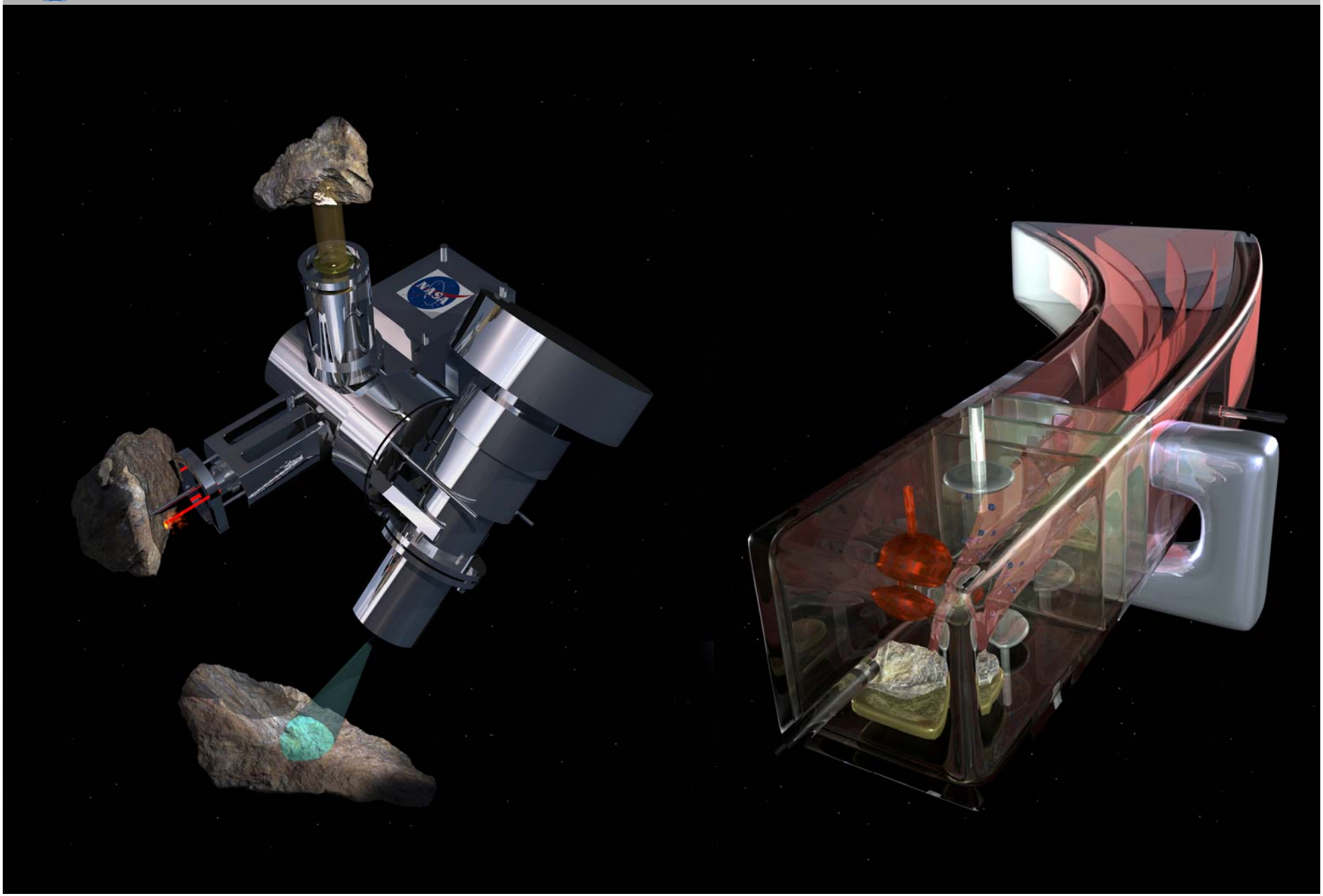


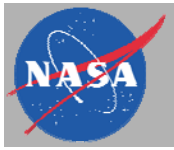






TECHNOLOGY DEVELOPMENT NEEDS





Technology

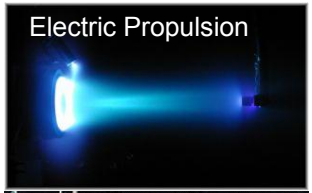
- Successful execution of the Roadmap's prioritized sequence of missions requires a *coordinated technology development program synchronized with mission plans*

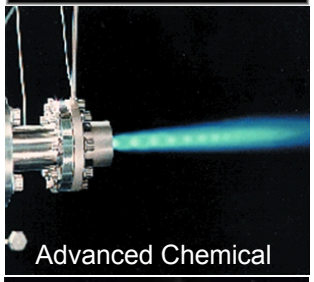
- Investment in *power generation, technologies for extreme environments and aerocapture technology* would
  - *reduce costs* for multiple missions
  - enable exploration of targets of greatest interest to the *habitability* theme driving the roadmap

- An *early investment in technology development* would have a dramatic impact on the cost and risk of the recommended Flagship mission set.

Systems Technologies

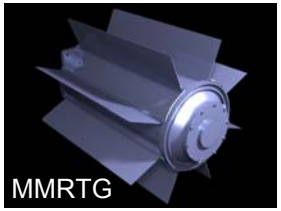
In-Space Propulsion
Electric Propulsion (EP);
Advanced Chemical Prop.;
Aerocapture

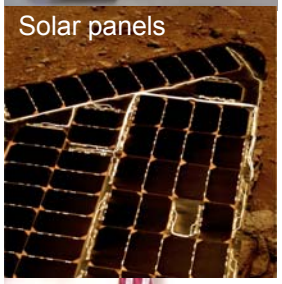


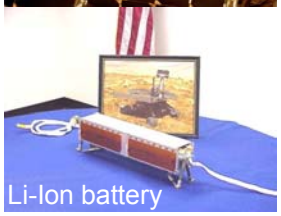


Communications
DSN & Proximity comm.

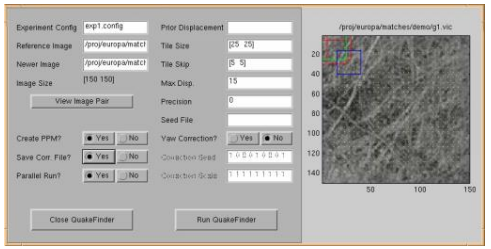
Power Systems
MMRTG; Adv. RPS;
LILT / Adv. Solar;
Adv. Power Storage
(Fission is not required)



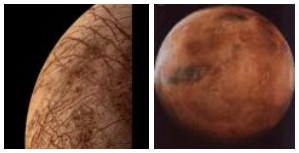




Software
Autonomy; Fault Protection



Planetary Protection
Forward Protection
Return Sample Handling



Viking
Contamination
Control

Stardust
Return Capsule

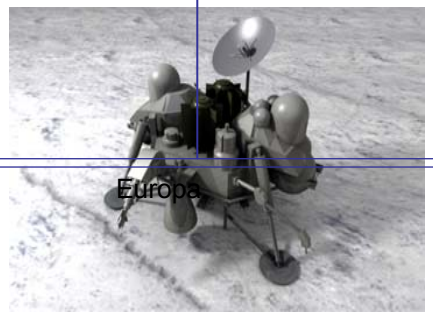
In-Situ Exploration Technologies

Mobility

Aerial mobility (Titan, Venus);
Surface (Titan, Venus, Europa);
Subsurface exploration & sampling


Titan balloon

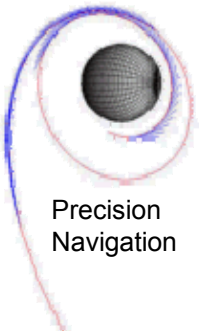

Venus metal bellows

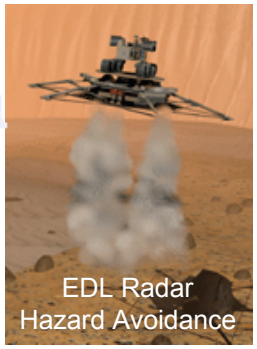

Europa

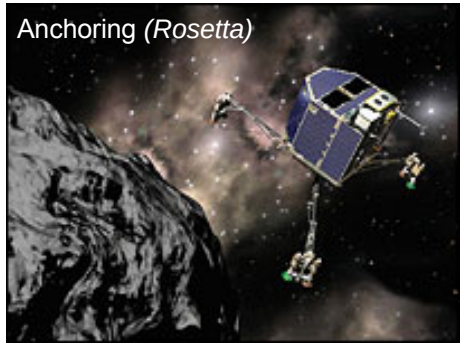
EAL drill

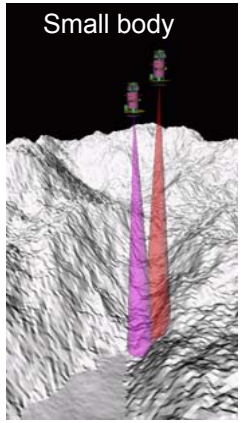
Entry – Descent – Landing (EDL)

Precision navigation & landing; Approach guidance;
Hazard avoidance; Anchoring to small bodies


Precision Navigation

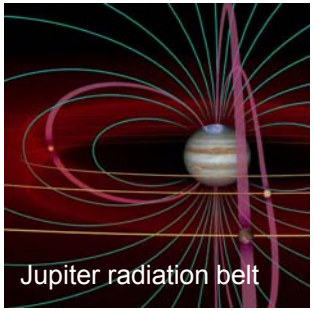

EDL Radar Hazard Avoidance


Anchoring *(Rosetta)*

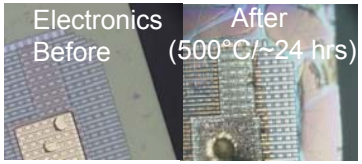

Small body

Extreme Environments

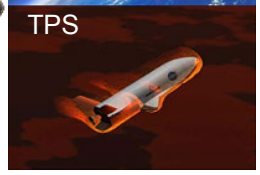
High pressure & temperature; Low temperature;
High radiation; High entry heat flux

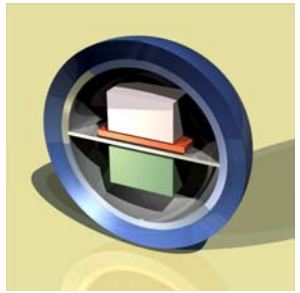

Jupiter radiation belt


Aerogel


Electronics Before

After (500°C/~24 hrs)


TPS

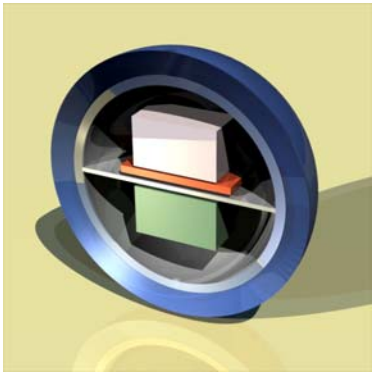

Pressure vessel / Thermal management

Venus In-situ Exploration Technologies

Materials

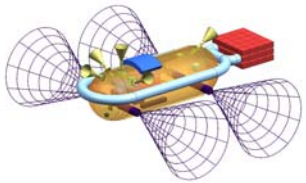
Power: for long missions
Stirling w/ active cooling

Thermal management



Pressure vessel

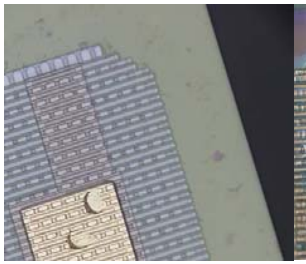
Mobility:
- Metallic bellows
- Surface mobility

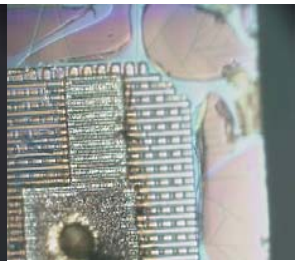


Technologies to mitigate extreme environments
460°C / 90 bar

Sample acquisition:

High T electronics:





Before

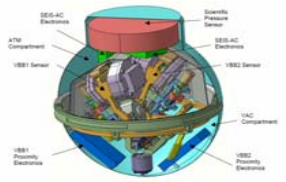
After
(500°C/~24 hrs)

Telecom / DSN

Science Instruments

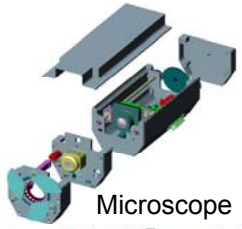
In-Situ Exploration Components

Detectors; sensors; GC/MS; Raman; LIBS, Cameras etc.

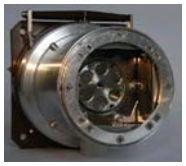

Seismometer

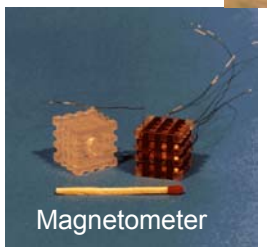

PanCam

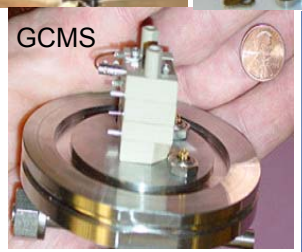
Rad


Microscope


APXS



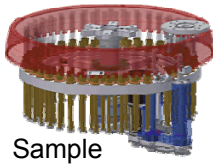

Magnetometer


GCMS


OD

Sample Acquisition & Contact Instr.

Drills; RAT; corer; etc.


Sample processing


RAT


Mini-corer


Ultrasonic drill

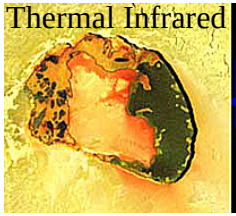

Phoenix arm

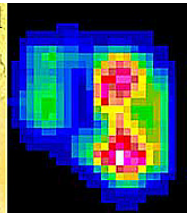

MARTE drill

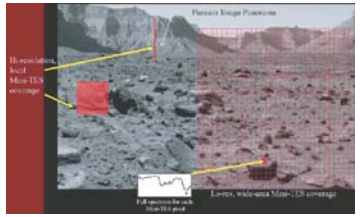
Miniaturization
Reduced power
Sensitivity/Resolution

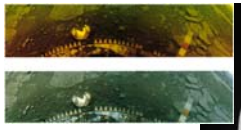
Passive Remote Sensing

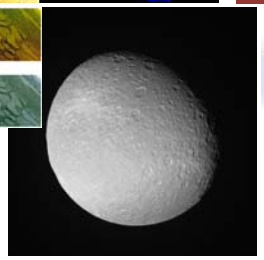
Thermal infrared; TES; optical etc.





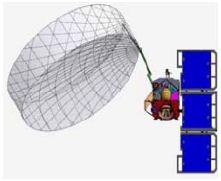


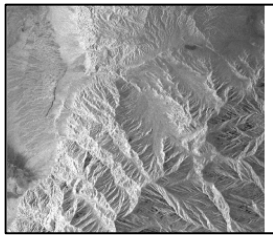

Optical imaging

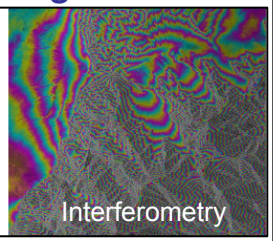


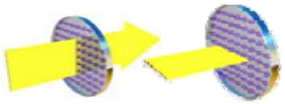

Thermal Emission Spectrometer

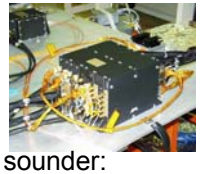
Active Remote Sensing


Decimeter SAR

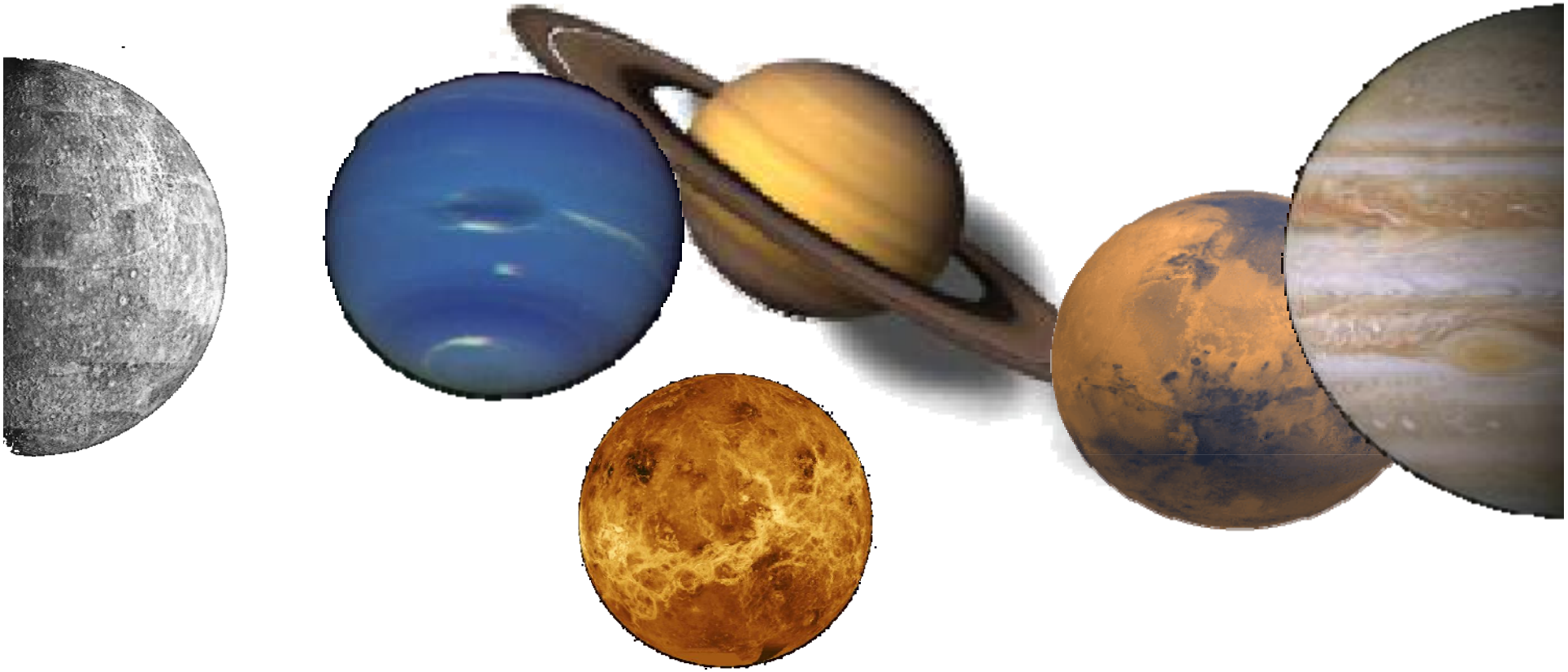



Interferometry


Polarimetry


MARSIS sounder: transmit/receive boxes

INTERDEPENDENCIES



Major Goal of Road Map process was to understand interdependencies WITHIN the solar system exploration roadmap and WITH OTHER ROADMAPS – particularly those for Mars and the Moon

Interdependencies Among Missions Classes

- Within the Flagship Program
  - Cassini → Titan / Enceladus Explorer
  - Europa Explorer → Europa Astrobiological Laboratory
  - Titan Explorer → Neptune–Triton Explorer (*re: Aerocapture*)
- Between the New Frontiers and Flagship Programs
  - Venus In Situ Explorer (New Frontiers) → Venus Mobile Explorer (FS) *(re: Extreme Environments technologies)*
  - Saturn Flyby with Shallow Probes (New Frontiers) → Neptune–Triton Explorer (FS) *(re: Thermal Protection Systems)*
  - Comet Surface Sample Return (New Frontiers) → Comet Cryogenic Sample Return (FS)
- Among the Discovery, New Frontiers, and Flagship Programs
  - Dawn → Titan Explorer & Neptune–Triton Explorer *(re: SEP)*
  - Deep Impact → Comet Surface Sample Return

Interdependences with Mars and Lunar Robotic Programs

- SSE & Mars Exploration Program
  - Mars Reconnaissance Orbiter → Europa Explorer *(re: remote sensing; high resolution imaging; radar sounding; communications)*
  - Mars Science Laboratory → Titan Explorer (orbiter) *(re: active trajectory control; RPS thermal management; New Millennium flight demonstration for aerocapture)*
  - Mars Science Laboratory → Titan Explorer (aerial platform) *(re: sample acquisition & processing; autonomous control; RPS)*

- SSE & Robotic Lunar Exploration Program
  - Lunar Reconnaissance Orbiter *(re: instrument development)*
  - Lunar Crater Observation and Sensing Satellite (LCROSS) *(re: impactors for Europa, outer planet satellites)*

ROADMAP IMPLEMENTATION

Key Recommendations

- A Flagship program should be implemented with missions every five years comprised of:
  - Small Flagship missions - up to $1.5B ($FY06)
  - Large Flagship missions – up to $3.0B ($FY06)

- To help support the cost of this program the flight rate of cost capped missions recommended by the NRC Decadal Survey might be reduced
  - Discovery from 7 to 4 per decade
  - New Frontiers from 4 to 2 per decade

- The highest priority Flagship mission is Europa Explorer

- NASA should attempt to establish a wedge for funding a Europa Explorer new start and a technology program.

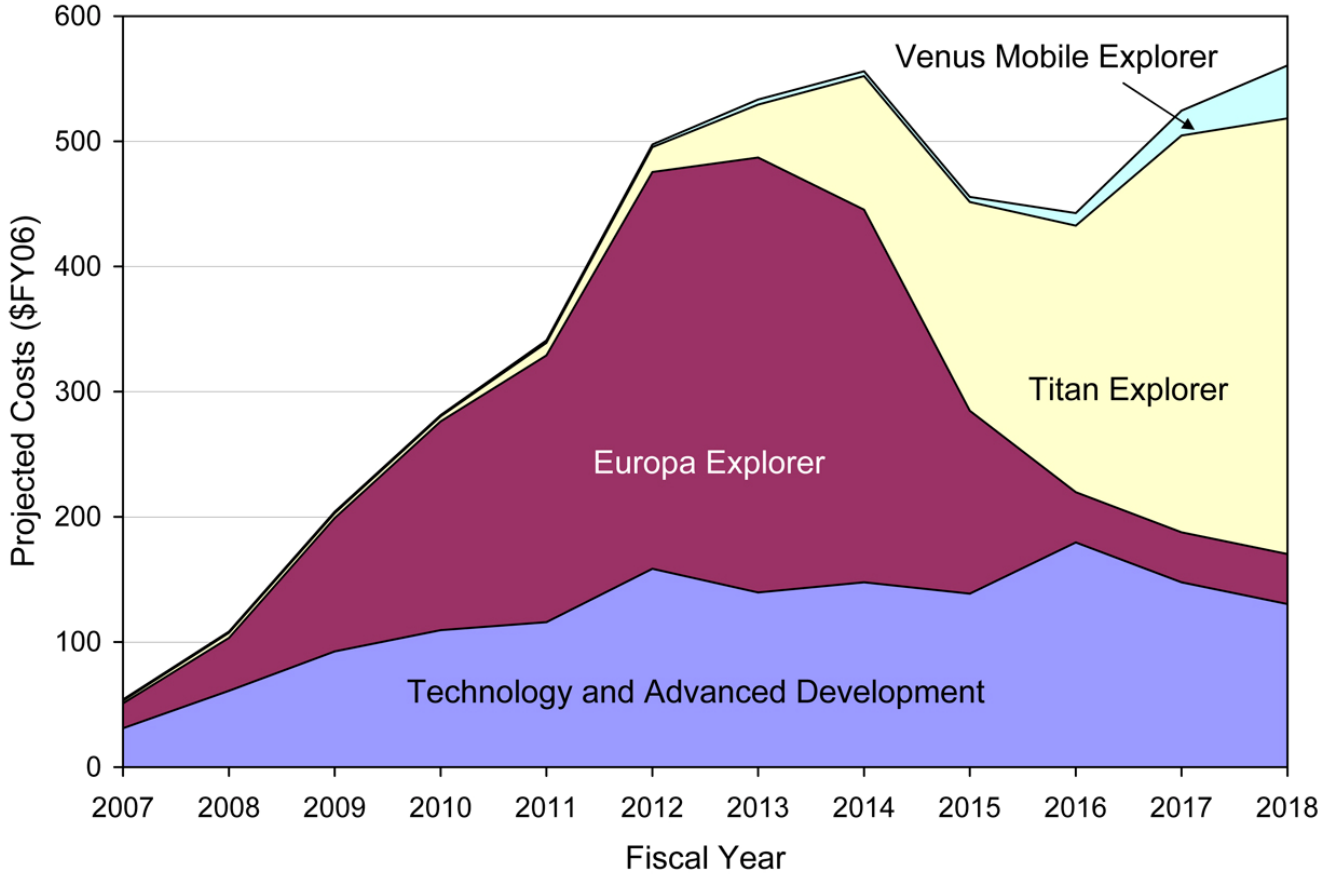
Trade Space of Flight Rates

Mission Class	Missions per Decade					
	NRC DS 2003	SSE-RM 2003	SRM3-2006 (This Roadmap)			
			Option A	Option B	Option C	Option D
Discovery	*7*	*7*	**7**	**7**	**6**	**4**
New Frontiers	*4*	*3*	**4**	**4**	**3**	**2**
Small Flagship	⊗	⊗	**0**	**2**	**1**	**0**
Large Flagship	*1*	⊗	**1**	**0**	**1**	**2**
Prometheus	⊗	*1*	⊗	⊗	⊗	⊗
Mission Class	**Cost Per Decade ($B)**					
	NRC DS 2003	SSE-RM 2003	SRM3-2006 (This Roadmap)			
			Option A	Option B	Option C	Option D
Discovery	*2.8*	*2.8*	**3.0**	**3.0**	**2.6**	**1.7**
New Frontiers	*2.8*	*2.1*	**3.0**	**3.0**	**2.3**	**1.5**
Small Flagship	⊗	⊗	**0**	**3.0**	**1.5**	**0**
Large Flagship	*N/A*	⊗	**3.0**	**0**	**3.0**	**6.0**
Prometheus	⊗	*11.0*	⊗	⊗	⊗	⊗
Total Cost per Decade*			**9.0**	**9.0**	**9.3**	**9.2**

Note: * The cost per decade includes direct mission costs only and not the R&A and technology development programs.

A balanced program can be achieved in multiple ways, that includes Discovery, New Frontiers and Flagship class missions

Investment Needs for SSE Roadmap Program of Flagship Missions



Baseline scenario assumption: **first mission** — **Europa Explorer** — is launched in **FY15**.

The **technology and advanced development** investment is targeted primarily at the second and third missions, **Titan Explorer and Venus Mobile Explorer**, which **require investments prior to the key decision points in 2010 and 2015**.

The total annual budget would include other programs (e.g., Discovery, New Frontiers); Research and Analysis; and Education & Public Outreach; in addition to this Flagship program investments

Future Challenges

- Managing a healthy debate in the planetary science community on the priorities for Flagship missions.

- Developing a stronger consensus in the science community on the importance of a long term strategy to for future progress in solar system exploration

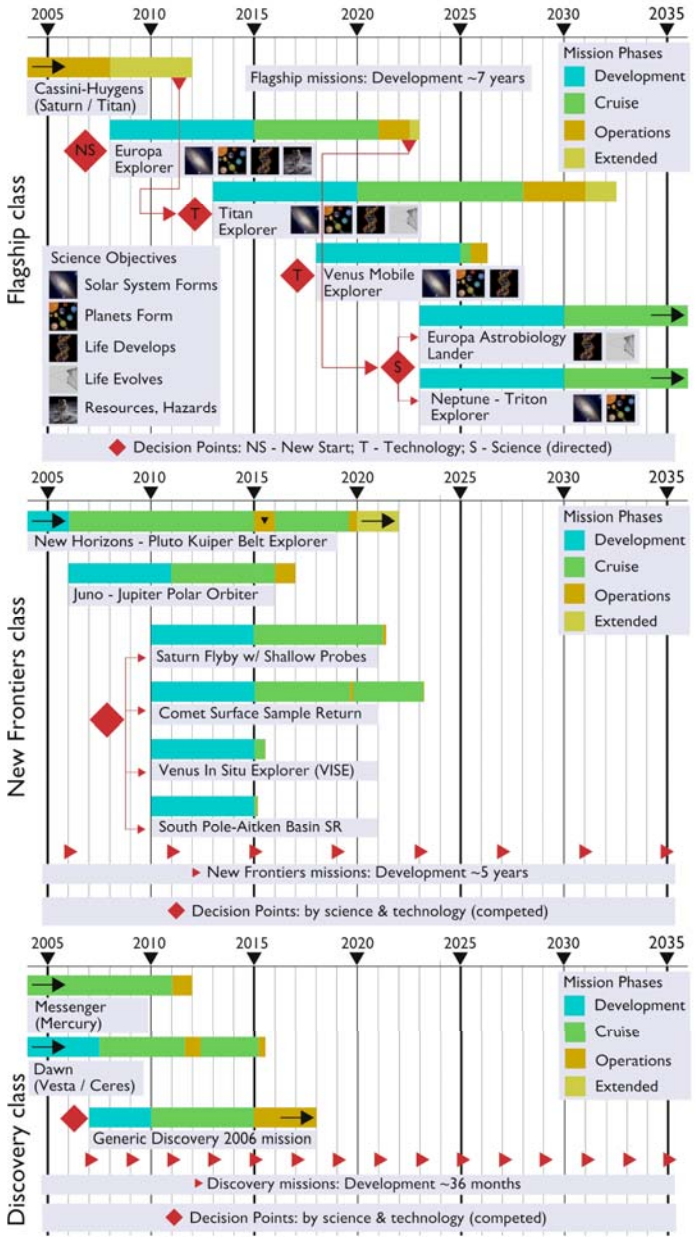
- Getting a solar system exploration Flagship mission and an effective technology program in the NASA budget

Backup Charts

- Consolidated Road Map
- Foundation Materials

Consolidated Roadmap

- Strategic Roadmap Process
- Science Objectives
- Proposed Missions
- Technology Development for SSE
- Research and Analysis (R&A)
- Education and Public Outreach (E/PO)
- Interdependencies
- Roadmap Implementation
- Conclusions and Recommendations

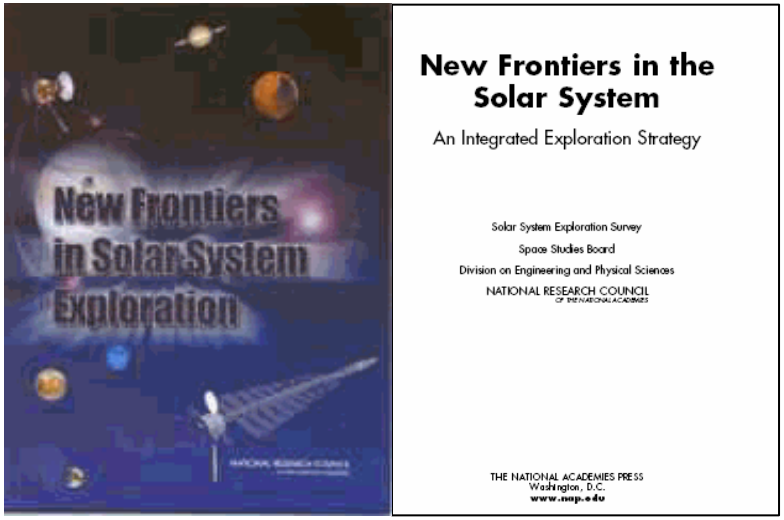


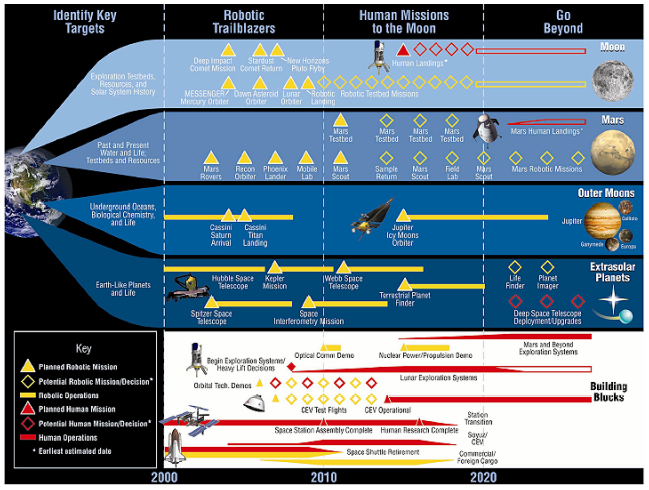
Reference:
SSE Roadmap Team, "Solar System Exploration; This is the Solar System Exploration Roadmap for NASA's Science Mission Directorate," National Aeronautics and Space Administration, Science Mission Directorate, Planetary Science Division, Report Number: JPL D-35618, September 15, 2006
Website: solarsystem.nasa.gov

Solar System Exploration Roadmap Foundation Materials

- New Frontiers in the Solar System - NRC Decadal Survey of 2003
  - Science strategy
  - First Decade - recommended mission set
  - Second Decade – mission options
  - Technology needs
- Solar System Exploration Roadmap of 2003
  - Accepted most but not all Decadal Survey recommendations
- Vision for Space Exploration – 2004
- Design Reference Missions set
  - reflecting an updated assessment of the range of mission candidates

NRC DS





Vision for Space Exploration 2004

SSE RM 2003