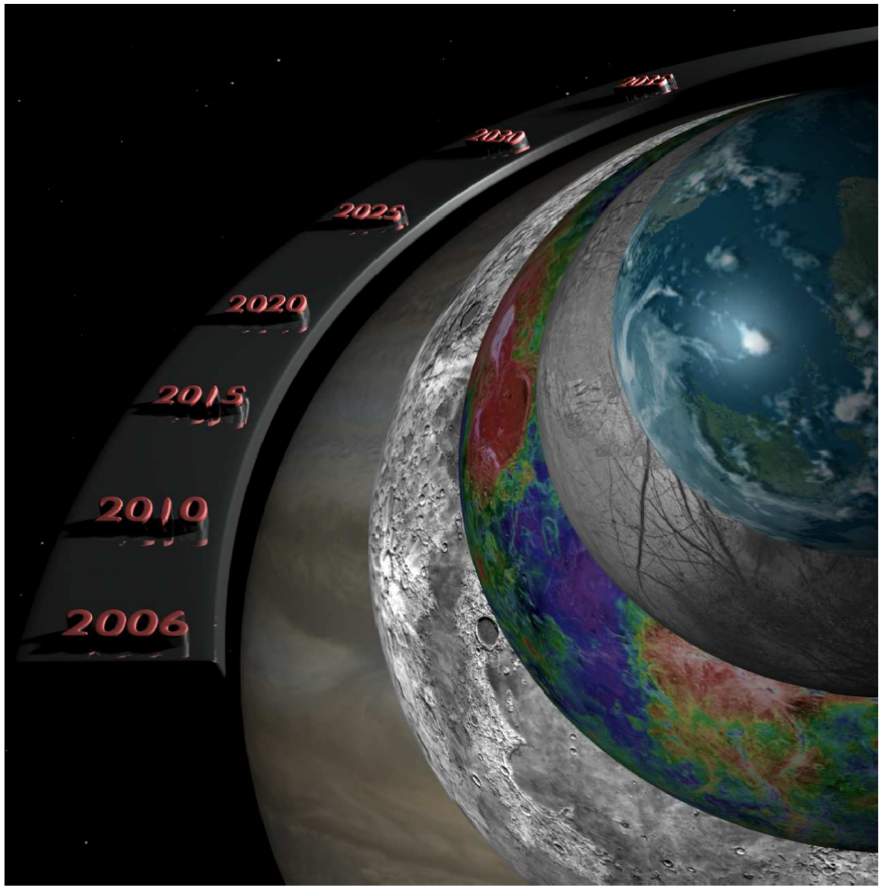
NASA No.XXX

Solar System Exploration

(Draft — Revision 7-8)

This is the 2006 Solar System Exploration Roadmap
for NASA's Science Mission Directorate



Jonathan Lunine
Jim Cutts
Melissa McGrath
Scott Hubbard
Orlando Figueroa
and
The Roadmap Team

2005	2006	Name	Affiliation
		Co–Chairs	
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▲	▲	Jonathan Lunine	University of Arizona Lunar & Planetary Laboratory
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●		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
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●	●	Ellen Stofan	Proxemy Research, Inc.
●	●	Meenakshi Wadhwa	The Field Museum
		Advanced Planning and Integration Support	
●		Carl Pilcher	Directorate Coordinator, Designated Federal Official
●		Judith Robey	Advanced Planning and Integration Office Coordinator
		Ex Officio and Liaison	
●		Andrew Dantzler	NASA Science Mission Directorate
●	●	Heidi Hammel	Space Science Institute, Education Roadmap Committee Liaison
●		Chris Jones	Jet Propulsion Laboratory
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	●	Curt Niebur	NASA HQ

▲ — co–chairs ; ● — team members

Outline of the Roadmap

•Drawn for a thirty year planning horizon in the context of the Presidential Moon, Mars and Beyond Initiative

•Moon and Mars were excluded from our purview

•Representatives from NASA, other Gov't, University, Industry

•Was to be part of a set of roadmaps in a process that was interrupted one year ago.

•Roadmap was reviewed last summer by the NRC; planetary roadmap process was restarted at HQ by Danzler, McGrath

•Distribution to NASA committees for review is underway now.

Underlying Scientific Questions:

1. How did the Sun's family of planets and minor bodies originate?
2. How did the Solar System evolve to its current diverse state?
3. What are the characteristics of the Solar System that led to the origin of life?
4. How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System?
5. What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?

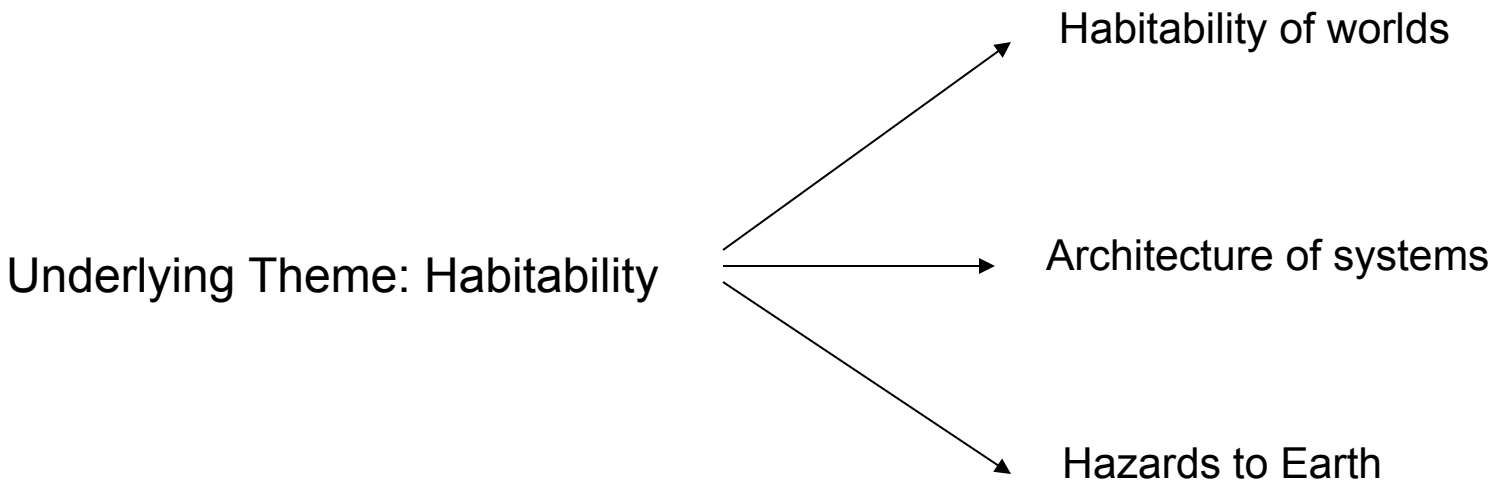


Table 2.3: Question Three: What are the characteristics of the Solar System that led to the origin of life?

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.

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	NSE	*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 chemicals important to prebiotic evolution and the emergence of life	●	▲	▲				▲						●	▲	●		●	▲	●	
Evidence for life on Europa, Enceladus, and Titan	▲	▲											▲	▲	●		●			
Evidence for past life on Venus	▲	▲														▲				●
Study Earth's geologic and biologic record to determine the historical relationship between Earth and its biosphere	●	▲																		
Identify environmental hazards and resources enabling human presence in space																				
Determine the inventory and dynamics of objects that may pose an impact hazard to Earth	●	▲	●				▲													
Inventory and characterize planetary resources that can sustain and protect human explorers	▲	▲	●						▲		●									

Convention: ● Major or Unique contribution; ▲ Support contribution;

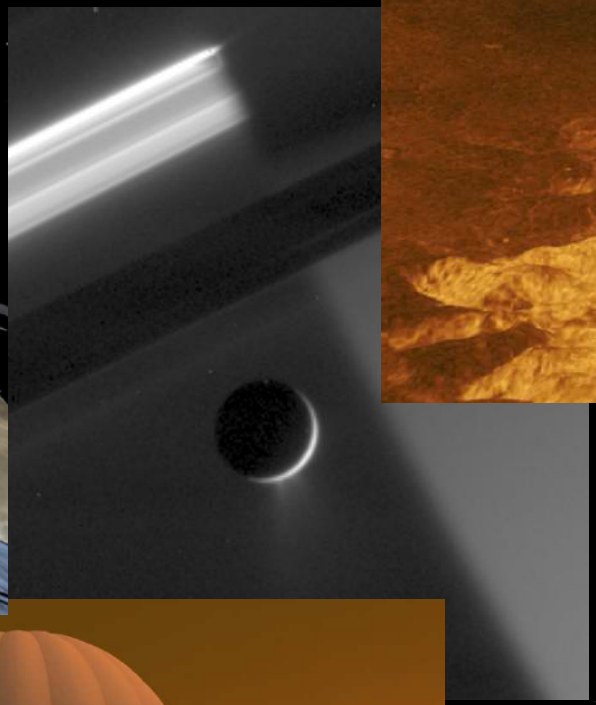
SB — small bodies; NH — New Horizons; SPABSR — South Pole Aitken Basin Sample Return; VISE — Venus In Situ Explorer; CSSR — Comet surface sample return; SP — Saturn Flyby with Shallow Probes; C–H — Cassini–Huygens; EE — Europa Explorer; TE — Titan / Enceladus Exp.; VME — Venus Mobile Exp.; EAL — Europa Astrobiology Lander; NSE — Neptune System / Triton Explorer; *CCSR — Cryogenic Comet Surface Sample Return; VSSR — Venus Surface Sample Return * — beyond the 5 proposed Flagship missions*

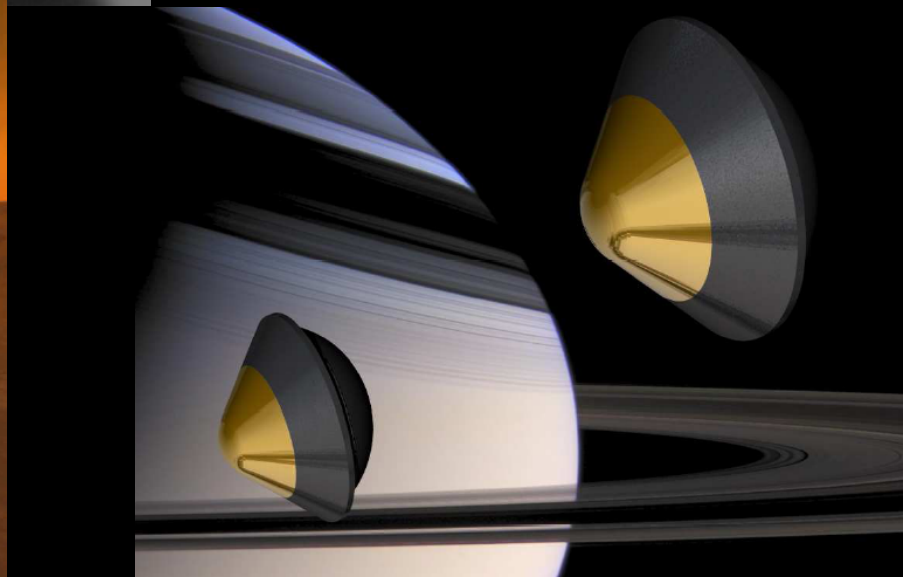
A balanced program

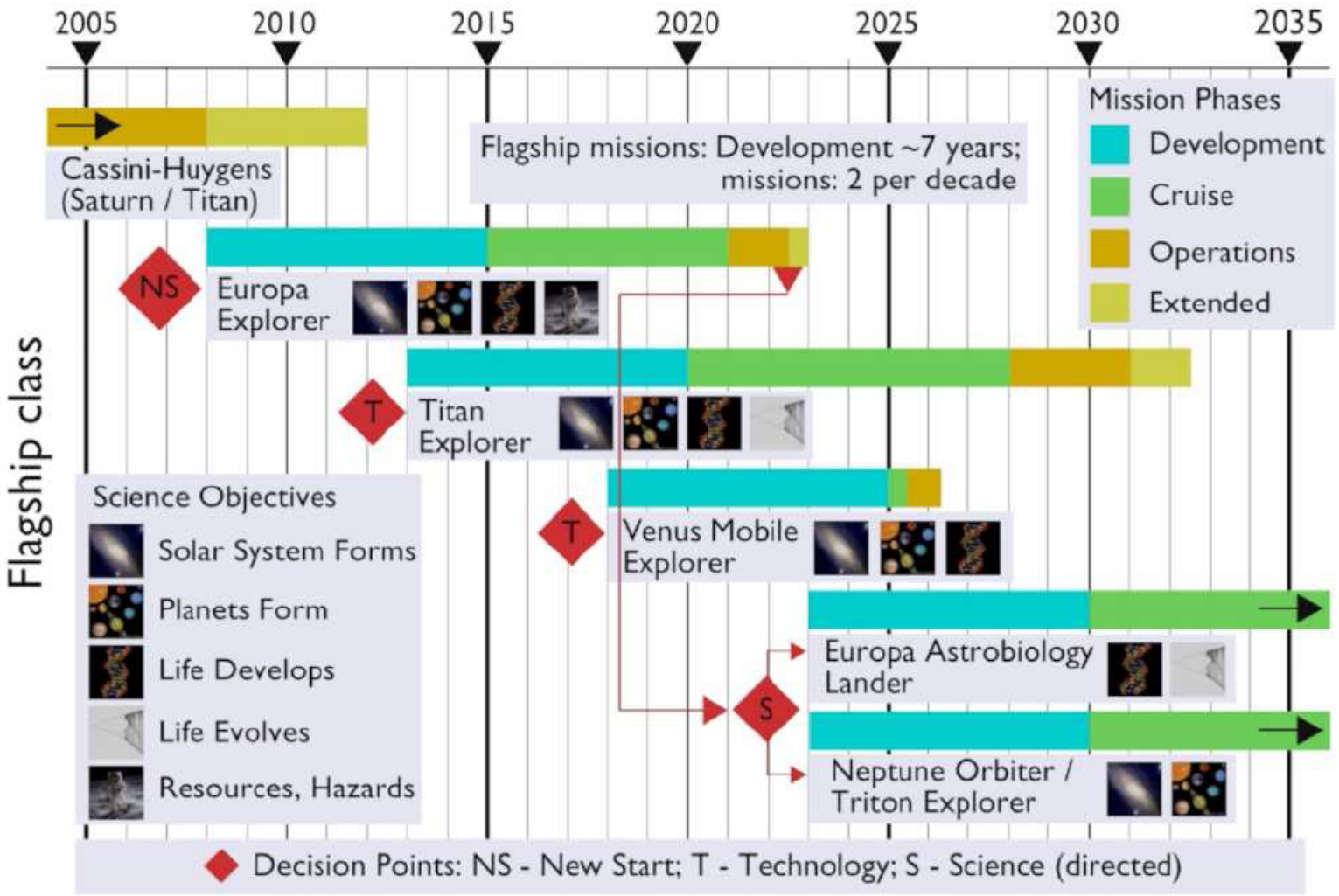
- Research and analysis
- Small (Discovery) Missions ($400M/mission)
- Medium (New Frontiers) Missions ($750M/mission)
- Large (Flagship) Missions
- EPO
- Technology development

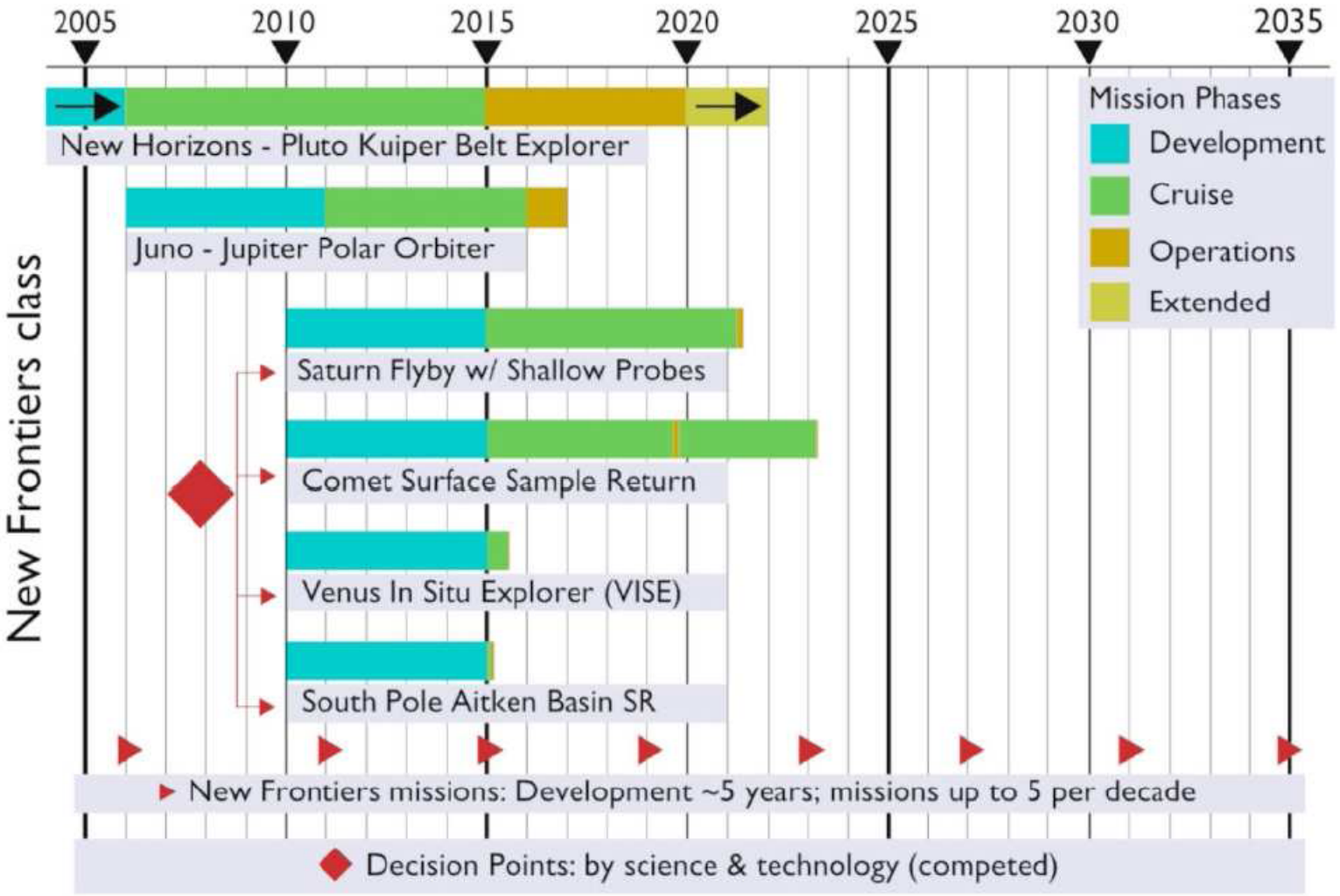
International Cooperation

- Has made major missions possible in the past (Cassini, e.g.)
- Is continuing at present (Mars, Jupiter/ Europa)
- The Roadmap is strongly positive with respect to such coopoeration but does not pre-specify on which missions to cooperate and how.






2005
2010
2015
2020
2025
2030
2035
Flagship class
Mission Phases
Development
Cruise
Operations
Extended
Cassini-Huygens
(Saturn / Titan)
Flagship missions: Development ~7 years;
missions: 2 per decade
NS
Europa
Explorer
T
Titan
Explorer
T
Venus Mobile
Explorer
Science Objectives
Solar System Forms
Planets Form
Life Develops
Life Evolves
Resources, Hazards
Europa Astrobiology
Lander
S
Neptune Orbiter /
Triton Explorer
Decision Points: NS - New Start; T - Technology; S - Science (directed)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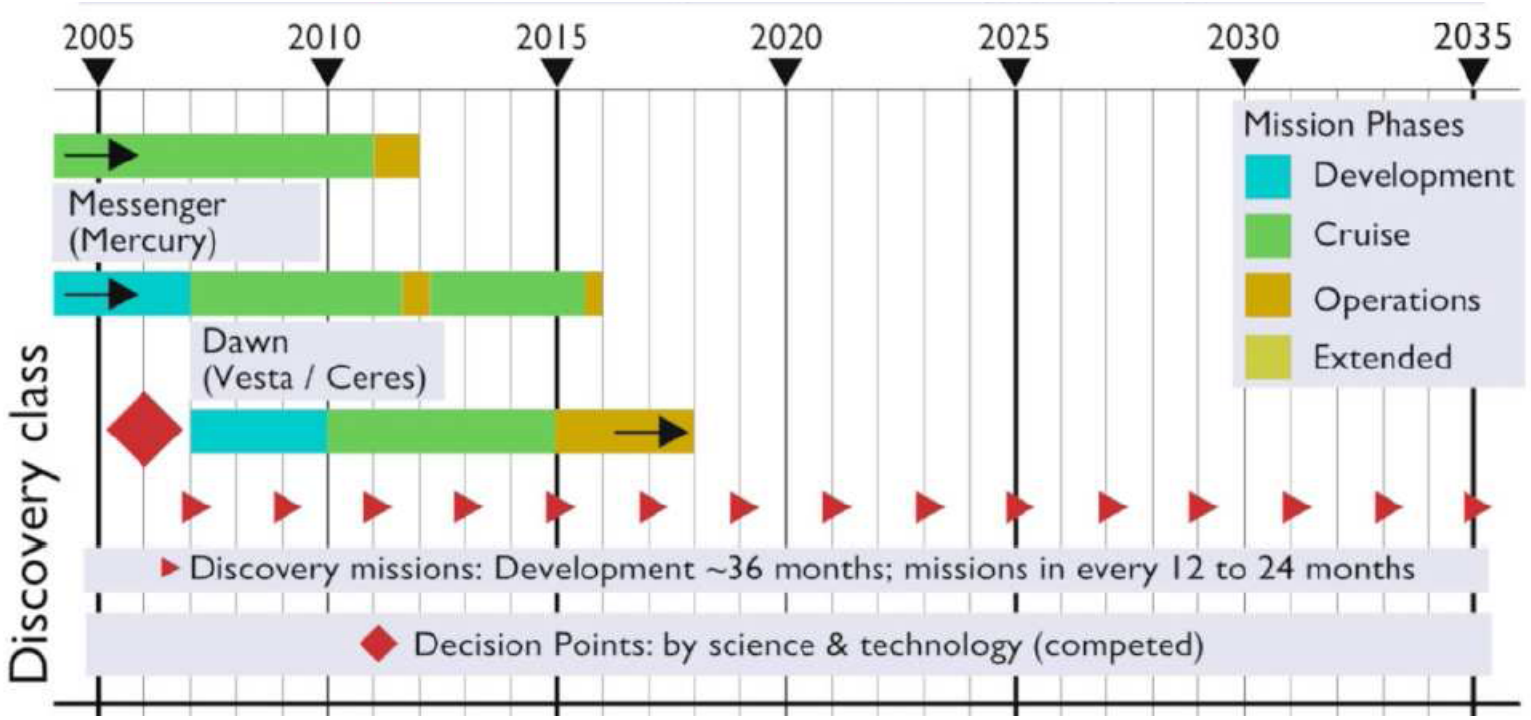
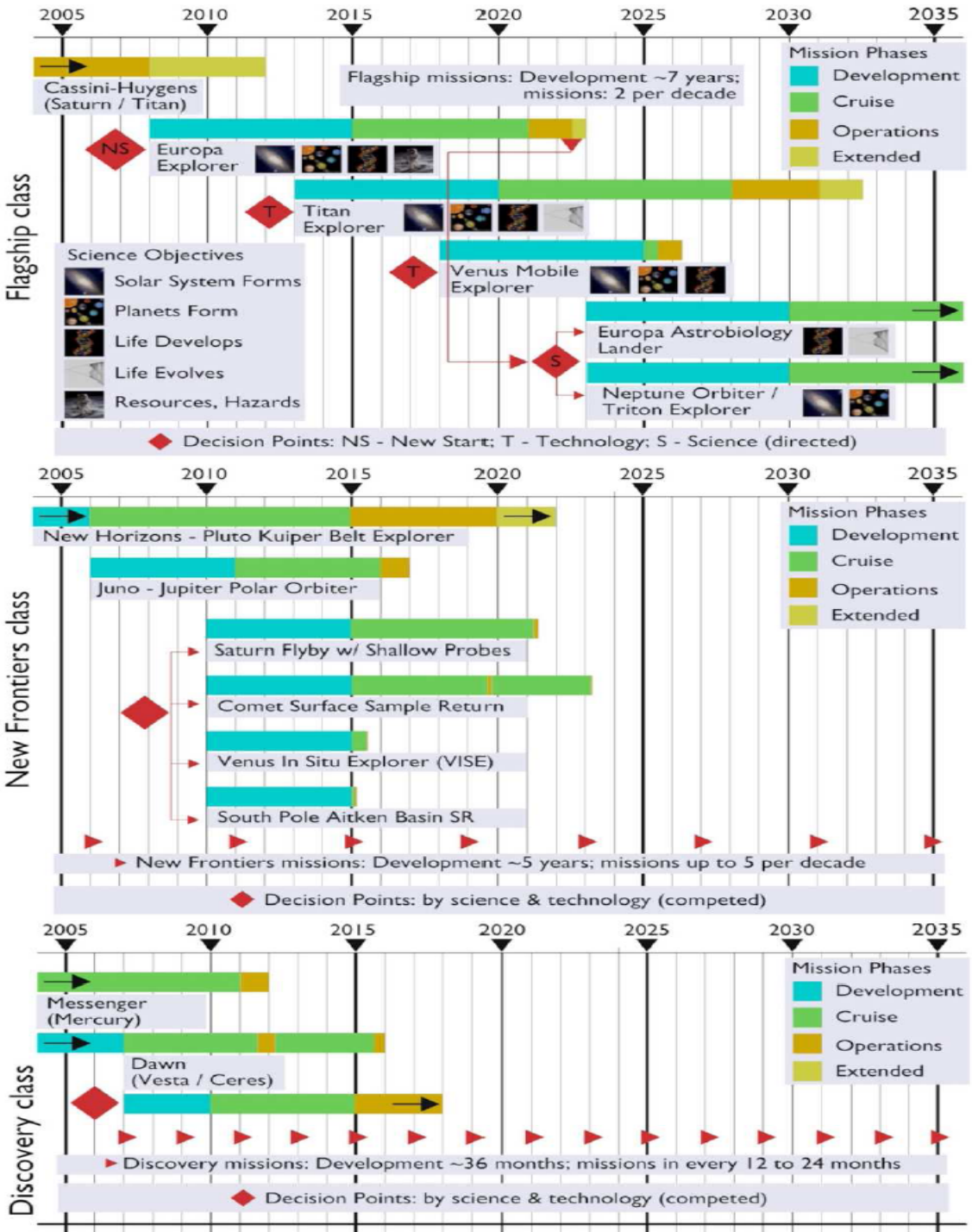
New Frontiers class
Mission Phases
Development
Cruise
Operations
Extended
New Horizons - Pluto Kuiper Belt Explorer
Juno - Jupiter Polar Orbiter
Saturn Flyby w/ Shallow Probes
Comet Surface Sample Return
Venus In Situ Explorer (VISE)
South Pole Aitken Basin SR
New Frontiers missions: Development ~5 years; missions up to 5 per decade
Decision Points: by science & technology (competed)


2005
2010
2015
2020
2025
2030
2035
Mission Phases
Development
Cruise
Operations
Extended
Messenger
(Mercury)
Dawn
(Vesta / Ceres)
Discovery class
Discovery missions: Development ~36 months; missions in every 12 to 24 months
Decision Points: by science & technology (competed)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Dawn (Vesta / Ceres)
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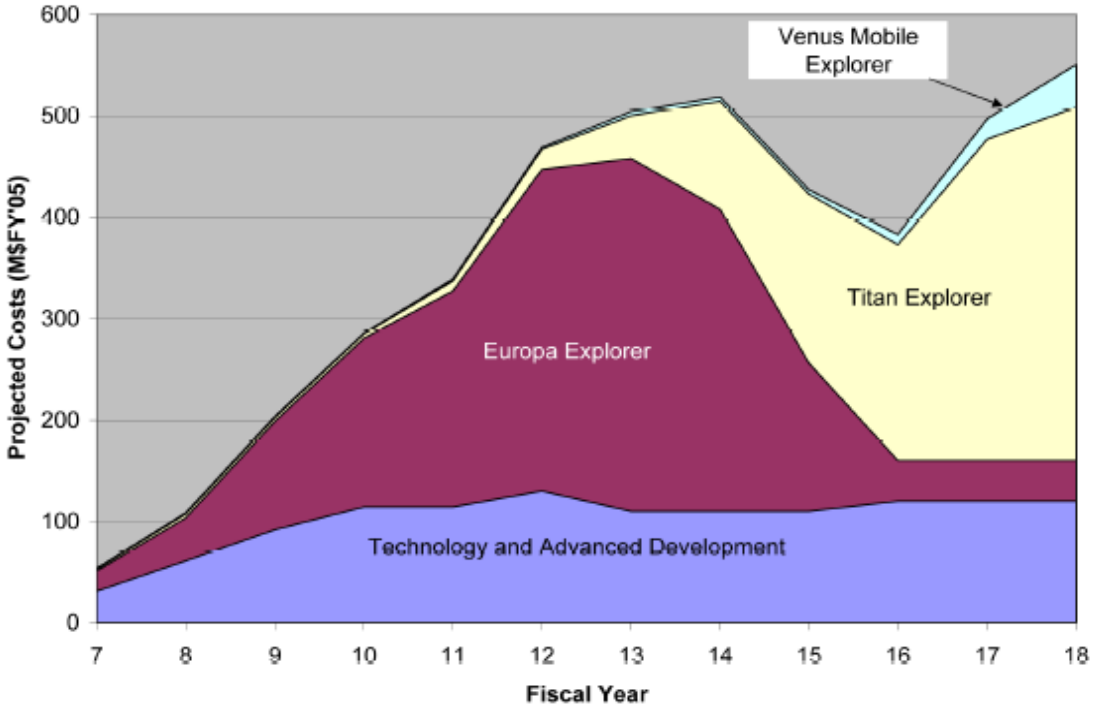
Decision Points: by science & technology (competed)

Technology	Priority	Comments
Spacecraft Systems		
Transportation	●	▷ Aerocapture is enabling for two Flagship missions. Solar electric propulsion is also key. Without these technologies are needed for rapid access to the Outer Solar System
Energy generation and storage	●	▷ Radioisotopic power is needed for **all five Flagship missions**. An assured supply of Plutonium is vital. Advances in efficiency can reduce the need and also have a major impact on mission margins.
Communications	●	▷ Major gains in science return from improvements in communications. Telecom is enhancing **assuming that** the capabilities of DSN are retained or expanded.
Planetary Protection	▲	▷ Planetary protection implementation can leverage the technology for going to special regions developed by the Mars Exploration Program for MSL. Some Europa/Titan/Enceladus unique capabilities are needed
Autonomy and software	▲	▷ This is a critical technology and can leverage prior investments in this area for the Mars Exploration Program. Verification and validation becomes increasingly challenging as complexity increase.
In Situ Exploration Systems		
Extreme Environments	●	▷ This is a vital technology for all Flagship missions. The needs span high and low temperatures, radiation as well as thermal protection systems needed for planetary entry.
Entry, Descent and Landing	▲	▷ Major challenges are for **landing on airless bodies including satellites and small bodies**. Titan and Venus are not a major challenge. Outer planet entry thermal protection is covered in extreme environments.
Planetary Mobility	▲	▷ Aerial Mobility is the key area of emphasis and needed for Titan Explorer and Venus Explorer. Surface mobility is much less important than for Mars and Moon and where needed can leverage these capabilities.
Science Instruments		
In situ sensing	●	▷ Astrobiology and life detection instrumentation is a major focus. Techniques that will work effectively in extreme environments (Venus surface, Titan atmosphere need particular attention).
Components and Miniaturization	●	▷ Major gap in component programs which is going to impact ability to implement Flagship missions unless rectified.
Remote Sensing	▲	▷ Primary need are is to advance existing technologies to flight readiness and achieve and incorporate advances in miniaturization. Both passive and active techniques are needed.

● Highest priority — new development are required for all or most of roadmap missions
▲ High Priority — either applications are more limited or can leverage existing work effectively

	Missions Per Decade						
Mission Class	NRC DS	SSE–RM	*SRM3–2006 (This report)*				
	2003	2003	Option A	Option B	Option C	Option D	Option E
Discovery	7	7	7	7	7	6	4
New Frontiers	4	3	4	4	4	3	2
Small Flagship	⊗	⊗	2	0	2	1	0
Large Flagship	1	⊗	1	1	0	1	2
Prometheus	⊗	1	⊗	⊗	⊗	⊗	⊗

	Cost Per Decade ($B)						
Mission Class	NRC DS	SSE–RM	*SRM3–2006 (This report)*				
	2003	2003	Option A	Option B	Option C	Option D	Option E
Discovery	2.8	2.8	2.8	2.8	2.8	2.4	1.6
New Frontiers	2.8	2.1	2.8	2.8	2.8	2.1	1.4
Small Flagship	⊗	⊗	2.8	0	2.8	1.4	0
Large Flagship	N/A	⊗	2.8	2.8	0	2.8	5.6
Prometheus	⊗	N/A	⊗	⊗	⊗	⊗	⊗
Total Cost per Decade			**11.2**	**8.4**	**8.4**	**8.7**	**8.6**


Venus Mobile Explorer
Titan Explorer
Europa Explorer
Technology and Advanced Development
Projected Costs (M$FY'05)
Fiscal Year
0
100
200
300
400
500
600
7
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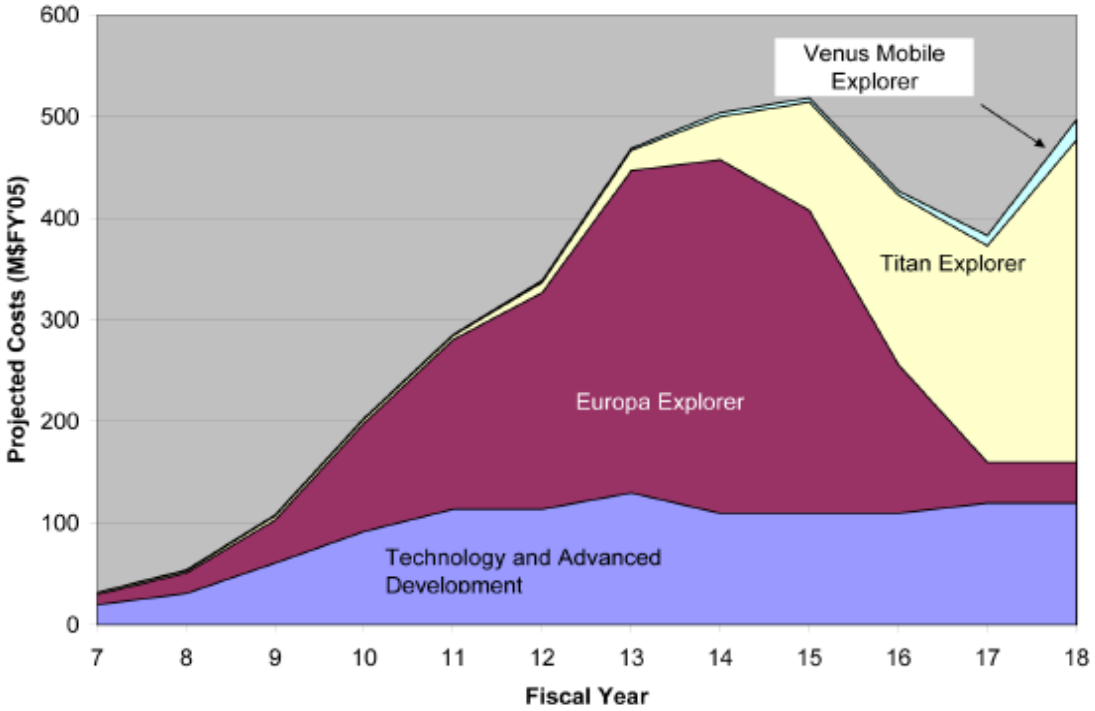
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Technology and Advanced Development
Projected Costs (M$FY'05)
Fiscal Year
0
100
200
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500
600
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Main points

- Solar System Exploration over the past decade has yielded an extraordinary list of discoveries—the second Golden Age?
- To address the key questions and maintain international leadership requires a balanced portfoglio ranging from a vigorous R&A program, through small, medium and large missions.
- Technology development—extreme environments, power, aerobraking, communications, miniaturization—are essential right now to enable this program.