

Thirty Years of Outer Solar System Exploration Planning and Execution

		Technology Drivers										Projected Cost in Millions FY75				True Cost in Millions \$ - Development Only	True Cost Base Year for Fixed \$																											
System Number (1975)	Name (1975)	Penetration of area	Technology	Requirements	Advanced	Proposed	Solar System Exploration Division Strategic Plan (1991)	SSES Recommendations (1994)	Space Science Enterprise Strategic Plan (1997)	Space Science Enterprise Strategic Plan (2000)	Implemented Mission	Type	Transportation	Illustrative Flight Dates	Implemented Launch Vehicle	Implemented Launch	1975-1980	1981-1985	1986-1990	1991-2000	Total	Total	Notes	Disposition (September 2003)	Remarks (October 2001)	Resolution Required to Enable (October 2001)	New Frontiers in the Solar System ("Decadal Survey")	NASA Space Science "Vision Mission" Studies	Project Prometheus															
1081	Jupiter Atmospheric Probes						Galileo in transit to Jupiter; Measure-Jupiter		<COMPLETED>	Galileo Probe	Strategic	Titan III/Centaur	1980 Shuttle / PAM D w/Galileo Orbiter	1989			100	50	50	205			Galileo Probe completed; impact Jupiter																					
1082	Saturn Atmospheric Probes						Saturn Probe - complement Cassini						Shuttle/IVS	1984			150	20	5	175			Saturn Atmospheric Probes	Discovery 2 candidate																				
1083	Titan Orbiter w/Penetrator						Titan Organic Explorer post-2005			Titan Explorer post-2007			Shuttle/Fug	1991			200	100	300				Titan Explorer - Huygens followon	Nuclear Thermal Rocket and/or aerocapture	Planning requires successful completion of Huygens mission and advanced propulsion and/or aerocapture		Titan Explorer - Study Case 16																	
1084	Uranus Atmospheric Probe						Uranus Orbiter/Probe - candidate for FY99-FY03						Shuttle/Fug	1984			200	35	235				Uranus Atmospheric Probe	Nuclear Thermal Rocket and/or aerocapture	"Reasonable" (<=15 yr) flight times require Jupiter flyby																			
1091	Jupiter Orbiters, spinning-3-axis						Galileo in transit to Jupiter	Galileo in operation in Jupiter orbit	Galileo Europa Mission (Galileo Extended Mission)	Galileo	Strategic	Shuttle/IVS or Titan III/Centaur	1985 Shuttle / PAM D	1989			135	45	180		1401	1992	Galileo Europa Mission (Galileo Extended Mission) - completed																					
							Jupiter Grand Tour - candidate for FY99-FY03	Measure-Jupiter	Jupiter Polar Orbiter post-2007	INSIDE Jupiter - Discovery Phase II Discovery competition																				Jupiter Icy Moons Orbiter (JIMO)														
							Europa Orbiter - derived from Galileo magnetometry results	Europa Orbiter	Europa Orbiter	Europa Orbiter														Europa Orbiter - cancelled	Payload competition awaiting selection; price estimate over \$1B		Solar System Large 1, Europa Geophysical Orbiter																	
							Europa Lander - follow Europa Orbiter post-2005	Europa Lander	Europa Lander	Europa Lander														Europa Lander	Nuclear Thermal Rocket needed; extreme radiation environment; RTG needed for power; specialized, major ATD needed																			
							Europa subsurface Explorer post-2007; follow Europa Lander	Europa subsurface Explorer	Europa subsurface Explorer	Europa subsurface Explorer																																		
							Io Volcanic Observer - derived from Galileo and Measure-Jupiter	Io Volcanic Observer	Io Volcanic Observer	Io Volcanic Observer																																		
1092	Titan Lander						Huygens in development	Huygens in transit with Cassini	Huygens in transit with Cassini	Huygens/ESA	Strategic	Shuttle/Fug	2000 Titan IV SRMU/Centaur w/Cassini	1997			700	700	ESA				Huygens in transit with Cassini																					
1093	Uranus Orbiter												Shuttle/Fug	1995			350	350						Uranus Orbiter	Nuclear Thermal Rocket and/or aerocapture	Decreased interest following Voyager 2 flyby of Neptune and Triton; 90 deg inclination restricts equatorial plane capture to equinox arrivals																		
1096	Saturn Orbiter						Cassini Orbiter in development	Cassini in transit with Huygens	Cassini in transit with Huygens	Cassini	Strategic	Shuttle/Fug	1986 Titan IV SRMU/Centaur w/Huygens	1997			200	100	300		1457	1992	Cassini in transit with Huygens				Solar System Small 2, Cassini Extended																	
							Saturn Ring Observer post-2007	Saturn Ring Observer	Saturn Ring Observer	Saturn Ring Observer														Saturn Ring Observer	Nuclear Thermal Rocket and/or Nuclear Electric Propulsion	Multiple maneuvering capabilities seen as driver for NEP development																		
1097	Neptune Orbiter						Pluto Flyby/Neptune Orbiter - recommended for 1996	Neptune Orbiter post-2007	Neptune Orbiter post-2007	Neptune Orbiter			Shuttle/Fug/SEP	2000			450	450						Neptune Orbiter	Nuclear Thermal Rocket and/or aerocapture	"Reasonable" (<=15 yr) flight times require Jupiter flyby; capture requires nuclear stage or aerocapture ballute in unknown environment		Neptune Orbiter with Probes - Study Case 17																
							Pluto Fast Flyby	Pluto/Kuiper Express	Pluto/Kuiper Express	Pluto/Kuiper Belt competition	Discovery II prototype													New Horizons now in development			Solar System Medium 1, Kuiper-Belt Pluto Explorer; New Horizons selected for flight																	
1107	Jupiter-Saturn Flyby						<COMPLETED>			Voyager 1 and Voyager 2	Strategic	Titan III/Centaur x 2	1977 Titan III/Centaur x 2	1977			350	350		776	1992	Voyager planetary encounters completed																						
1108	Uranus Flyby						<COMPLETED>			Voyager 2	Strategic	Titan III/Centaur	1979 Titan III/Centaur	1977			165	15	180																									
1109	Neptune Flyby						Voyager 2 flyby completed	<COMPLETED>		Voyager 2	Strategic	Titan III/Centaur	1992 Titan III/Centaur	1977			50	175	225																									
							Genesis in transit	Genesis	Genesis	Genesis	Discovery		Delta II	2001										Genesis in transit						Genesis Cost														
Total Cost in Millions of FY75																	615	755	500	1780	3850																							

Regolith mining
Acquisition
Technology
Landing
Power supply
Non-chemical
Orbiters/Probes
Aerocapture

??????? Denotes questionable as enabling versus enhancing

Mission completed or in completion phase
Mission in development or launched but not yet at target

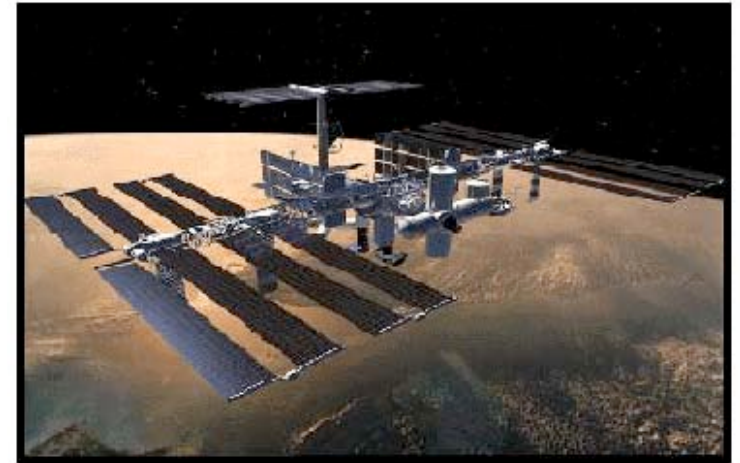
OPAG Meeting #1 Bethesda, MD

Required technology not currently available
Possible Discovery mission candidate
Possible Discovery candidate with larger mission lifecycle cost cap

Science Goals Help Drive NASA Exploration

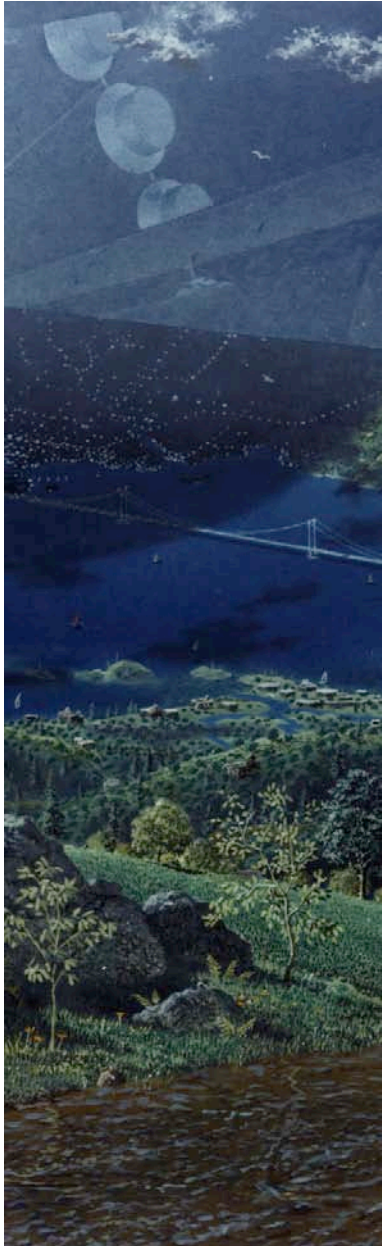


**Space
Exploration
has
historically
been
aligned with
an outward
look**



**...with the idea
that humans
would follow**

How Good Is Our Crystal Ball For Space Technology?



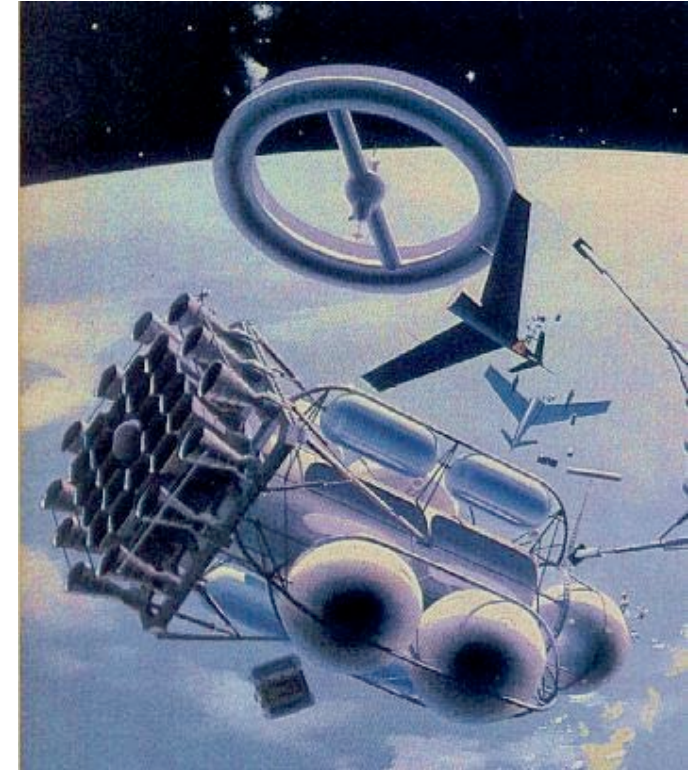
**Large-scale projects
were predicted in
the late 1940s and
early 1950s**

**Space stations were
staging grounds
for multiple-vehicle
voyages to the
Moon and Mars**

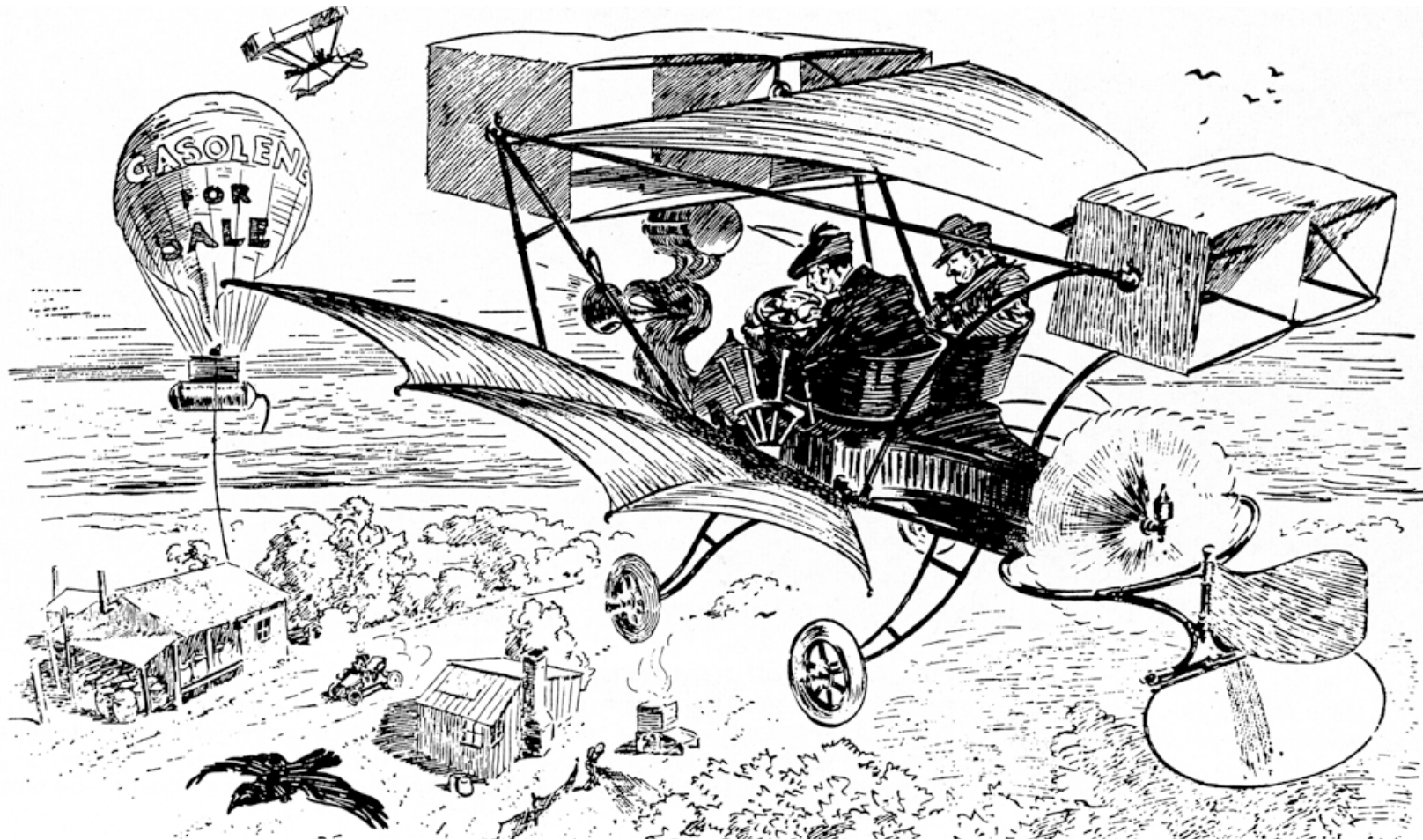
**BUT ... Reality lay in
small instrumented**

probes - and then in the “Moon race”

**Following Apollo, the Shuttle held promise for “easy
access to space.” Fiscal realities and the end of the
cold war have led to slower gains**



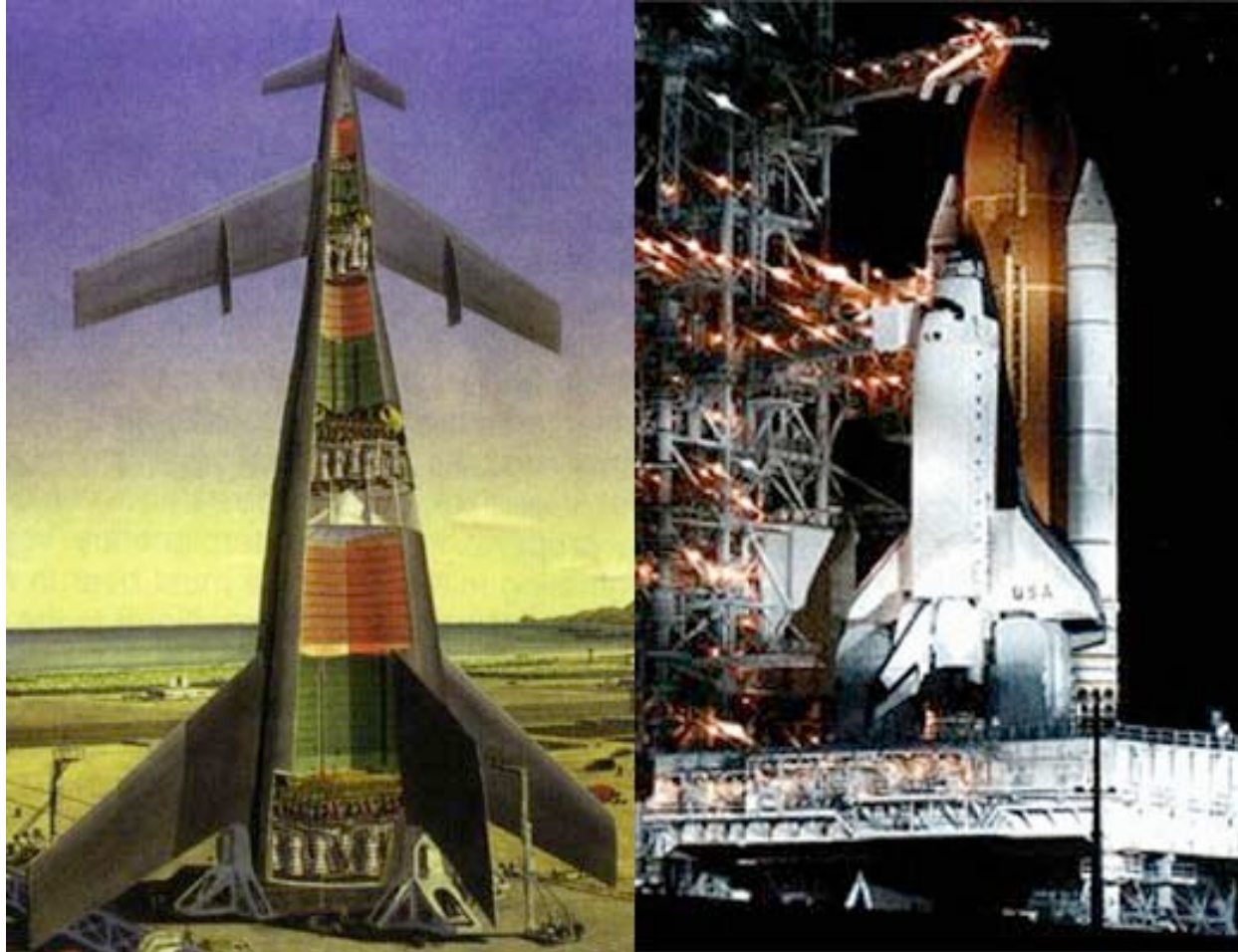
Future Predictions Can be Misleading...



[Cartoon from 1907]

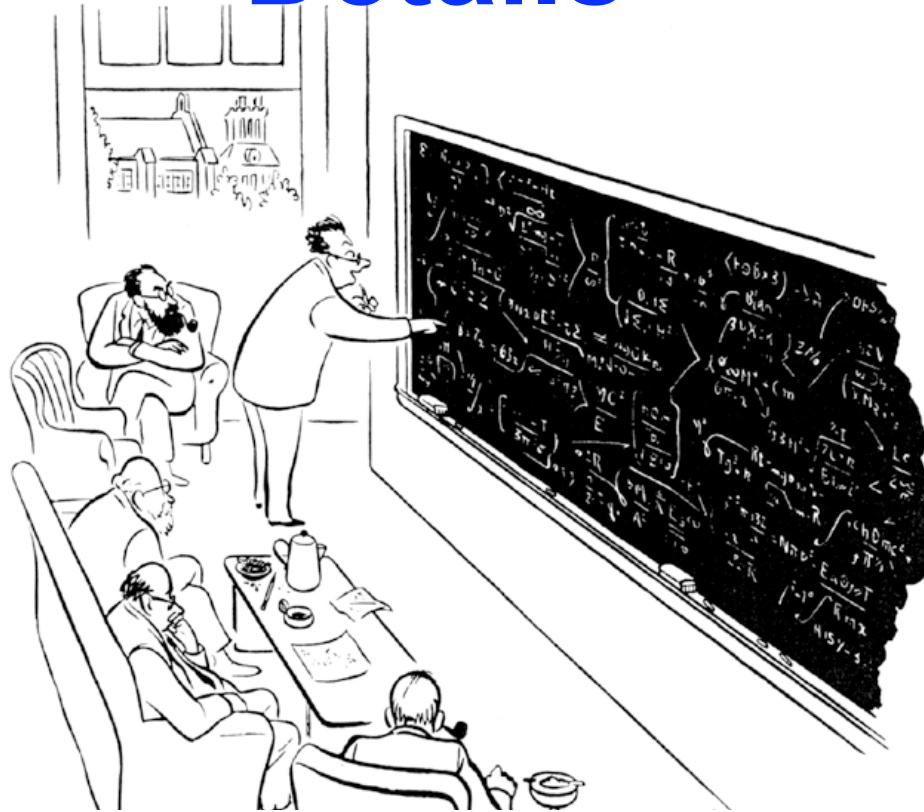
IN 1950. "Why, there's an automobile! How funny it looks!"
"Yes. That's old fossil Jones - says he can't stand these newfangled notions."

...Or Fulfilling



But not as easily as we had thought

The Devil is ALWAYS in the Details



**Say, I think I see where we went off.
Isn't eight times seven fifty-six?**

For Any Mission There Are Four Key Elements



- Science the case for going
- Technology the means to go
- Strategy all agree to go
- Programmatic money in place

A well-thought-out systems approach incorporating all key elements is **required** to promote **and accomplish** a successful exploration plan

The Robotic Probe Vision (or “Do we need Astronauts?”)



Apollo 17

11 February 2005

Launch a probe to a target
Probe returns knowledge - not data

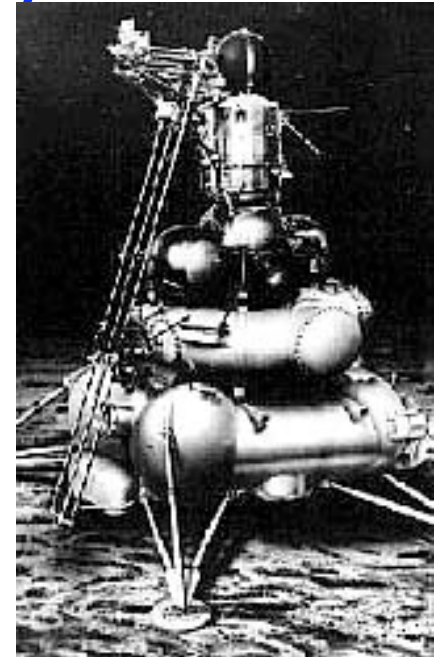
BUT without return of all data, how is the knowledge to be validated?

Return of all data requires large bandwidth

Drives receiver and transmitter sizes and transmitter power
“Compression” leaves doubts of data fidelity

Data return drives power and, hence, mass
Mass drives propulsion

...Did we REALLY think EVERYTHING through ahead of time, though?



Luna 24

The Technology Element



11 February 2005

- Propulsion Systems
- Power Systems
- Communications Systems
- Spacecraft Architecture
- Instrumentation
 - mass
 - power
 - data downlink

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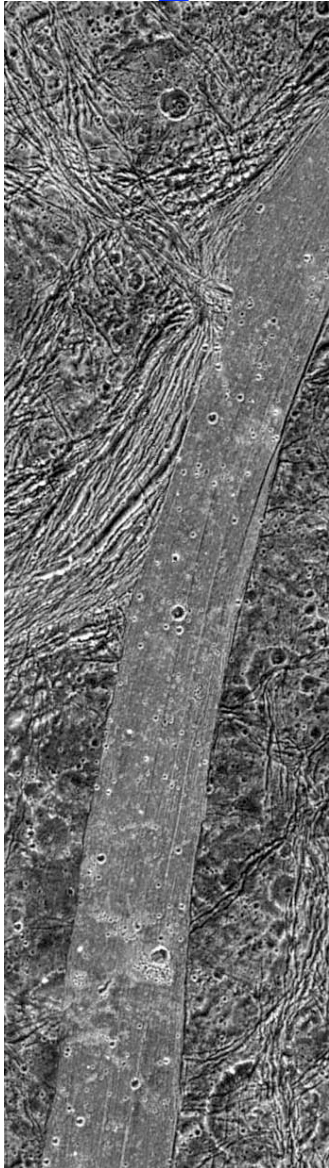
Propulsion Issues for Robotic Missions



Object	Equatorial escape speed (km/s)
Earth	11.18
Venus	10.36
Mars	5.02
Mercury	4.25
Moon	2.38

- Going to the outer solar system and into orbit
- Landing on any solid planet (Mercury through Pluto + minor bodies) - high thrust required
- Sample returns to Earth - high thrust required

High Thrust Requires Thermal Rockets



For a chemical biprop system $I_{sp} \sim 320s$

--> $v_{exhaust} = 3.1 \text{ km/s}$

For a cryogenic biprop $I_{sp} \sim 420s$

--> $v_{exhaust} = 4.1 \text{ km/s}$

For a nuclear thermal system $I_{sp} \sim 900s$

--> $v_{exhaust} = 8.8 \text{ km/s}$

LH2 storage is an issue

LOX and hydrazine is a possibility

Integrated systems studies are required

All targets are also effectively vacuum environments - notable exception of Titan

What works for the Moon can work for all cases - most stressing is Ganymede of 2.74 km/s (versus 2.38 km/s for the Moon)

Propulsion Systems Status

Chemical propulsion remains the primary propulsive means **and is the only current high-thrust option**

Large ΔV at low thrust in the inner solar system now seen as “enabling” for multiple advanced exploration missions

BUT...

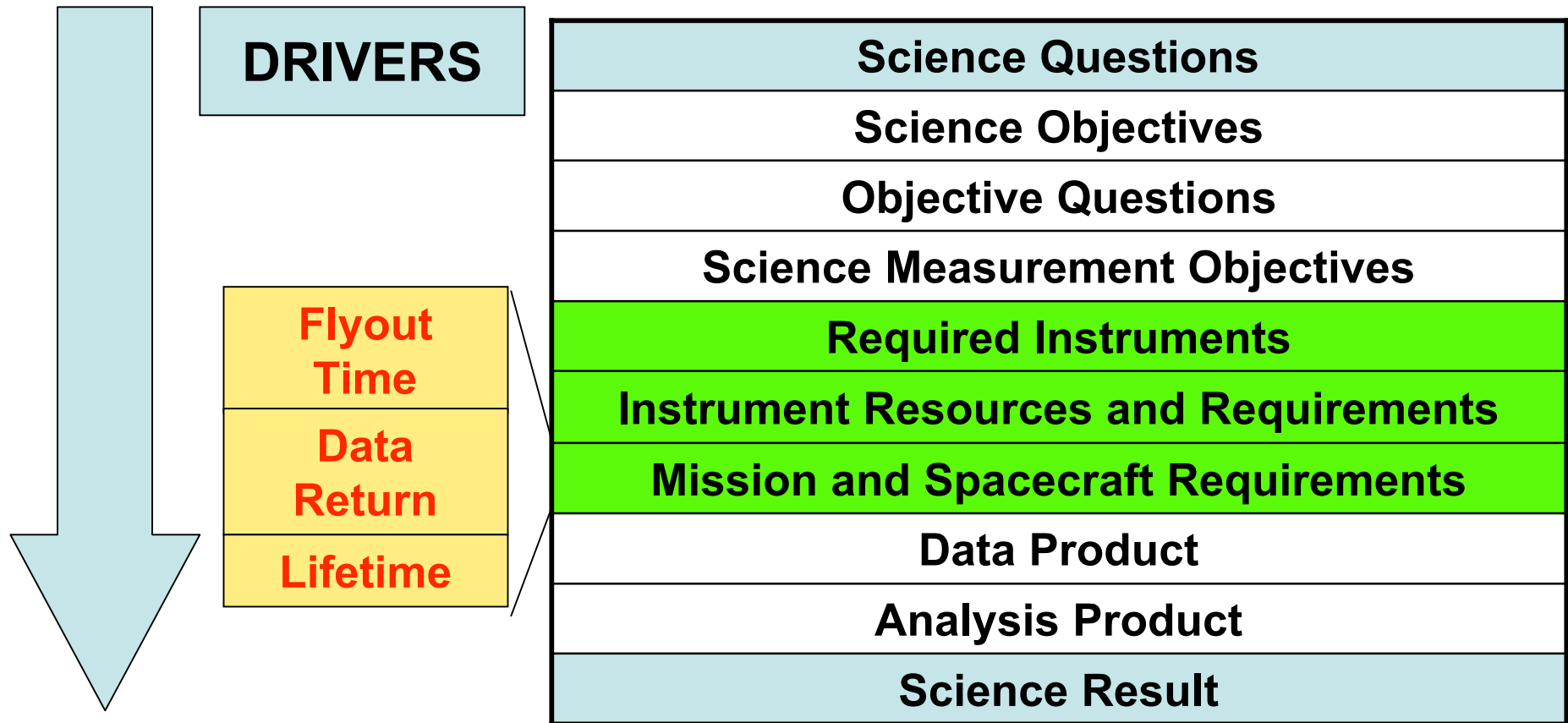
Solar Electric Propulsion tested (DS-1) but currently limited by specific mass (~65 kg/kW) of power plant

Nuclear Electric Propulsion has similar limitations and requires extensive (reactor) development (min. size?)

Aerocapture - braking into planetary orbits - requires good knowledge of the target atmosphere

Solar sails required in-space testing remains elusive

Answering the Science Questions is a “System of Systems” Problem to Reach Closure



We Make the “Past” of Future Generations

- From the prologue of *Orphans of the Sky* by Robert A. Heinlein (original publication 1941):

“The Proxima Centauri Expedition sponsored by the Jordan Foundation in 2119, was the first recorded attempt to reach the nearer stars of this galaxy. Whatever its unhappy fate we can only conjecture...”

**We decide where we will be in 2100.
It really is up to us...**

The Solar System Is a SYSTEM

- **The outer solar system holds the keys to solar system origins**
 - **Composition - the building blocks**
 - **Chronology - the events and evolution**
 - **Planets and small bodies - the assembly**
- **There ARE other solar system in our Galaxy**
 - **They are different from our system**
 - **NONE found (so far) are like our system**
- **As J.B.S. Haldane said “It is my supposition that Universe is not only queerer than we imagine, it is queerer than we can imagine.”**

How Rare Is The Earth?

- **The inner planets are an outcome of the history of formation of the entire system**
 - **Terrestrial planets**
 - **Conditions for life: Earth, Mars????**
 - **Conditions against life: Venus?**
 - **Other places/other climes - conditions for a second genesis?**
 - **The Earth - conditions for INTELLIGENT life**

Fermi Paradox

- **Physicist Enrico Fermi, said to be a firm believer in the existence of extra-terrestrials, was frustrated by the lack of firm evidence of their existence. Reasoning that advanced civilizations should by now have filled the Galaxy, Fermi came downstairs for lunch one afternoon at Los Alamos and blurted out his now-famous question, "Where are they?"**
- **"They are among us," it is reported that Hungarian-born physicist Leo Szilard responded, "but they call themselves Hungarians."**
- **<http://www.setileague.org/askdr/hungary.htm>**

How Do We Contain Costs?

- **Cost realism is paramount...for any missions past the first**
- **Some costs are fixed...and must be accounted for**
 - **To go beyond Mars with significant payloads, maximum initial mass in low-Earth orbit (IMLEO) is a DRIVER**
 - **NASA does NOT drive the launch vehicle market**
 - **Current EELVs are THE ONLY realistic options for the “top end”**
 - **Atlas V 551 (Lockheed - Martin)**
 - **Delta IV 4050H (Boeing)**
 - **MMRTGs and/or SRGs have costs fixed by infrastructure, Pu-238 availability, and safety**
 - **Legally required safety analysis costs escalate with launch vehicle options**
 - **Designs are modular and have large upfront (NRE) costs - major redesigns of GPHS modules will NOT occur**
 - **“New” technology will NOT lead to cost decreases - only increases**
- **Minimize and limit UP FRONT launch vehicle/RPS combinations**

What Strategy Is Needed?

- **Science rationale articulated**
- **Required measurements quantitatively defined**
- **Performance floor identified**
- **Missions prioritized with descopes**
- **New technology considered ONLY if ENABLING the performance floor**
- **Consistent programmatic documents**

Exploration IS Science

**“We shall not cease from exploration
And the end of our all our exploring
Will be to arrive where we started
And know the place for the first time.”**

— T.S. Eliot - from *Little Gidding*

[<http://www.tristan.icom43.net/quartets>]