JPL ISM STP Study Summary

Nitin Arora, Jonathan Murphy, Leon Alkalai, Jonathan Sauder and JPL Team-X Study Team

Detailed Team-X report can also be provided if needed

High-level Team-X Mission Requirements

Mission class = B, for comparison with 2014 study (probably should be A)

Technology cutoff = (future, including assumed technology development)

Redundancy = Dual Cold

Cost = (no explicit target)

Spares = Selected spares

Mission/system level requirements: Send probe to Interstellar Medium at 20 AU/yr

Summary

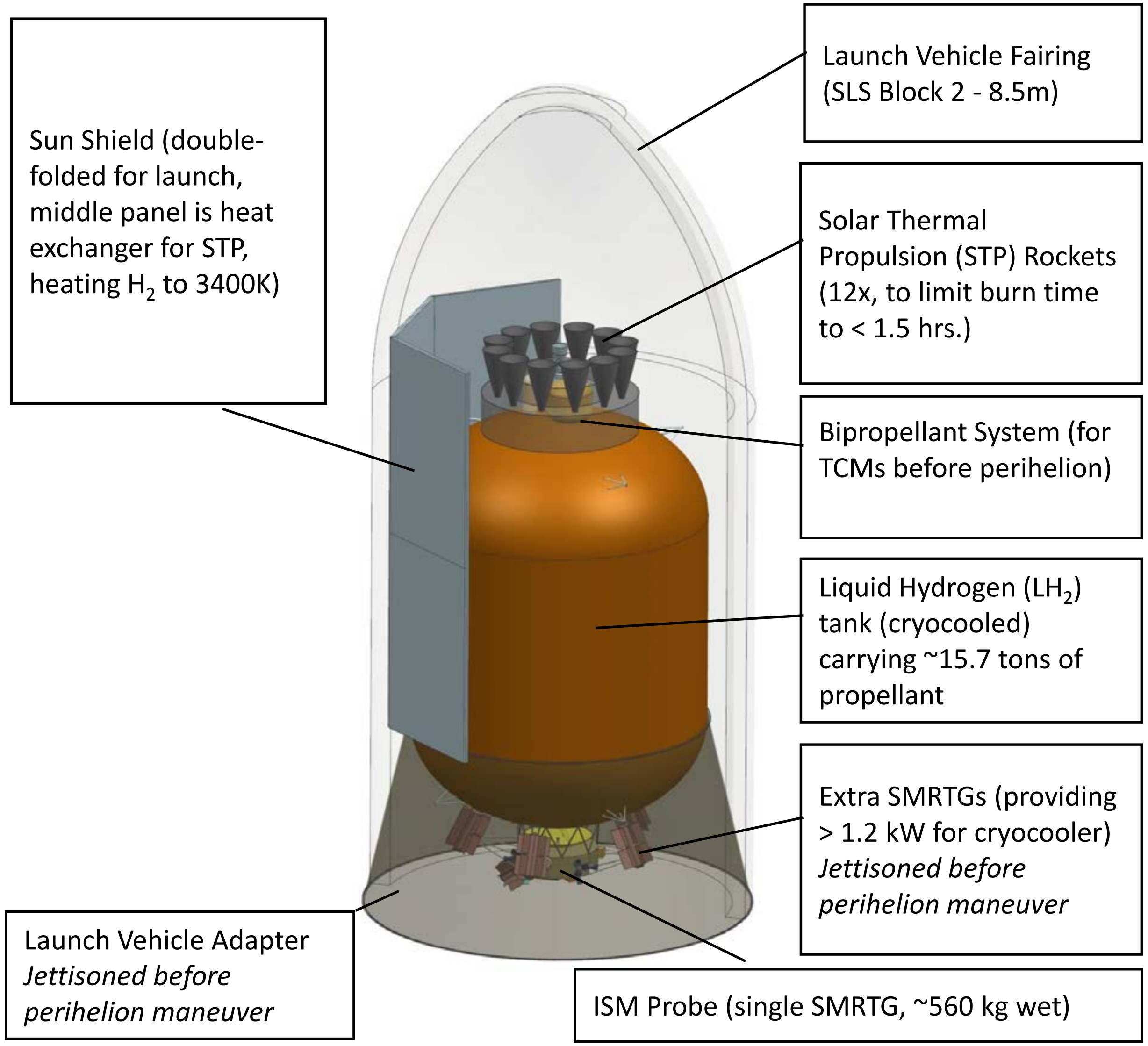
Probe to the Interstellar Medium (ISM)

- Probe contains instruments to study ISM
- Also has a camera for imagery of a Kuiper Belt Object (KBO)
- The probe is a simple, New Horizons-class spacecraft

Objective is to leave the Solar System at 20 AU/yr (95 km/s)

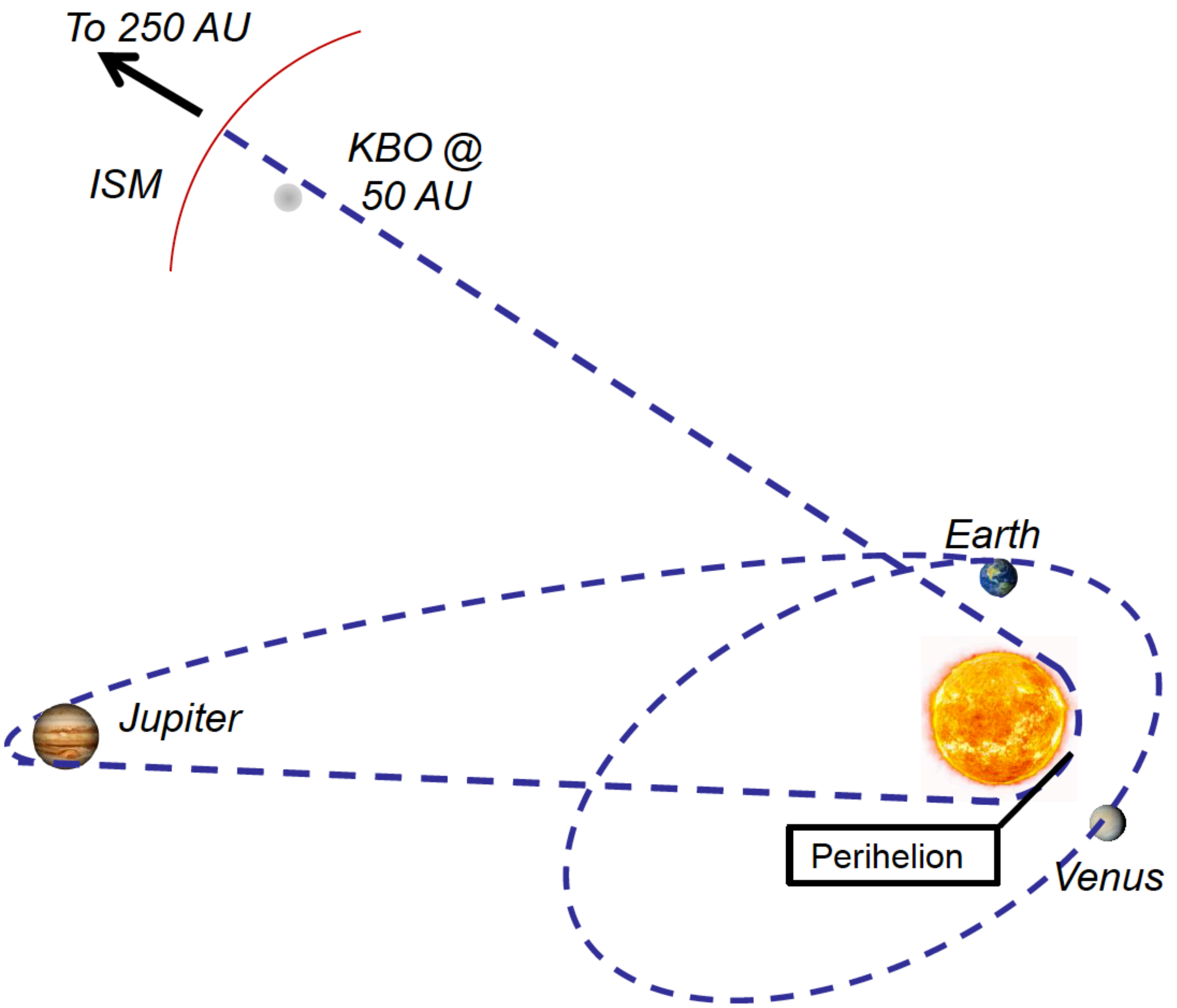
The “need for speed” motivates an extreme and unusual mission design

- Pass very close to the sun (3 solar radii from center)
- Need a large Sun Shield to protect the spacecraft
- At perihelion, we execute a very large burn (11.2 km/s) using a Solar Thermal Propulsion (**STP**) system



Mission Scenario

- **Trajectory:**
  - Earth-Venus-Venus-Earth-Jupiter-Perihelion-KBO-ISM
- **Perihelion kick sequence:**
  - Reach distance of 3 solar radii
  - Drop SMRTGs from STP stage
  - STP burn to 11.2 km/s ΔV
  - Separate probe from STP stage at ~1 AU
- **KBO flyby @ ~50 AU**
- **20-year total mission duration → ~250 AU**



Mission Design Summary

E-VVEJ-Ha-ISM

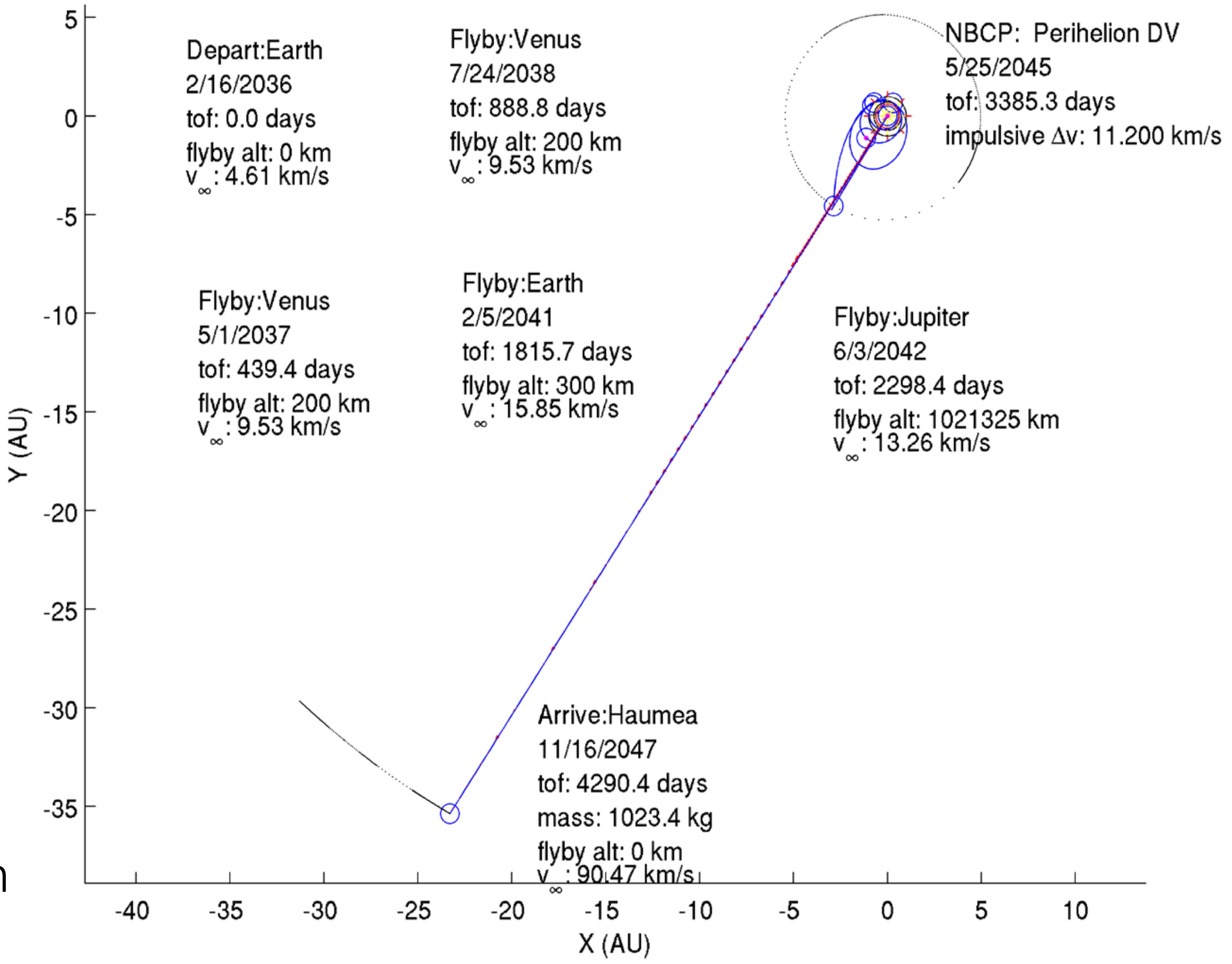
Exit Velocity= 19.1 AU/Yr.

Launch Date= 2/2036

KBO Flyby in ~11 years from Launch

LV = SLS Block 2 (8 m)

550 AU in < 40 years from Launch



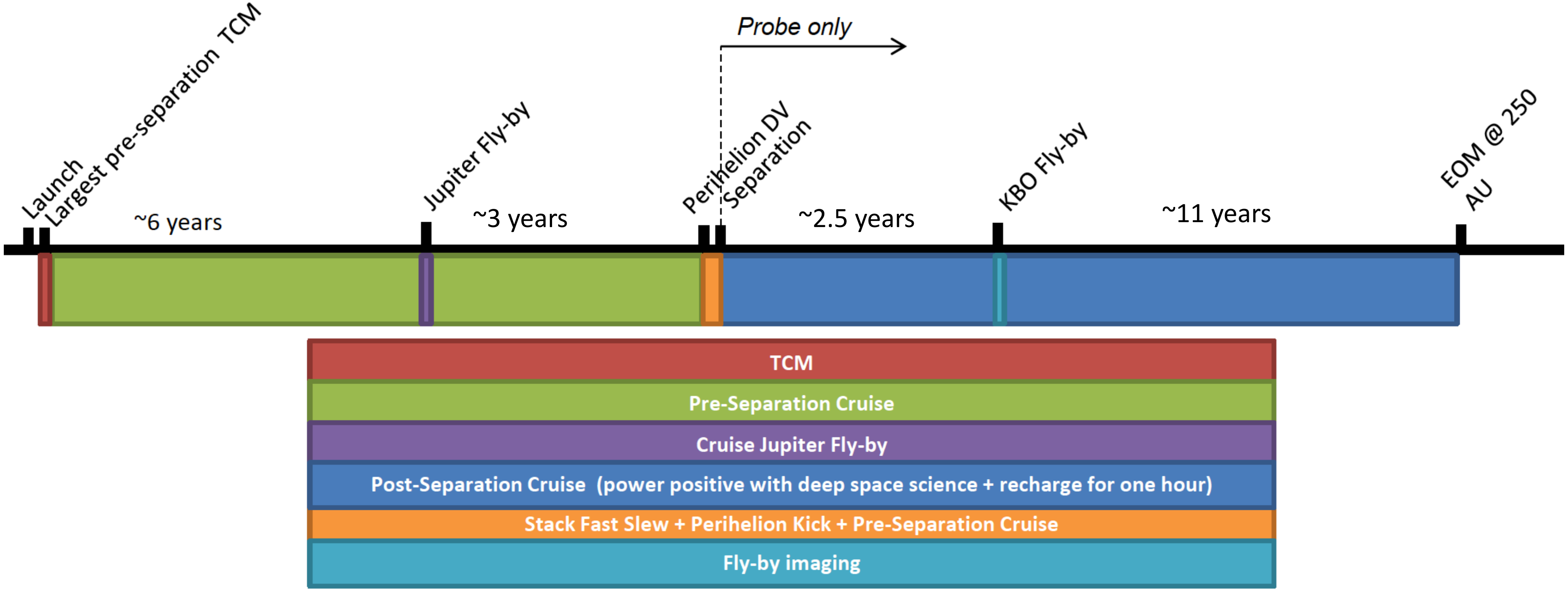
Mission Design Delta-V Budget

STP DV = 11.2 km/s

Probe DV = ~94 m/s

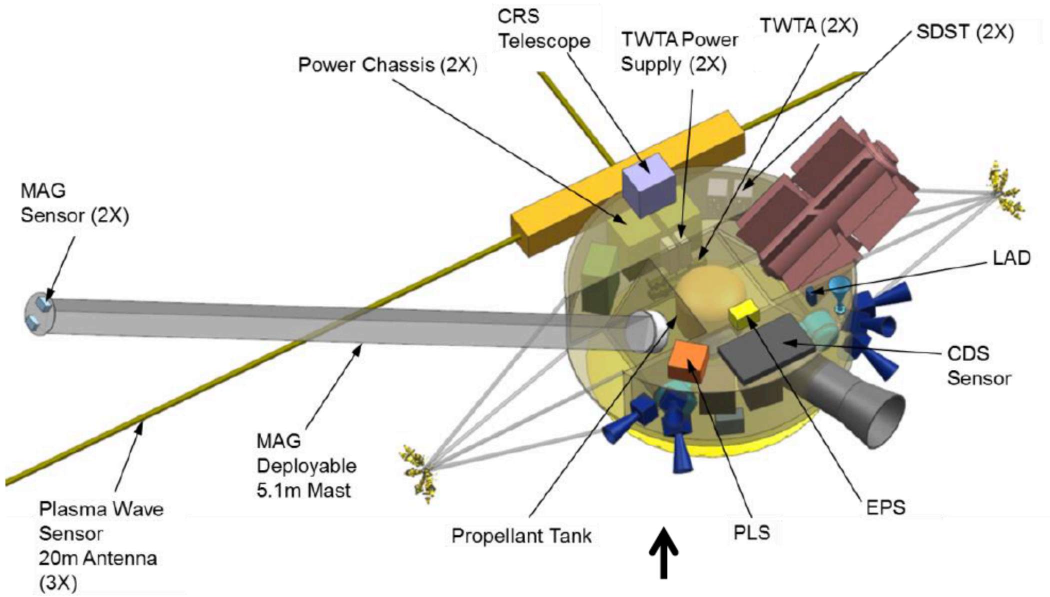
Nominal Mission Plan		DV (m/s)	Comments
Event	Description		
1	TCM-1	20.0	3-sigma injection
2	TCM-2	5.0	nondeterministic
3	TCM-3	5.0	nondeterministic
4	VGA-1		
5	TCM-4	5.0	nondeterministic
6	TCM-5	5.0	nondeterministic
7	VGA-2		
8	TCM-6	5.0	nondeterministic
9	TCM-7	5.0	nondeterministic
10	EGA		
11	TCM-8	5.0	nondeterministic
12	TCM-9	5.0	nondeterministic
13	JGA		
14	TCM-10	5.0	nondeterministic
15	TCM-11	5.0	nondeterministic
16	Perihelion DV	11200.0	STP system
17	TCM-12	30.0	KBO targeting
18	TCM-13	5.0	KBO targeting
19	TCM-14	5.0	KBO targeting
20	Makemake Flyby		

Mission Power Modes



Pre-Separation Cruise *24 hours*	**TCM** *0.25 hours*	**Cruise Jupiter Fly-by** *24 hours*	**Stack Fast Slew** *0.2 hours*	**Perihelion Kick** *1.2 hours*	**Fly-by Imaging** *3 hours*	**Recharge** *3 hours*	**Post-Separation Cruise** *24 hours*
• Star trackers • CDH • Telecom duty cycled 10% • Thermal control with shield + thruster heating	• Star trackers and IMUs • CDH • RCS • Telecom • Thermal control with shield	• Star trackers and IMUs • CDH • Telecom duty cycled 10% • Thermal control with shield	• Star trackers and IMUs • CDH • Telecom • Thermal control with shield	• Star trackers and IMUs • CDH • Telecom • Thermal control with shield + thruster heating	• Star trackers and IMUs • Imaging • CDH • RCS • Telecom • Thermal control + thruster heating	• CDH • Telecom stand-by • Thermal control + thruster heating	• Star trackers and IMUs • CDH • Telecom duty cycled 10% • Thermal control + thruster heating

Mission Architecture Summary

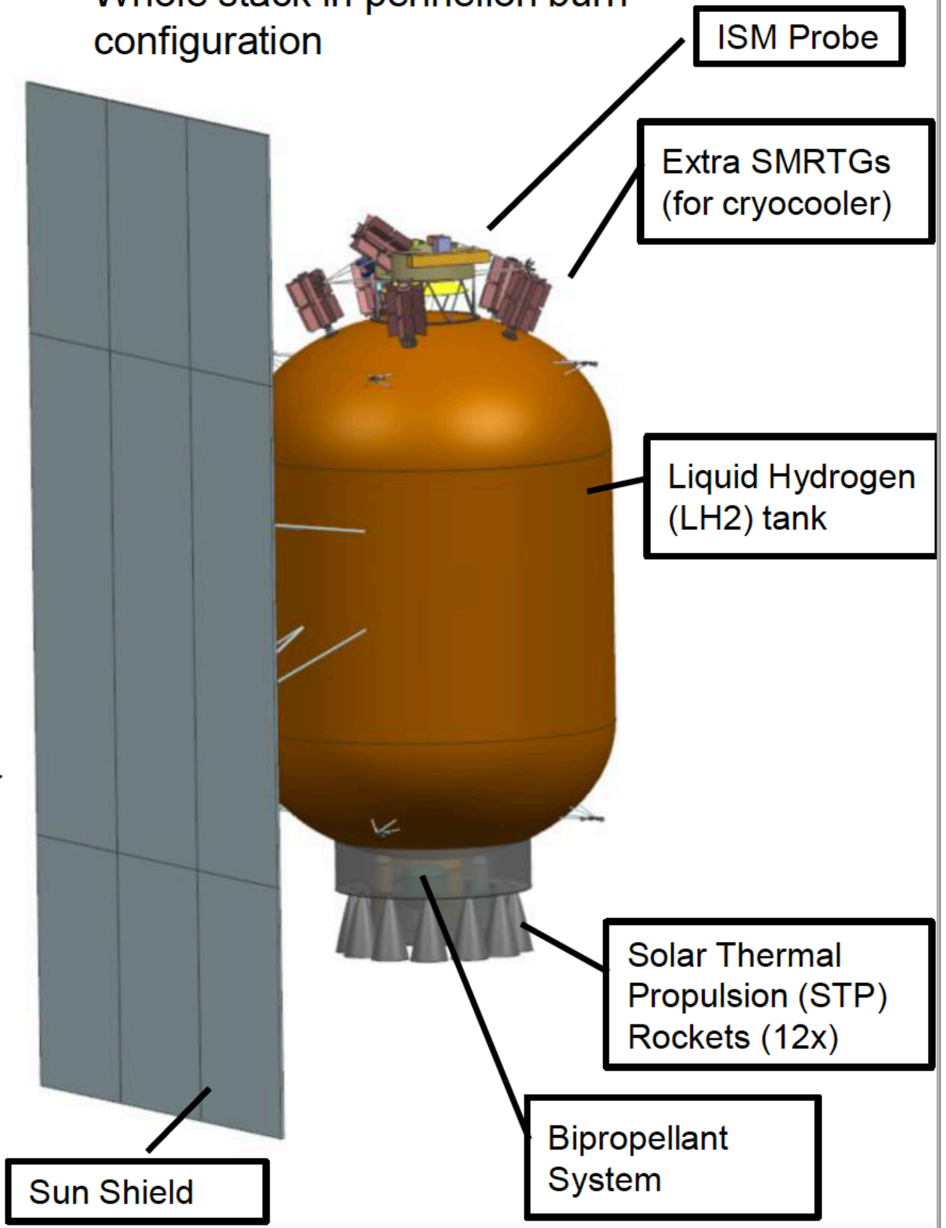


- **Interstellar Medium Probe (ISM Probe)**
  - A small "New Horizons Class" spacecraft for probing the Interstellar Medium (ISM), with a KBO flyby for good measure
  - Carries 8 instruments

- **Solar Thermal Propulsion (STP) Stage**
  - Uses a Solar Thermal Propulsion (STP) system to provide 11.2 km/s of ΔV at Perhelion ("Perihelion Burn") to eject the Probe from the Solar System *really fast*
  - Has a huge Liquid Hydrogen (LH2) tank. LH2 has low density but allows for very high Isp (1350s)
  - Carries Sun Shield (see next slide)

- **The Interstellar Medium Probe rides "on top" of the STP stage during the Perihelion burn**

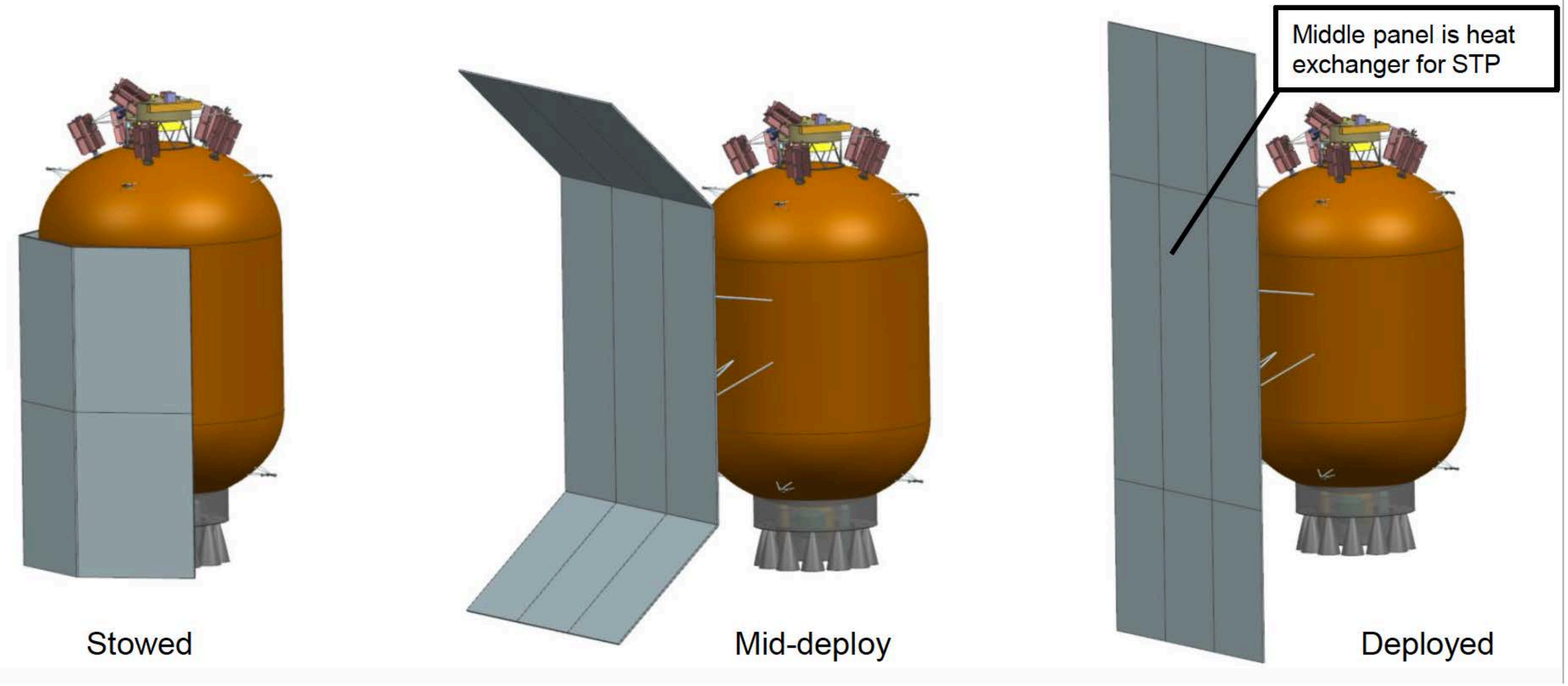
Whole stack in perihelion burn configuration



Sun Shield + Heat Exchanger Summary

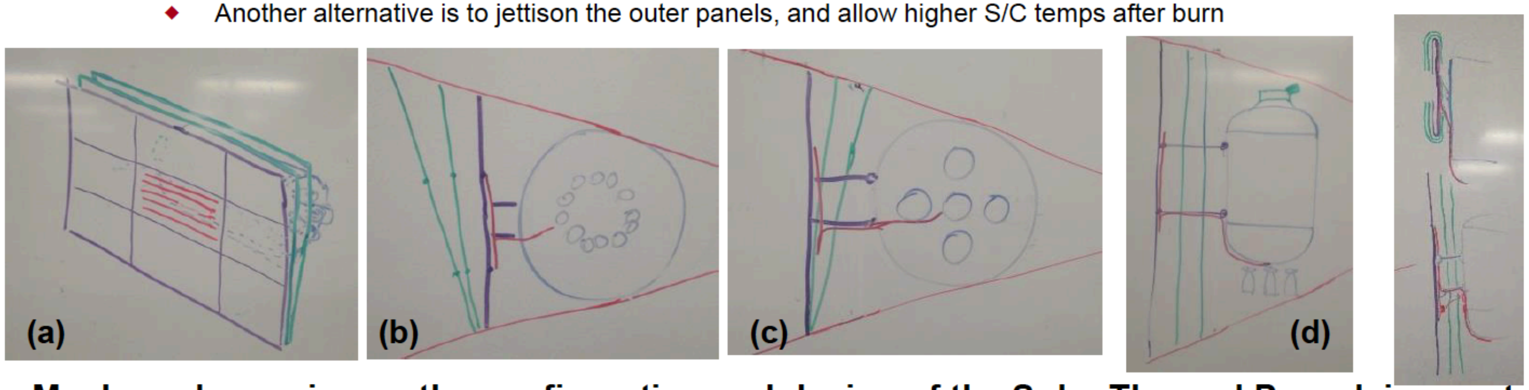
The STP stage carries a huge folded “Sun Shield” to protect the whole stack at Perihelion (3 solar radii)

- Sun Shield also contains an integrated heat exchanger, to power the Solar Thermal Rocket
- The Sun Shield is larger than the rest of the stack when un-folded, so it must be “double folded” along two axes and four fold lines
- It must also be deployed to get it 2 m away from the LH2 tank for thermal reasons
- An additional set of actuations are needed for the Sun Shield to open like a book (not shown, see “Notes about the Sun Shield” slide)

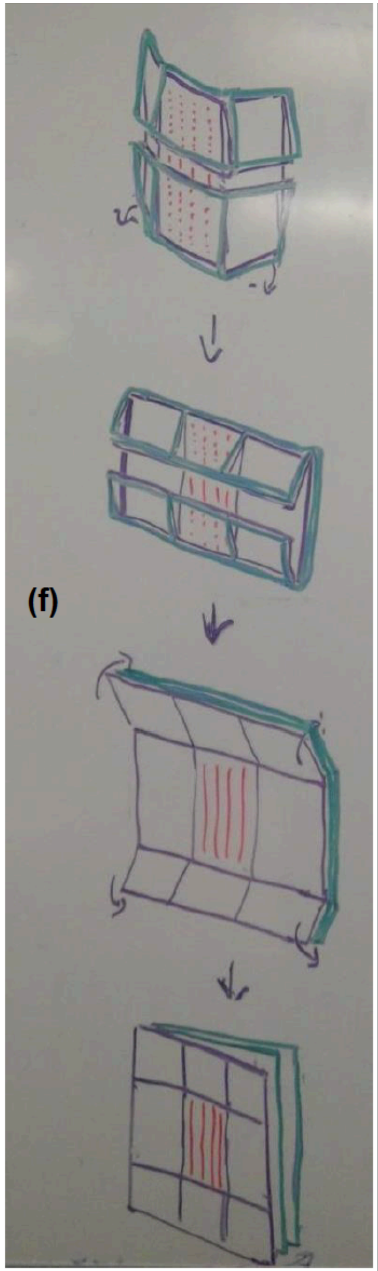


Sun Shield Design 1

- **The Sun Shield is a significant design challenge**
  - We arrived at a design that seems promising, but needs further work
  - Note that the shield has to be significantly larger than the area it protects, because at 3 solar radii the Sun is a large disk rather than a point source.
  - The shield folds in two dimensions, along four fold lines (see diagram (f) at right)
  - The center panel has an integrated heat exchanger for the STP engine (red lines in diagrams)
  - The shield must pack close to the tank for launch, but to keep the tank cool it must deploy to 2 m away (diagram (e), below)
    - Which means flowing hot hydrogen through an articulation
  - To keep the inner shield cool enough (to not overheat the tank), we needed a three-layered shield, so the layers have to open (like pages of a book, green layers in diagrams). The inner shield has the heat exchanger, as shown in diagram (b).
  - Prior to the STP burn, we assume that “the book closes” so the heat exchanger can get hot through conduction through the shield layers.
    - An alternative is to put the heat exchanger on the outer panel, diagram (c)
    - Another alternative is to jettison the outer panels, and allow higher S/C temps after burn



(e)

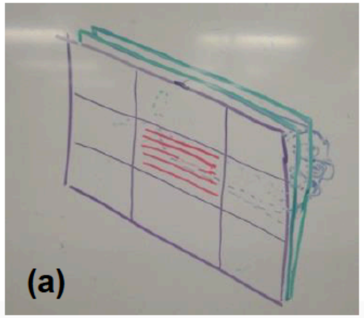

(f)

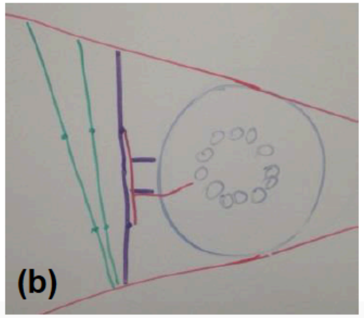
- **Much work remains on the configuration and design of the Solar Thermal Propulsion system**
  - Design of the heat exchanger, high-temperature H2 plumbing, and full thermal analysis
  - This study assumes a (probably very difficult) actuated heat exchanger with flexible Hydrogen pipes; but there may be a way to fit with a fixed heat exchanger, especially if we can use a 10 m fairing
  - **Can a flat plate Carbon-Carbon solar shield actually survive at 3 solar Radii?**
  - **Can we actually get our heat exchanger to 3400 K ? (see Thermal report)**

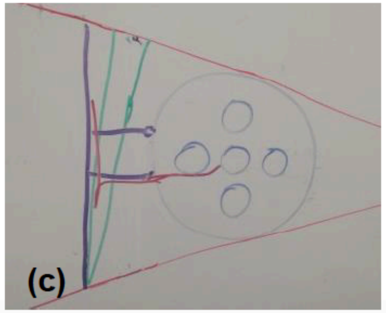
Sun Shield Design 2

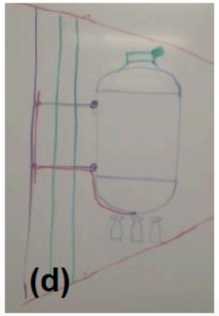
The Sun Shield is not modeled explicitly, but simply left as a mass allocation

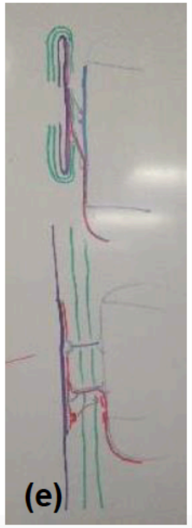
- **The STP stage propulsion, structures, etc. are sized to the Launch Vehicle allocation**
- **After all subsystems are sized, any remaining mass allocation is allocated to the Sun Shield**
  - → 1,866 kg
- **Based on the geometry of the flight stack, we can calculate how much area of Sun Shield is required (see details in additional notes at end of Systems report)**
  - → (10.3 m width x 18.7 m length) = 193 m^2
- **We calculate an allocation per area**
  - → 9.9 kg/m^2
  - Comparisons:
    - 2001 Thiokol paper: 3.3 kg/m^2 (un-margined)
    - 2014 Team X ISM study: 8.2 kg/m^2 side shield, 22.9 kg/m^2 conical nose shield (un-margined)
    - Richard Otero's models (from 2014): 14.9 kg/m^2 side shield, 148 kg/m^2 conical nose shield (un-margined)
- **This mass includes:**
  - Three layers of heat shield
  - An integrated heat exchanger
  - All Hydrogen plumbing from the tank to the heat exchanger and back to the engines
  - Mechanism for un-folding, along two dimensions and four fold lines (see diagram f at right)
  - Mechanism for deploying the entire Sun Shield out to 2 m from the LH2 tank (diagram e)

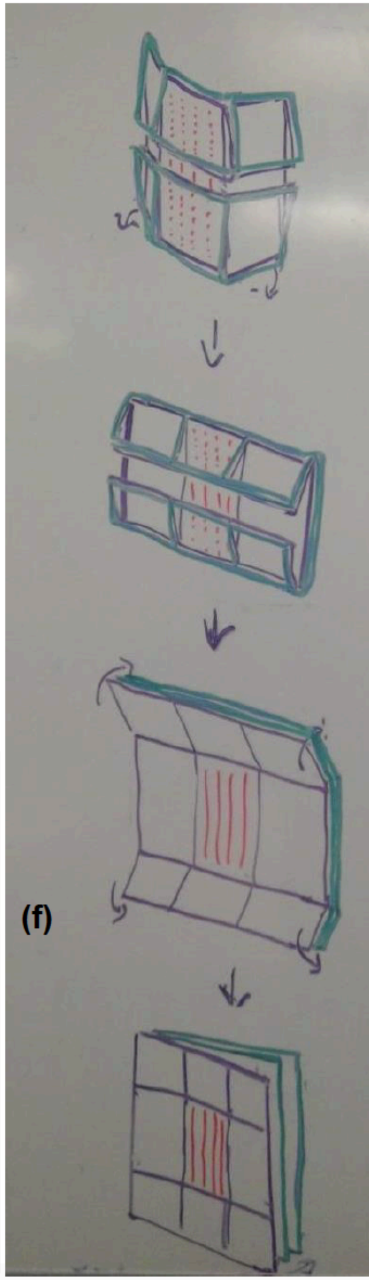

(a)


(b)


(c)


(d)

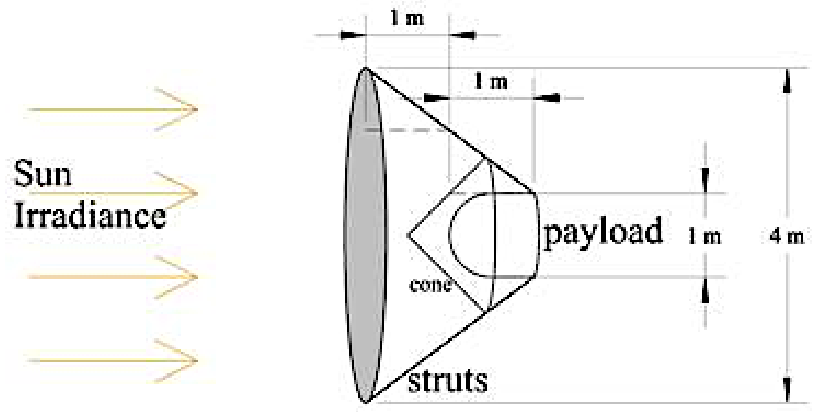

(e)


(f)

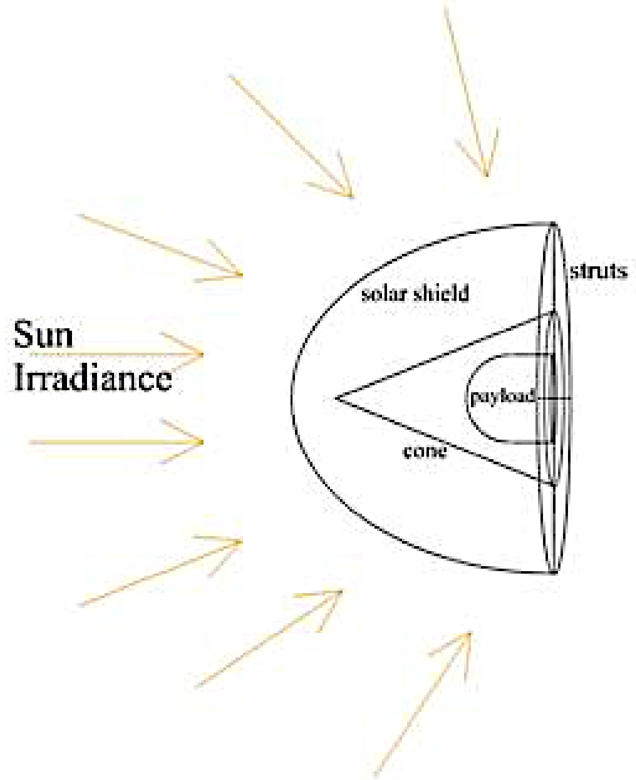
NIAC (via Jonathan)

1.67 solar radii to the center of the Sun with a flat shield !

- Our design is at 3 Solar Radii



1.4 solar radii to the center of the sun with a curved shield



Probe: Design Summary

- **ACS**
  - Sun Sensors, IMUs, Star Trackers
    - No reaction wheels
  - Mass: 33.8 kg
- **CDS**
  - 3U form factor of JPL Reference Bus
  - Mass: 14.9 kg
- **Power**
  - 1 SMRTG with 16 GPHS modules (558 W beginning of mission)
  - 22-Ah Li-ION battery
  - Mass: 99.2 kg
- **Propulsion**
  - Monoprop system for post-separation control and TCMs
  - 16 0.2-lbf thrusters
  - N2H4 Fuel Mass = 22.4 kg
  - Prop System Mass = 17.2 kg
- **Structures**
  - Primary Structure Mass = 63.7 kg
  - Secondary Structure Mass = 7.6 kg
  - Mechanisms
    - STP separation interface = 13.0 kg
- **Telecom**
  - Direct-to-Earth Communication
  - 1.5-m fixed X-band HGA on spin axis
  - Two X-band LGA
  - Mass = 29.6 kg
- **Thermal**
  - Passive and active thermal control
  - Mass = 30.1 kg
- **Instruments**
  - Deep space science suite
  - LORRI/MER camera for fly-by imaging of KBO
  - Mass= 42.4 kg
- **Ground Systems**
  - Ground Network = DSN
  - 1 pass per week at 0.2 kb/s at 100 AU

All masses CBE + contingency

Probe: Mass and Power Summary

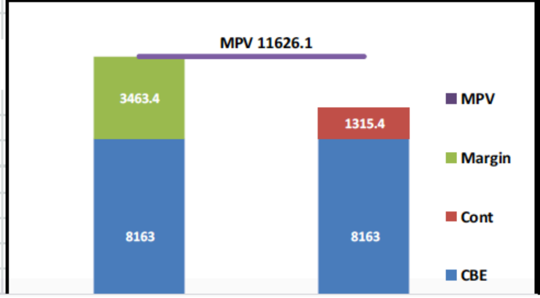
		Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Pre-Separation Cruise	Mode 2 Power (W) TCM	Mode 3 Power (W) Stack Fast Slew	Mode 4 Power (W) Perihelion Kick	Mode 5 Power (W) Cruise Jupiter Flyby	Mode 6 Power (W) Fly-by imaging	Mode 7 Power (W) Probe Downlink	Mode 8 Power (W) Recharge	Mode 9 Power (W) Post-Separation Cruise	Mode 10 Power (W) TBD
Power Mode Duration (hours)						*24*	*0.25*	*0.2*	*0.5*	*24*	*3*	*2*	*8*	*24*	
Payload on this Element															
Instruments		10%	35.7	19%	42.4	0	0	0	0	0	19	0	0	0	0
Payload Total		10%	**35.7**	19%	**42.4**	**0**	**0**	**0**	**0**	**0**	**19**	**0**	**0**	**0**	**0**
Additional Elements Carried by this Element															
Carried Elements Total		0%	**0.0**	0%	**0.0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
RSDO Option -->															
Spacecraft Bus				do not edit formulas below this line, use the calcualtions and override tables instead -->											
Attitude Control		9%	30.7	10%	33.8	10	53	53	53	53	53	53	0	53	0
Command & Data		4%	13.0	15%	14.9	38	38	38	38	38	38	38	38	38	0
Power		23%	80.6	23%	99.2	29	24	27	27	27	27	27	27	27	0
Propulsion1 ☐ SEP1		4%	15.7	9%	17.2	1	64	1	1	1	64	32	1	1	0
Propulsion2 ☐ SEP2		0%	0.0	0%	0.0	0	0	0	0	0	0	0	0	0	0
Propulsion3 ☐ SEP3		0%	0.0	0%	0.0	0	0	0	0	0	0	0	0	0	0
Structures & Mechanisms		27%	96.6	30%	125.5	0	0	0	0	0	0	0	0	0	0
S/C-Side Adapter		0%	0.0	0%	0.0										
Cabling		9%	31.5	30%	40.9										
Telecom		7%	25.8	15%	29.6	24	125	125	125	24	12	125	12	24	0
Thermal		7%	25.1	20%	30.1	18	10	10	0	18	28	28	28	28	20
Bus Total			318.9	23%	391.2	120	314	254	244	161	222	304	106	171	20
Thermally Controlled Mass					391.2										
Spacecraft Total (Dry): CBE & MEV			**354.5**	22%	**433.6**	120	314	254	244	161	241	304	106	171	20
Subsystem Heritage Contingency	22%		79.0	SEP Cont	10%	0	0	0	0	0	0	0	0	0	0
System Contingency	21%		73.4			51	135	109	105	69	104	131	46	73	8
Total Contingency ☐ Include Carried?	**43%**		152.5												
Spacecraft with Contingency:			**507**	of total	w/o addl pld	**171**	**449**	**363**	**349**	**230**	**345**	**434**	**152**	**244**	**28**
Propellant & Pressurant with residuals1		4%	22.4		For S/C mass =	550.0		Delta-V, Sys 1	20.0	m/s	residuals =	0.5	kg		
Propellant & Pressurant with residuals2		0%	0.0		For S/C mass =	0.0		Delta-V, Sys 2	0.0	m/s	residuals =	0.0	kg		
Propellant & Pressurant with residuals3		0%	0.0		For S/C mass =	0.0		Delta-V, Sys 3	0.0	m/s	residuals =	0.0	kg		
Spacecraft Total with Contingency (Wet)			**529**												

STP Stage: Design Summary

- **ACS**
  - (No hardware)
- **CDS**
  - Control box for the deployments and SMRTG release
  - Mass: 28.1 kg
- **Power**
  - 5 SMRTGs with 16 GPHS modules each (2130 W at perihelion, ejected prior to burn)
  - 22-Ah Li-ION battery
  - Mass: 339.2 kg
- **Propulsion**
  - Biprop system for TCMs and ACS
    - Single 200-lbf main engine
    - 16 5-lbf thrusters
    - N2H4 Fuel Mass = 668.5kg
    - Biprop System Mass = 114.6 kg
  - Solar Thermal Propulsion System for Perihelion burn
    - 12 STP Engines
    - LH2 tank (assumed 0.39 mass tax on LH2)
    - LH2 propellant mass = 15,705 kg
    - STP System Mass = 4,758 kg
- **Structures**
  - Structure Mass = 372 kg
  - SMRTG ejection mechanisms = 39 kg
  - Balance/Ballast = 630 kg
  - S/C side adapter = 165 kg
  - Harness = 390 kg
- **Telecom**
  - X-Band Patches for comm when HGA is obscured
  - Mass = 0.5 kg
- **Thermal**
  - Cryocoolers and Tank insulation are assumed to be included in the LH2 tank mass
  - Mass = 0 kg bookkept
- **Instruments**
  - (none)

STP Stage: Mass and Power Summary

		Mass Fraction	Mass (kg)	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Pre-Separation Cruise	Mode 2 Power (W) TCM	Mode 3 Power (W) Stack Fast Slew	Mode 4 Power (W) Perihelion Kick	Mode 5 Power (W) Cruise Jupiter Flyby	Mode 6 Power (W) TBD	Mode 7 Power (W) TBD	Mode 8 Power (W) TBD	Mode 9 Power (W) TBD	Mode 10 Power (W) TBD
Power Mode Duration (hours)						*24*	*0.25*	*0.2*	*1.2*	*24*					
Payload on this Element															
Instruments		0%	0.0	0%	0.0	0	0	0	0	0	0	0	0	0	0
Payload Total		0%	0.0	0%	0.0	0	0	0	0	0	0	0	0	0	0
Additional Elements Carried by this Element															
Probe (mass only)		5%	377.0	40%	529.4										
Sun Shield		17%	1304.9	43%	1866.1										
(none)		0%	0.0	43%	0.0										
Carried Elements Total		21%	1681.9	42%	2395.5	0	0	0	0	0	0	0	0	0	0
RSDO Option -->															
Spacecraft Bus				do not edit formulas below this line, use the calcualtions and override tables instead -->											
Attitude Control		0%	0.0	0%	0.0	0	0	0	0	0	0	0	0	0	0
Command & Data		0%	25.5	10%	28.1	36	36	36	36	36	0	0	0	0	0
Power		3%	263.6	29%	339.2	18	18	18	18	18	0	0	0	0	0
Propulsion1 ☐ SEP1		1%	107.5	7%	114.6	26	25	26	14	26	0	0	0	0	0
Propulsion2 ☐ SEP2		58%	4601.6	3%	4758.6	0	0	0	0	0	0	0	0	0	0
Propulsion3 ☐ SEP3		0%	0.0	0%	0.0	0	0	0	0	0	0	0	0	0	0
Structures & Mechanisms		10%	771.3	30%	1002.7	0	0	0	0	0	0	0	0	0	0
S/C-Side Adapter		2%	126.8	30%	164.8										
Cabling		4%	300.2	30%	390.2										
Telecom		0%	0.5	2%	0.5	0	0	0	0	0	0	0	0	0	0
Thermal		0%	0.0	0%	0.0	1150	1150	1150	0	1150	0	0	0	0	0
Bus Total			6196.9	10%	6798.8	1229	1229	1229	67	1229	0	0	0	0	0
Thermally Controlled Mass					6798.8										
Spacecraft Total (Dry): CBE & MEV			7878.9	17%	9194.3	1229	1229	1229	67	1229	0	0	0	0	0
Subsystem Heritage Contingency	17%		1315.4	SEP Cont	10%	0	0	0	0	0	0	0	0	0	0
System Contingency	26%		2062.9			529	528	529	29	529	0	0	0	0	0
Total Contingency ☐ Include Carried?	43%		3378.3												
Spacecraft with Contingency:			11257	of total	w/o addl pld	1758	1757	1758	96	1758	0	0	0	0	0
Propellant & Pressurant with residuals1		2%	668.5		For S/C mass =	27668.0		Delta-V, Sys 1	70.0	m/s	residuals =	17.5	kg		
Propellant & Pressurant with residuals2		57%	15705.4		For S/C mass =	27668.0		Delta-V, Sys 2	11200.0	m/s	residuals =	457.4	kg		
Propellant & Pressurant with residuals3		0%	0.0		For S/C mass =	0.0		Delta-V, Sys 3	0.0	m/s	residuals =	0.0	kg		
Spacecraft Total with Contingency (Wet)			27631	27631.065											
Aeroshell Mass			n/a		Entry System Dia.	0.0	m								
Entry System Mass			n/a		Ballistic Coefficient	n/a	kg/m^2								
L/V-Side Adapter			368.9		Wet Mass for Prop Sizing	27631		BOL Power:	0.0	W					
Launch Mass			28000		Dry Mass for Prop Sizing	11257		EOL Power:	0.0	W					
Launch Vehicle Capability			28000		28000.0										
						Launch C3	0								
Launch Vehicle Margin			0.0			Mission Unique LV Contingency	0%								
						Fairing dia., m	0								
Dry Mass Allocation: MPV			11626.1												



Mission Risk Summary

The design is right on the edge of infeasibility (with margins)

- It is VERY sensitive to tank mass fraction, shield mass, Isp, structures mass…
- A degradation in any of these assumptions quickly renders the design infeasible

Liquid Hydrogen (LH2) tank

- **The mass of the LH2 tank was calculated using a fixed mass tax (m_tank = m_fuel * 0.39) (based on discussion with MSFC)** and includes margin, so the tank CBE is backed out as m_fuel * 0.39 * 0.7
- The tanks are assumed to provide primary structural support for everything else.
- This includes the mass of the insulation and cryocoolers. However, our thermal requirements are more stringent than MSFC may have been assuming, so our tax may be too low

Solar Thermal Propulsion

- **We assume an Isp of 1350s, which is high, and requires a Hydrogen temperature of 3400K**
- This is higher than our initial Isp assumption of 1100s, and may not be technologically achievable
- This temperature is very close to the Carbon-Carbon melting temperature of 3800K (as cited by the 2001 Thiokol paper).
- **However, if the Isp is lower than about 1250s, our design does not close**

Radioisotope Thermal Generator (RTG)

- We assumed the future Segmented Modular RTG (SMRTG), currently under development
- We had to use five SMRTGs on our STP stage just to power the cryocooler, plus one on the probe
- It is unclear whether that many SMRTGs would be available, and there could be challenges with integrating them on the pad (due to their awkward positioning in our configuration)