JPL ISM STP Study Summary

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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

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<thead>
<tr>
<th>Nominal Mission Plan</th>
<th>DV (m/s)</th>
<th>Comments</th>
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<td>19</td>
<td>TCM-14</td>
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<td>20</td>
<td>Makemake Flyby</td>
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STP DV = 11.2 km/s

Probe DV = ~94 m/s
Mission Power Modes

- **Pre-Separation Cruise**: 24 hours
  - Star trackers
  - CDH
  - Telecom duty cycled 10%
  - Thermal control with shield + thruster heating

- **TCM**: 0.25 hours
  - Stack Fast Slew 0.2 hours
    - Star trackers and IMUs
    - CDH
    - Telecom duty cycled 10%
    - Thermal control with shield

- **Cruise Jupiter Fly-by**: 24 hours
  - Stack Fast Slew 0.2 hours
    - Star trackers and IMUs
    - CDH
    - Telecom
    - Thermal control with shield

- **Perihelion Kick**: 1.2 hours
  - Stack Fast Slew 1.2 hours
    - Star trackers and IMUs
    - CDH
    - Telecom
    - Thermal control with shield + thruster heating

- **Fly-by Imaging**: 3 hours
  - Perihelion Kick 3 hours
    - Star trackers and IMUs
    - CDH
    - Telecom
    - Thermal control + thruster heating

- **Recharge**: 3 hours
  - Fly-by Imaging 3 hours
    - CDH
    - Telecom standby
    - Thermal control + thruster heating

- **Post-Separation Cruise**: 24 hours
  - Recharge 3 hours
    - 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 Perihelion (“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*
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

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
  - \( \rightarrow 1,866 \) 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)
  - \( \rightarrow (10.3 \text{ m width} \times 18.7 \text{ m length}) = 193 \text{ m}^2 \)

- We calculate an allocation per area
  - \( \rightarrow 9.9 \text{ kg/m}^2 \)
  - 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)
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

### Power Mode Duration (hours)

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<tbody>
<tr>
<td>Pre-Separation Cruise</td>
<td>TCM</td>
<td>Fast Slew</td>
<td>Perihelion Kick</td>
<td>Cruise</td>
<td>Fly-by</td>
<td>Downlink</td>
<td>Recharge</td>
<td>Post-Separation Cruise</td>
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### Payload on this Element

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<th>Total</th>
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<td>10%</td>
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### Additional Elements Carried by this Element

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<th>Carried Elements Total</th>
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### Spacecraft Bus

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<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
<th>Subsys Cont. %</th>
<th>CBE+ Cont. (kg)</th>
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<tr>
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<tr>
<td>Command &amp; Data</td>
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<td>Propulsion2 □ SEP2</td>
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<td>Propulsion3 □ SEP3</td>
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<td>0.0</td>
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<td>Thermal</td>
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<td>Bus Total</td>
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### Spacecraft Total (Dry): CBE & MEV

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<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
<th>Subsys Cont. %</th>
<th>CBE+ Cont. (kg)</th>
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<tbody>
<tr>
<td>Subsystem Heritage Contingency</td>
<td>79.0</td>
<td>22%</td>
<td>433.6</td>
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<tr>
<td>System Contingency</td>
<td>73.4</td>
<td>21%</td>
<td>152.5</td>
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<tr>
<td>Total Contingency</td>
<td>152.5</td>
<td>43%</td>
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### Spacecraft with Contingency

- Propellant & Propellant with residuals 1: 4%<br> 224.0 m/s<br> Mass = 550.0 kg<br> Delta-V, Sys 1: 20.0 m/s<br> Residuals = 0.0 kg
- Propellant & Propellant with residuals 2: 0%<br> Mass = 0.0 kg<br> Delta-V, Sys 2: 0.0 m/s<br> Residuals = 0.0 kg
- Propellant & Propellant with residuals 3: 0%<br> Mass = 0.0 kg<br> Delta-V, Sys 3: 0.0 m/s<br> Residuals = 0.0 kg

### Spacecraft Total with Contingency (Wet)

| Mass (kg) | 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 = 668.5 kg
    - 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

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<td>Payload on this Element</td>
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### Additional Elements Carried by this Element
- Probe (mass only): 377.0 kg, 40% CBE+ 528.4 kg
- Sun Shield: 1304.9 kg, 43% CBE+ 1866.1 kg
- None: 0 kg, 0% CBE+ 0 kg
- Carried Elements Total: 1681.9 kg, 42% CBE+ 2395.5 kg

### Spacecraft Bus
- Attitude Control: 0% 0% 0% 0% 0% 0% 0% 0% 0% 0% 0% 0% 0% 0% 0%
- Command & Data: 25.6 kg, 10% CBE+ 28.1 kg
- Power: 253.6 kg, 29% CBE+ 338.2 kg
- Propulsion 1 SEP1: 107.3 kg, 7% CBE+ 146.4 kg
- Propulsion 2 SEP2: 460.1 kg, 3% CBE+ 476.8 kg
- Propulsion 3 SEP3: 0 kg, 0% CBE+ 0 kg
- Structures & Mechanisms: 771.3 kg, 30% CBE+ 1002.7 kg
- Service-Exp Adapter: 126.8 kg, 30% CBE+ 154.8 kg
- Cabling: 300.2 kg, 30% CBE+ 390.2 kg
- Telecom: 0 kg, 0% CBE+ 0 kg
- Thermo: 0 kg, 0% CBE+ 0 kg
- Bus Total: 6196.9 kg, 10% CBE+ 6798.8 kg

### Spacecraft Total (Dry): CBE & NEV
- 7678.9 kg, 17% CBE+ 9194.3 kg

### System Contingency
- 3378.3 kg, 43% CBE+ 3378.3 kg

### Spacecraft with Contingency
- 11257 kg, 17% CBE+ 15178 kg

### Dry Mass Allocation: MPV
- 11826.1 kg

### Additional Notes
- Do not edit formulas below this line; use the calculations and override tables instead.
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 \( m_{\text{tank}} = m_{\text{fuel}} \times 0.39 \) (based on discussion with MSFC) and includes margin, so the tank CBE is backed out as \( m_{\text{fuel}} \times 0.39 \times 0.7 \)
• 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)