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A VISION FOR PLANETARY AND EXOPLANETS SCIENCE: EXPLORATION OF THE INTERSTELLAR MEDIUM – THE SPACE BETWEEN STARS

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Abstract

A science and exploration program is proposed in which traditional Planetary, Heliophysics, Astrophysics and Exoplanet sciences are served with robotic missions that explore the far reaches of our solar system and eventually, embark on a long road to visit an exoplanet. As we learn more about our own solar system we can apply that knowledge to the observations of distant stars and resident exoplanets. This paper describes a program that consists of a series of missions to deploy robotic probes to explore the interstellar medium (ISM) as a pathway towards one-day reaching an exoplanet. We divide this program of ISM probes into 4 elements: 1) Exploration of the Local ISM (LISM) using groups of small satellite explorers for the in-situ exploration of the ISM at distances of 50-200 AU from the Sun; 2) deep-ISM probes to explore the pristine ISM and travelling at > 20AU/year reaching distances of 200 - 400 AU from the Sun in ~20 years from launch; 3) probes to deliver imaging telescopes to the Solar Gravity Lens Focus area of our Sun at distances of 500 – 800 AU, for the multi-pixel high-resolution imaging of exoplanets prior to sending a dedicated probe towards an exoplanet; 4) technology development program to develop and demonstrate technologies that will one day allow our robotic explorers to leave our solar system at increasing higher velocities and reach an exoplanet that was previously imaged by the SGL observatory emplaced by the probes developed under item 3 above.

INTRODUCTION

As of today (2017), the international space science community and the international space agencies can claim that we (humanity) have visited all planets and Pluto (with the New Horizons [2] spacecraft) in our solar system, we have landed and returned samples from comets and asteroids, and pierced the Heliosphere and sensed the interstellar medium (Voyager-1), the space between stars in our galaxy. We have continuous robotic presence on Mars for the past 20 years, with plans to return samples and send humans to the red planet.

However, as evidenced by recent breakthrough discoveries by the Cassini spacecraft at Saturn and its moons [20], and by the Juno spacecraft at Jupiter and its moons [19], as well as by other robotic explorers and telescopes currently operating in space, our understanding of the origins, evolution and workings of our own solar system are still at an early stage of discovery. As we plan to send robotic explores to sample the geysers of Saturn's moon Enceladus [9], land in the lakes on Saturn's moon Titan [18], or reach the liquid oceans of Juno's moon Europa [10], we will look for evidence of past and present forms of life, and we will continue to seek the answer to the question: *How did our solar system evolve from a primordial proto-stellar nebula of dust and particles, into a life bearing solar system intelligent enough to investigate its own past and scientifically forecast its future*?

Among the most stunning developments of the past decade in space exploration is the fact that we now know that planets around other solar systems are in abundance. At the latest count, Kepler [3] and other space observatories as well as ground-based telescopes have found over four thousand exoplanets, some of which are deemed to be Earth-like in what is referred to as the 'Goldilocks zone'.

The pursuit of knowledge of our own solar system's evolution and the further observation of distant solar systems provides for an intra-galactic scientific testbed by which our own solar system acts as a control-case for the understanding of distant solar systems. The more we understand our own solar system and the processes that were essential in its formative years and subsequent evolution to the present state, the better we can understand the same for other solar systems in our galaxy. Therefore, it is reasonable to assume that in the future, these two, otherwise disjoint fields will continue to overlap and inform each other as new discoveries are made. There are, after all, only eight planets in our solar system, and so far over four thousand planets discovered in neighboring solar systems.

The discovery of plethora of exoplanets was accompanied by another remarkable event in space exploration history. Voyager-1, launched 40 years ago, survived long-enough to transition from a planetary fly-by mission within our solar system, traveling through the Heliosphere into the Heliopause, to become the first functioning inter-stellar explorer sensing the medium between stars, that is, the interstellar medium (ISM).

In 2013-2014, just as Voyager-1 [1] was exiting the Heliosphere, Stone, Alkalai and Friedman co-led a team of scientists and engineers in a study funded by the Caltech Keck Institute for Space Studies (KISS) [4, 5] called "*The Science and Enabling Technologies for the Exploration of the Interstellar Medium*." This study focused on answering 3 questions, summarized below:

1. *Is there compelling science in the exploration of the interstellar medium*?

The answer was a strong endorsement detailed with goals and objectives that spanned Planetary, Heliophysics, Astrophysics, and Exoplanets science. The team identified overlapping science regions of interest based on the distance from the Sun:

a. Planetary science 1 – 70 AU;
b. Zodiacal dust science 1 - 10 AU;
c. Kuiper Belt Objects 50 – 700 AU;
d. Heliophysics, Local ISM 100 – 200 AU;
e. Heliophysics, Pristine ISM 200 – 400 AU;
f. Exoplanet science 550 – 800 AU.
g. Astrophysics, astrometry: 100 – 700 AU;
h. Fundamental physics: 100 – 200 AU;

2. *What is a meaningful first step in the exploration of the ISM, as a pathway towards another star*?

The team agreed that exploration of the local and deep (pristine) ISM are reasonable first steps towards reaching another star. The Sun's supersonic solar wind and magnetic field create a protective bubble (Heliosphere) around the Sun with a frontal bow-shock as it travels through the ISM.

It was noted that waiting 40 years to reach the ISM where Voyager is today, was clearly not acceptable. If the cruise time were reduced to < 8-10 years, it would indeed become very attractive to the science community. Thus, a strong recommendation was made to explore innovative and advanced mission design and advanced propulsion technologies to be able to escape the pull of our Sun at higher and

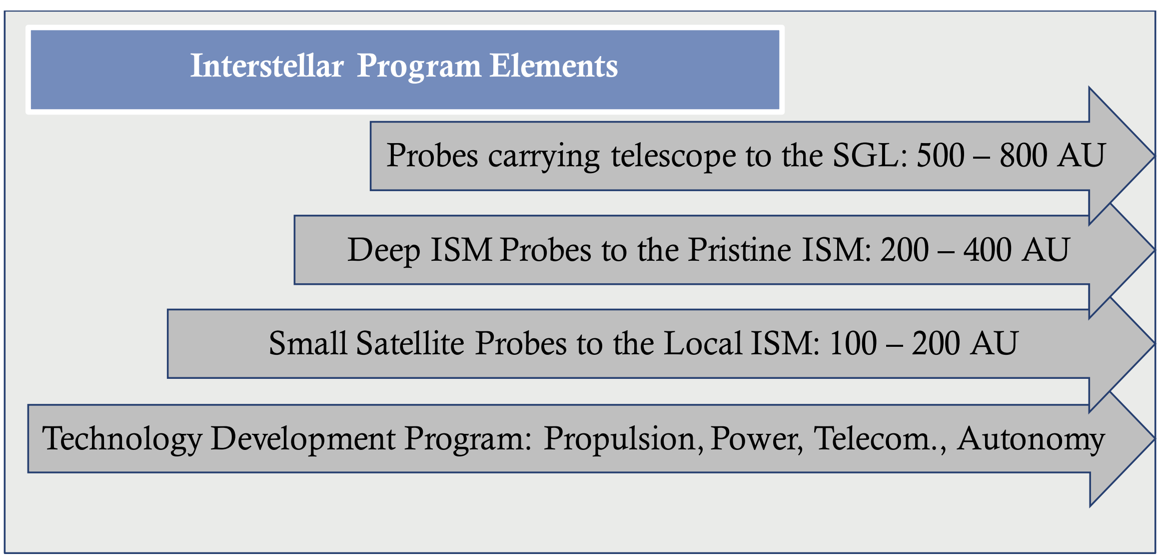

Figure 1: Interstellar Precursor proposed Program Elements : Probes to the Local ISM, Pristine ISM, Solar Gravity Lens (SGL) telescopes, and a long-term technology development program.

higher velocities. Currently, Voyager is traveling at 3.6 AU/year. A near-term goal was set to reach 20 AU/year with technologies that are under development and can be matured in ~10 years.

3. The team also endorsed the goal to study a mission to deploy an optical telescope at the Solar Gravity Lens (SGL [4, 5, 17]) focal line (> 500 AU from the Sun) to obtain high-resolution images of exoplanets using the gravitational lensing of our Sun, before any in-situ mission to an exoplanet is considered.

In this paper, we propose a program for the exploration of the ISM as a first step on a pathway to one-day send a robotic explorer to an exoplanet. In the following section, we outline the scope of each of the four program elements which includes: i) sending multiple small probes to the Local ISM (LISM); ii) sending a smaller set of larger deep-ISM probes to sample the pristine ISM and demonstrate escape velocities of > 20 AU/year; iii) deliver imaging telescopes to the SGL region in 25 – 30 years from launch to provide detailed images of a target exoplanet prior to sending a probe to that exoplanet; iv) a dedicated technology development program to develop advanced technologies in areas such as: propulsion, power, mission and trajectory design, telecommunications, miniaturized instruments, guidance navigation and control, avionics and autonomy.

PROGRAM ELEMENTS:

Figure 1 depicts 4 program elements as follows:

1. Sets of small probes to the Local ISM (LISM)
2. Larger probes to explore the pristine ISM
3. SGL focal line as a destination to deploy telescopes for the detailed imaging of exoplanets
4. A technology development program to serve the above 3 program elements.

We now describe each program element in turn.

1. **Small probes to the Local ISM (LISM):**

The LISM is a scientifically exciting and complex region where the magnetic field and solar wind particles emanating from our Sun interact with the magnetic field and elements that constitute the ISM. Interstellar hydrogen atoms penetrating the Heliosphere interact with the solar wind protons in a charge-exchange process creating energetic ions resulting in a complex set of interactions of magnetic fields from both the ISM and the Sun. A much richer set of in-situ measurements of the local ISM are clearly needed to understand this complex environment. This region, shown in the Figure 2, is currently being explored by both Voyager-1 and its twin probe Voyager-2. Their observations challenge long held ideas about this region as well as the nature and shape of the Heliosphere (Stone et al. 2013). Voyager 1 showed that the Heliosheath is 50% thinner than current models predict, dominated by suprathermal particles. Additioanlly there is an indication that perhaps physical phenomena such as reconnection is taking place in the Helisoheath (Richardson et al. 2015). One of the challenges is that the magnetometer on Voyager spacecraft were designed for the strong magnetic field of the outer planets but not for sensing the weak fields of the solar wind interaction with the ISM. The Voyager

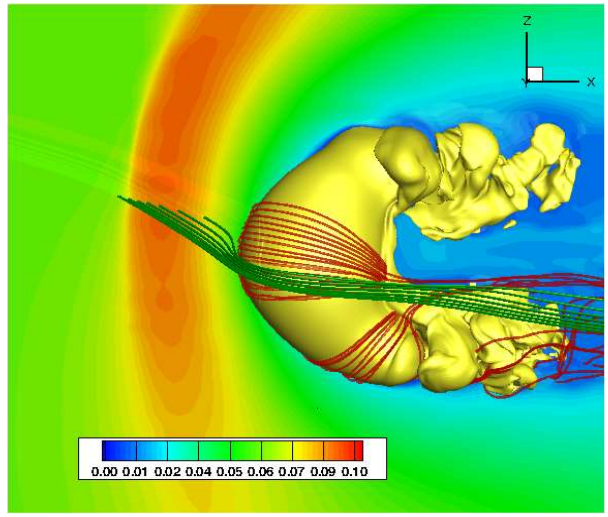

Figure 2: Interaction of the interstellar neutral Hydrogen atoms (color contours in #/cm3) and the interstellar magnetic field (red and green lines) coming into contact with the solar wind protons and magnetic fields in the Heliosphere. Picture courtsey of Merav Opher

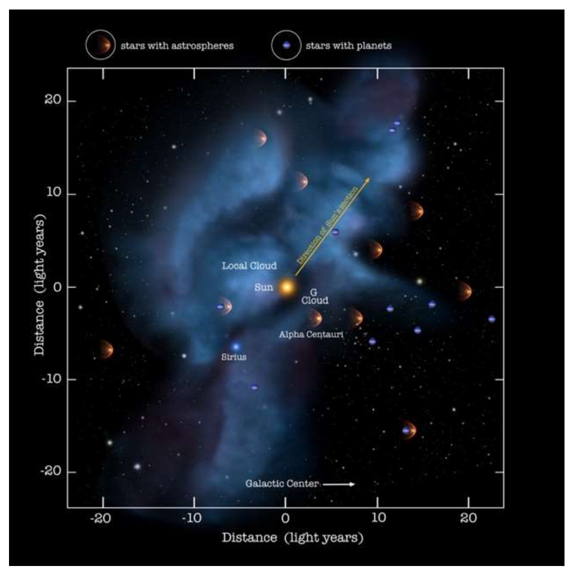

Figure 3: Pristine ISM illustration (image credit: NASA/Adler/U. Chicago/Wesleyan)

discoveries warrant a new visit to this exciting region, the only astrosphere that we know where we can probe with in situ-data using more advanced instrumentation.

In this program element, we envision launching multiple probes on the same launch vehicle to explore the LISM in the 100 – 200 AU region from the Sun. This involves small probes (150 – 200 kg) and building upon the emerging capabilities in the small satellites industry and using miniaturized sensors for the in-situ exploration of the ISM (electro-magnetic fields, particles, etc.). One of the challenges posed by this class of missions will be to achieve long-life (10-20 years of operations), low-mass and low-power, miniaturized integrated systems, deployable structures, on-board autonomy and miniaturized instruments.

2. **Deep (Pristine) ISM Explorers**:
The pristine ISM is truly unexplored territory. Galaxies are roughly equal parts stars and ISM. Just as the Sun has had a profound influence on our understanding of stars, as our closest example, the study of the pristine ISM will likewise be of fundamental importance.

Beyond the Heliopause an unexplored transitional zone exists where the ISM is disturbed by the interaction with the Heliosphere. A buildup of hydrogen (the hydrogen wall) caused by charge exchange between solar system ions and interstellar neutrals is found here. Analogous hydrogen "walls" can be detected around other nearby stars and represents the only means of observing the "astrospheres" of other stars [Wood et al. 2005, ApJ, 628, 143]. A bow shock or bow wave is also present, where the velocity of the interstellar material is decelerated. The Voyager spacecraft has yet to encounter these structures and therefore their detailed properties remain poorly understood.

Line-of-sight spectroscopic observations (principally by the Hubble Space Telescope) indicate that the pristine local ISM is a complex and dynamic environment (see Figure 3 and review by Frisch et al. 2011, ARA&A, 49, 237). The Sun is located at the very edge of the Local Interstellar Cloud, the ISM that defines the structure of the Heliosphere, while a dozen other clouds are closely packed within 15 pc of the Sun [Redfield & Linsky 2008, ApJ, 673, 283]. The origin and evolution of this suite of ISM clouds remains poorly understood.

Several fundamental properties of the pristine local ISM remain difficult or impossible to measure using line-of-sight spectroscopic observations. In particular, the elemental inventory is woefully incomplete. The Heliosphere filters material streaming into the solar system, and line-of-sight spectroscopy is dependent on availability of electronic transitions of gas phase elements.

To compound this issue, there are several components that make up the matter in the pristine local ISM, such as neutral atoms, ions, isotopes, molecules, and dust. A complete inventory of all these components is necessary

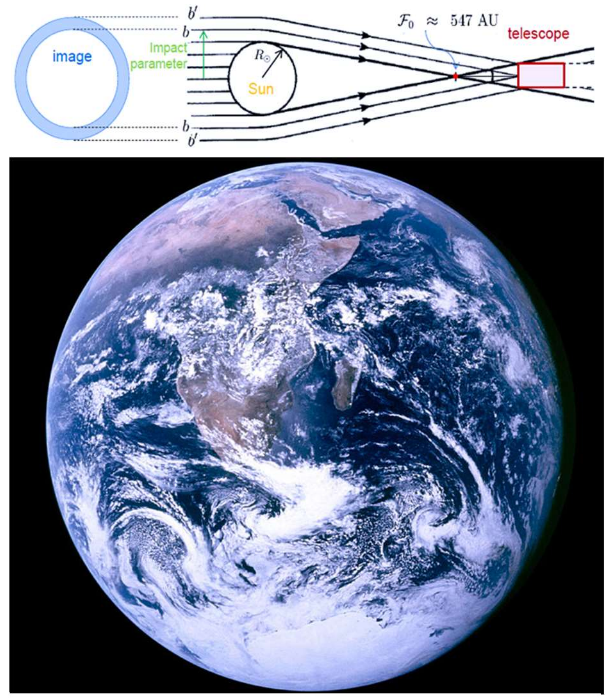

Figure 4: Solar Gravity Lens Concept (top), example 1000 pixel exoplanet image (below)

to evaluate the chemical evolution and mixing that has occurred in the local ISM.

Dust is of particular importance. It is a ubiquitous component of the ISM and is vital to the chemistry of galaxies, from the most abundant molecule (H_2) to the most complex organic molecules (e.g., PAHs). Despite its dominant presence, it is notoriously difficult to measure in detail from afar. We have a very poor knowledge of the composition or size of dust even in the most local ISM environments.

Aside from its fundamental importance to the origin and evolution of the ISM, dust is likely the most important component in terms of the health and safety of any spacecraft traveling through it. Even small dust particles can lead to significant damage or erosion if encountered at high speed. Therefore, as we design and build missions through the ISM, it is vital that the physical properties of the dust be determined.

Finally, just as the Voyager spacecraft opened our eyes and minds to the rich and complex structures of the heliosphere, an interstellar spacecraft capable of in situ measurements of the pristine ISM will provide a whole new understanding of the small-scale structures in this environment. Detailed measurements of density, velocity, temperature, turbulence, and magnetic field, will revolutionize our understanding of the ISM and our place in it.

The pristine ISM is truly the next frontier in terms of unexplored territory. Voyager will not make it out to these regions before power is lost. Therefore, the scientific return from a mission into the pristine local ISM will be of tremendous science value.

We envision a series of probes launched for the explicit purpose of reaching 200 – 400 AU from the Sun and achieving escape velocities of > 20 AU/year. Equipped with state-of-the-art miniaturized instruments for the in-situ exploration of the pristine ISM, these nuclear-powered probes would be designed to last 50 years; hibernate for long-periods of time; conserve power resources and thermal stability; operate autonomously and navigate in deep space, sample the pristine ISM and communicate results back to Earth using perhaps optical communications technology. The high escape velocities would be used as precursors for the delivery of an optical telescope to the SGL for exoplanet imaging.

3. Solar-Gravity Lens Focus (SGLF) Telescope:

According to Einstein's general relativity, gravity imparts refractive properties on space-time causing a massive object to act as a lens by bending photon trajectories. As a result, the gravitationally deflected rays of light passing from all sides of the lensing mass converge at a focus, as shown in Figure 4 below. Gravitational lensing is a well-known effect and has been observed over cosmological distances where relatively nearby galaxies, or even clusters of galaxies, act as gravitational lenses for background galaxies. Even in our Galaxy micro-lensing of stars in the Galactic bulge or in the Magellan clouds are caused by intervening (sub-) stellar bodies. In our Solar System, this effect was originally observed by Eddington in 1919 (thus confirming formally Enstein's theory) and now is routinely accounted for in astronomical observations and deep space navigation (Turyshev 2008).

Building upon the propulsion, mission design and other enabling technologies demonstrated by the deployment of the deep-ISM probes to reach > 20 AU/year escape velocities, and by the low-mass, low-power technologies from the small exploders to the LISM, the SGLF mission will be tasked with placing a state-of-art telescope at the SGLF (>550 – 700 AU) in < 40 years from launch. The SGLF with a ~ 1m telescope will demonstrate the first multi-pixel imaging of a potential life harboring exoplanet and would serve as a precursor to an in-situ exoplanet explorer.

4. Technology Development Program

A long-term technology development program is required that spans many decades and focuses on enabling capabilities such as to develop small satellite explorers to the LISM, deep-ISM explorers to the pristine ISM and the deployment of an imaging telescope to the SGL focal line. Topics for such a technology program include but are not limited to:

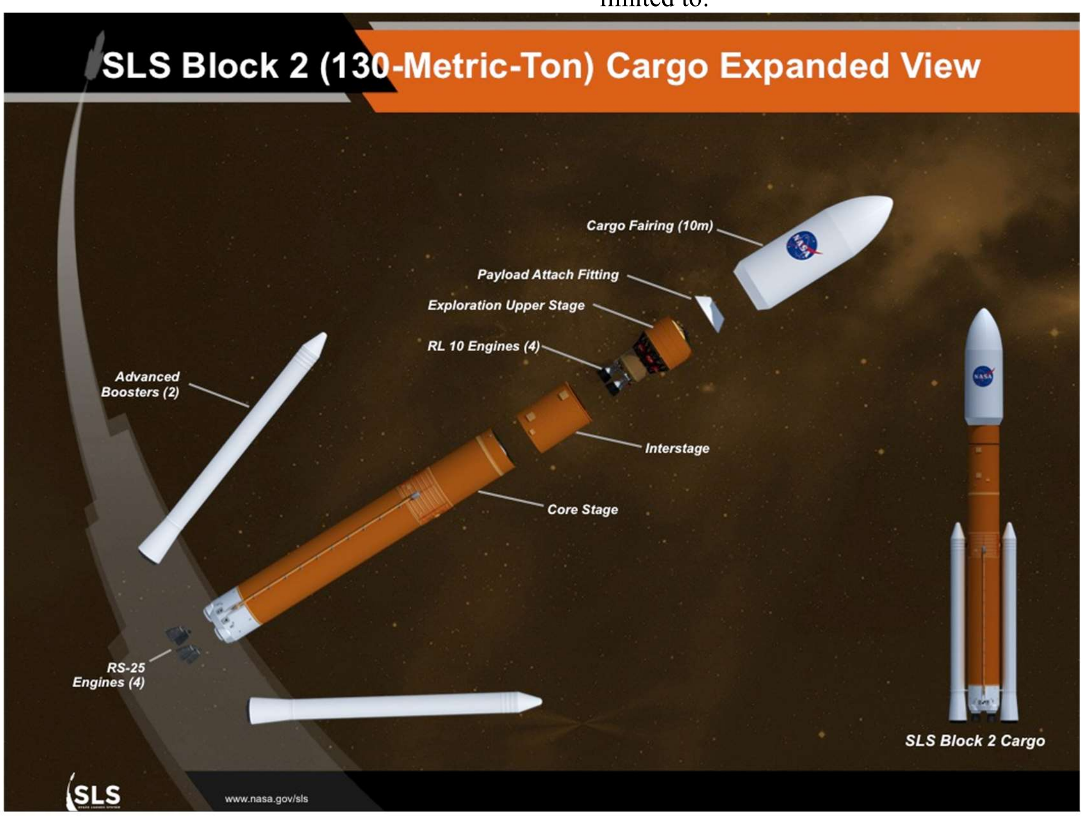

Figure 5: SLS Block 2 Cargo (image credit: NASA)

a) Mission Design and trajectory design to trade between high escape velocity versus flight time;
b) Propulsion systems, such as nuclear-thermal, nuclear fusion, nuclear fission, solar thermal propulsion, laser beamed energy, laser ablation, solar-sails, e-sails and more;
c) Power systems, including nuclear power;
d) Structures such as light weight multi-functional structures, deployable structures, etc.
e) Thermal design and stability, low-power mode, low-temperature systems, etc.
f) Telecommunications systems utilizing both RF and optical communications;
g) Guidance, Navigation & Control including spacecraft stability, pointing to Earth.
h) Avionics systems to support long-term survivability and autonomous operations;
i) Instruments and payload, including highly miniaturized sensors for the in-situ sensing of the ISM.

<u>ISM PROBES MISSION ARCHITECURE</u>

Key elements of the ISM Probes architecture include:

- **Launch Vehicle (LV):** Launch on the largest US launch vehicle: SLS 1b, SLS 2.0 [16], and other future government-furnished or commercial large launch vehicles available.
- **Mission Design**: Use state of the art mission [4, 5, 6, 7, 12] and trajectory design tools to optimize the mission trajectory and utilize techniques to harness the energy in the solar system to achieve high escape velocities relative to the Sun.
- **Flight System**: Use advanced lightweight flight system materials, integrated avionics, multifunctional structures, deployable structures and all means available to reduce the mass of the probe, and design for long-term survivability in deep-space:
    - Power: Use enhanced Nuclear Power (RTG) source of energy for power (no other known solution is available in deep-space).
    - Propulsion: Explore hybrid use of multi-stage advanced propulsion technologies that optimize the use of the propulsion system based on the proximity to the Sun, and consider all options based on their technical readiness, cost and risk: solar sails, e-sails, nuclear thermal propulsion, solar thermal propulsion, laser beamed propulsion, laser ablation propulsion, and other emerging technologies currently under development or under study.
    - Telecom: Use a hybrid of optical and RF communications techniques; use deployable mesh antenna technologies to achieve high aperture from a small volume.
    - Avionics: use radiation hardened avionics developed for the CubeSat industry enhanced for redundancy and low-power and hibernation mode technology.
    - Structures: use of multifunctional structures, deployable or inflatable structures to effectively reduce launch volume and system mass.
    - Payload: use of highly miniaturized set of instruments for both in-situ sensing of the local and pristine ISM, as well as an integrated optical telescope that can also double as a system for optical laser communications with ground stations on Earth or in Earth orbit.
    - Guidance Navigation and Control remain a key challenge, especially navigating and pointing back to Earth from distances of > 200 AU which has never been attempted before.

Launch Vehicle (LV) Capability

Given the lift mass and ΔV requirements, NASA Space Launch System (SLS) was used as the baseline LV. A fairing size of 8.5 m was assumed and a performance equivalent to the SLS-Block 2 configuration with advanced booster and Exploration Upper Stage (EUS), as shown in Figure 5, was assumed.

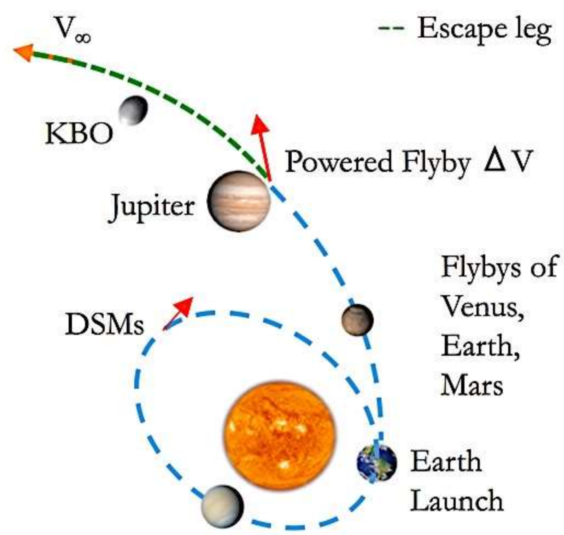

Figure 6: Notional Type 1 Mission Design with powered Jupiter flyby

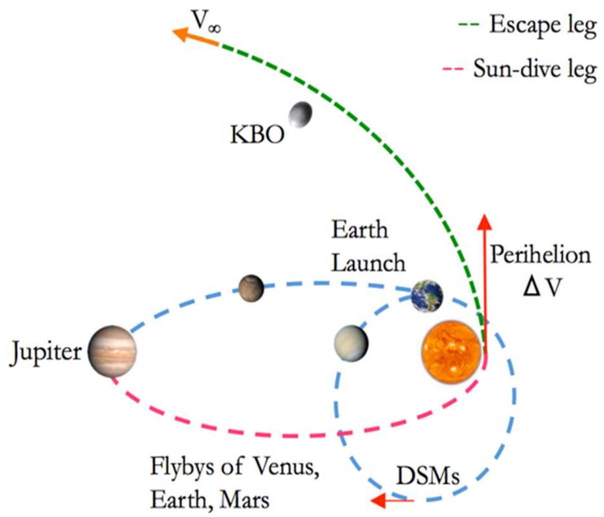

Figure 7: Notional Type 2 Mission Design with perihelion maneuver

Mission-Design

In general, there are two classes of solar-system escape trajectories identified:

- Type 1 trajectories: rely on a powered Jupiter flyby to get the required change in velocity.
- Type 2 trajectories: rely on an impulsive maneuver very close to the Sun before escape.

Maneuvers at the perijove (closest point during Jupiter flyby) and at the perihelion (closest point to the Sun) take advantage of the well-known Oberth effect [8], which states that the efficiency of a propulsive maneuver is proportional to the speed of the spacecraft. This effect is directly proportional to the mass of the gravitational body and the distance from its center.

Figure 6 illustrates a type 1 trajectory broken into three phases:

a. Energy build-up phase: In this phase, the spacecraft increases its orbital energy and achieves required phasing (for targeting a KBO post-Jupiter flyby). The energy build phase may involve a combination of multiple inner solar-system gravity assists and DSMs (for targeting, leveraging, or plane change).

b. Powered flyby phase: In this phase, the spacecraft approaches Jupiter on a hyperbolic trajectory (relative to the planet), performs a ΔV at or near the perijove (Oberth maneuver), and escapes the Jupiter planetary system at significantly higher relative

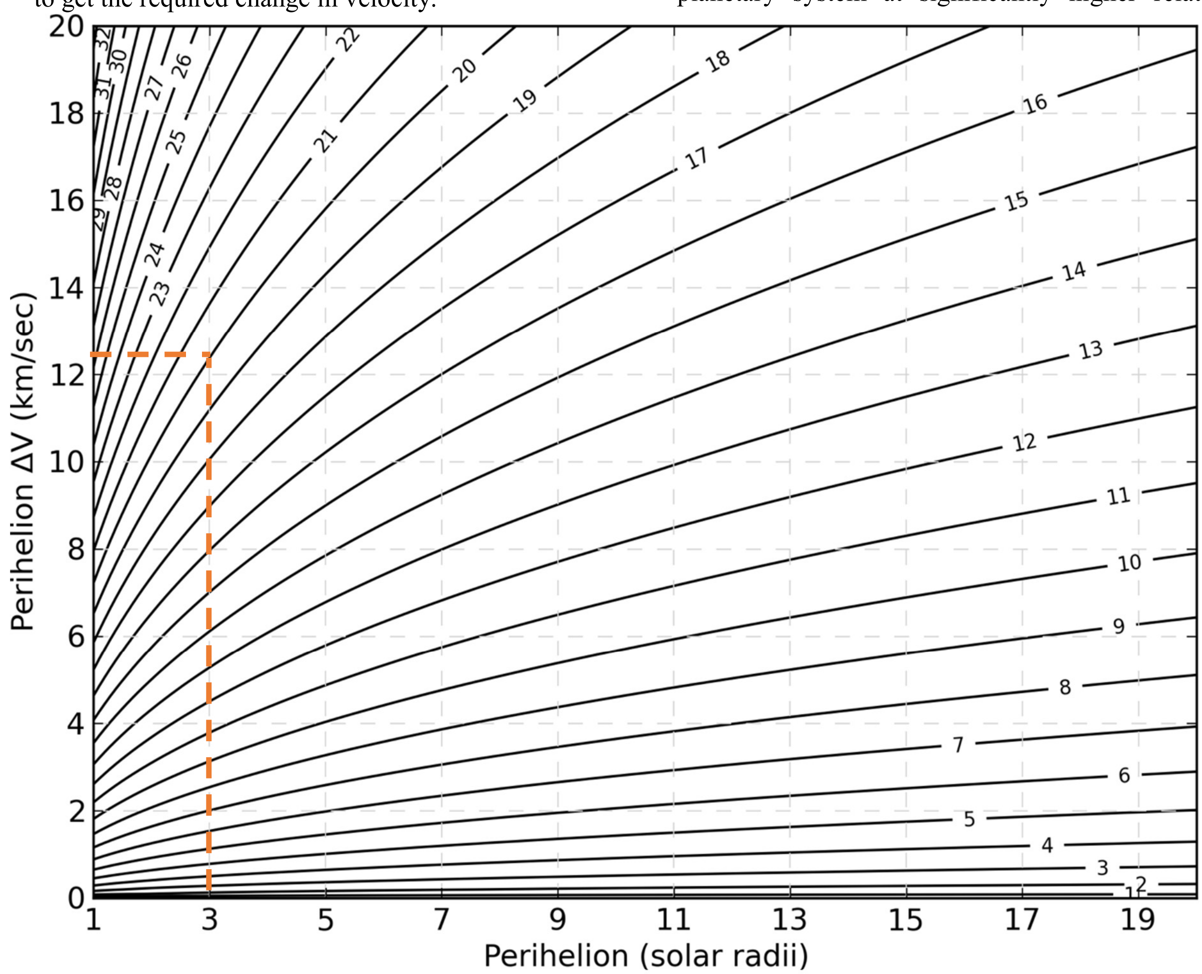

Figure 8 : Escape velocity (AU/year) contours for idealized perihelion maneuver

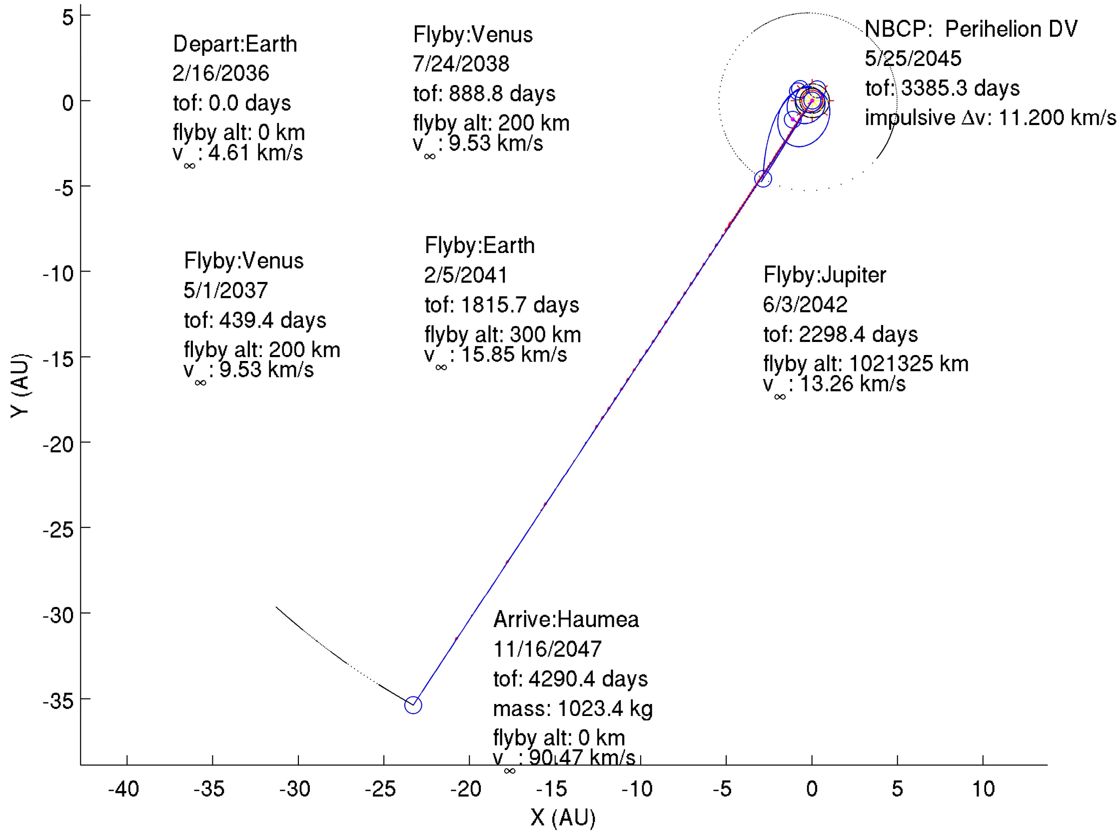

Figure 9: STP Mission Design

velocity. In the frame centered at the Sun, this results in a powered gravity assist at Jupiter, resulting in a increase in spacecraft sun-relative velocity. The Jupiter flyby can also be used for targeting a KBO on the escape leg.

c. Escape Phase: In this phase, the spacecraft may or may not deploy on-board propulsion as it proceeds towards its target destination and distance.

Figure 7 illustrates a type 2 trajectory broken into four phases:

a. Energy build-up phase: This phase is similar to a type 1 trajectory, where the spacecraft increases its energy and achieves required phasing (for targeting a "hair-pin" Jupiter flyby). The energy build phase may involve a combination of multiple inner solar system gravity assists and DSMs (for targeting, leveraging, and or plane change).

b. Sun-dive phase: In this phase, the spacecraft performs a dramatic Jupiter "hair-pin" gravity assist, putting it on a Sun-dive trajectory. For a given perihelion distance from the Sun, the minimum relative velocity at Jupiter can be analytically calculated by assuming post flyby aphelion at Jupiter. A perihelion distance of 3 solar radii requires a Jupiter relative flyby velocity of ~12 km/sec.

c. Perihelion maneuver phase: As the spacecraft approaches the perihelion, it performs a ΔV (Oberth maneuver) which results in a large change in spacecraft energy. For an optimal type 2 trajectory, the Jupiter flyby does the required plane change for targeting the KBO (if KBO flyby is desired) while the ΔV at perihelion maximizes spacecraft escape velocity. For KBOs with relatively high inclination (e.g., MakeMake and Haumea), this results in a near polar approach to the Sun.

Figure 8 shows escape velocity contours (in AU/year) for parametrically varying values of the perihelion distance (x-axis) and the perihelion ΔV (y-axis). The spacecraft escape velocity is the speed of the spacecraft far away from the Sun, at which point Sun's gravitational influence on the spacecraft becomes negligible. The pre-perihelion approach trajectory is assumed to be parabolic. As expected, the solar-system departure velocity increases substantially (slope of the contours increases) as the perihelion distance goes down and as the ΔV of the maneuver goes up. To achieve 20 AU/year escape velocity, a ΔV of ~12.25 km/s at 3 solar-radii is needed. For this case, the spacecraft will be travelling at speeds > 250 km/s at perihelion.

d. Escape phase: In this phase the spacecraft escapes the solar system, performing a fast KBO flyby and

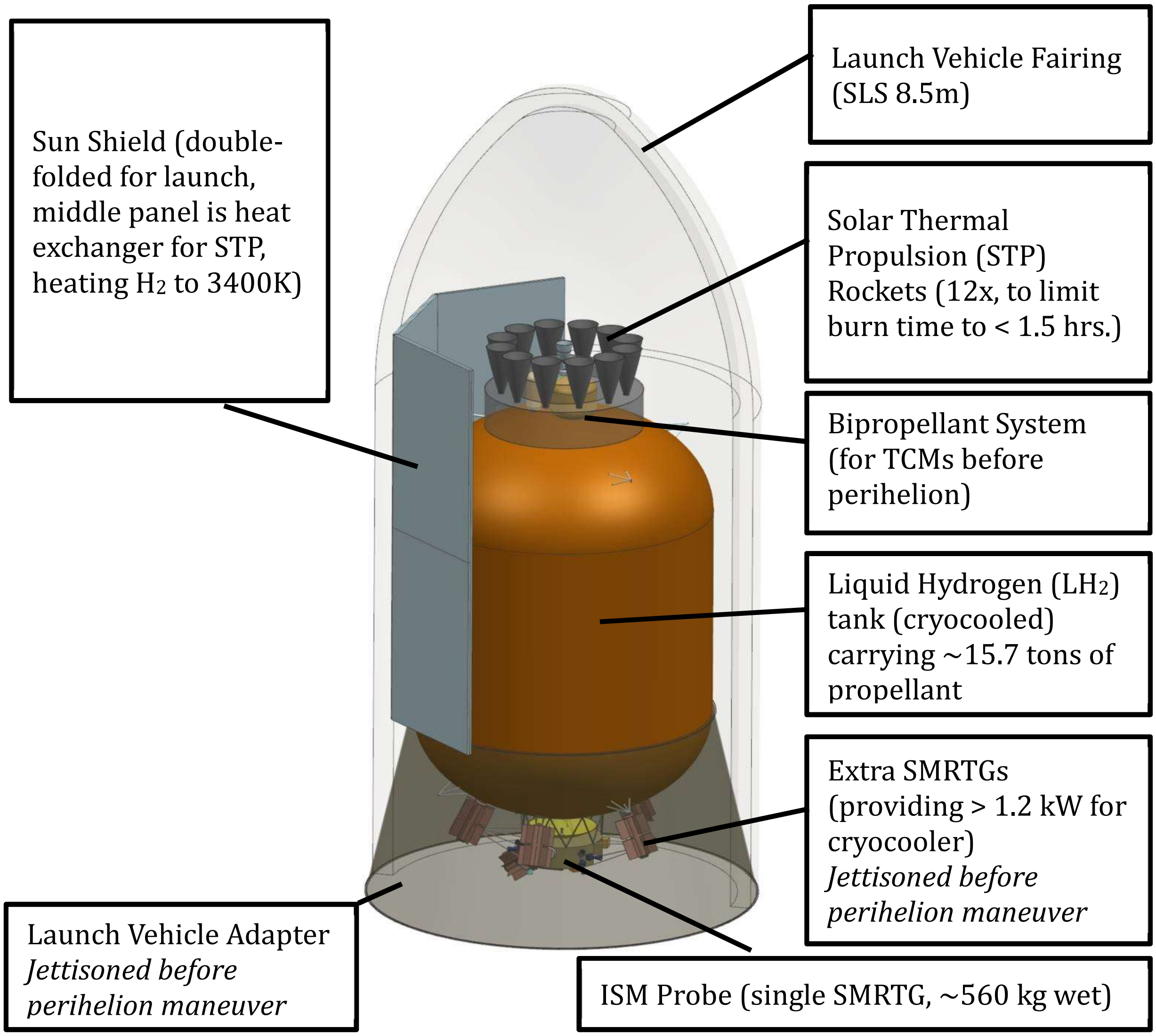

Figure 10: STP Flight-system for deep ISM Explorer concept (inside the SLS 8.5 m fairing)

scientific observations, as it ventures deep into the ISM. To further increase the escape velocity, a solar sail, electric sail or on-board electric propulsion may be deployed once the spacecraft reaches to a distance of 0.1 AU from the Sun.

The details on both these approaches can be found in this article [12].

Flight System

Interstellar probes, whether to the local ISM, deep ISM or to the SGL and beyond, are likely to have many common building block elements.

For example, given that the ISM probes will be operating at large distances beyond the Sun, nuclear power (RTG) is required on all probes. For this study, advanced Segmented Modular RTGs (SMRTGs[1]) are assumed. SMRTGs are proposed next generation of vacuum RTGs, capable of providing almost 5x EOL power over the Mars Curiosity MMRTG [15] and 2x power over the Cassini GPHS RTG. They take advantage of the skutterudite technology which is already being matured for the eMMRTG and use multi-foil insulation and aerogel encapsulation to achieve high efficiency and low degradation rate. Furthermore, they can be "right-sized" due to a segmented design.

To achieve large ΔV at the perihelion or at perijove requires advanced propulsion technology capable of delivering high thrust and ISP. Table 1 lists various propulsion options that were considered for this study,

[1] http://www.lpi.usra.edu/opag/meetings/feb2017/posters/Fleurial.pdf

along with their projected performance and use case.

Table 1. Propulsion options

Option	Fuel Type	ISP	Usage	Other comments
Solid Rocket Motor (SRM)	Solid	308s	Perihelion or Powered flyby	High ISP is available via deployed nozzle
Nuclear Thermal Propulsion (NTP)	H2	850s - 940s	Perihelion or Powered flyby	H2 tank is heavy and needs to be cryocooled. Nuclear Fission based reactor results in large dry-mass
Solar Thermal Propulsion (STP)	H2	1200s - 1350s	Perihelion	Utilizes heat from proximity to the Sun to heat up the H2 (at 3400k) and expel it at high velocity using engine nozzles. This concept requires a heat-exchanger
RTG powered EP (REP)	Xenon	~1800s	Probe	Propellant is carried on the probe and used during the escape phase
Electric or Solar Sail	-	-	Probe	Sail can be deployed on the probe beyond 0.1 AU

For example, given the nature of the small explorers to the local ISM, SRM or NTP based propulsion system was deemed to be most realistic. For a type 1 trajectory carrying multiple (2-3) probes of 150-200 kg each to the ISM, coupled with SLS lift capacity and propellant carrying capability, the maximum available ΔV ranges between ~6.5 km/s (SRM) to ~9 km/s (NTP). For deep ISM explorer, we need to achieve ΔV close to ~12 km/s. This results in selecting the higher ISP, low-dry mass, low-TRL STP propulsion option.

Deep ISM Explorer:

The Deep ISM explorer concept was formulated to satisfy the following four mission goals:

1. Launch using NASA's SLS using 8.5m fairing.
2. Reach Deep ISM > 250 AU in 20 years from launch using a type 2 trajectory.
3. Perform flyby of a major KBO.
4. Achieve an escape velocity of ~20 AU/Yr.

The last objective is particularly driving and requires a ΔV of >10 km/s at the perihelion. Building upon the results from a recently publish ISM trajectory design article [12] and KISS study[2] it quickly became clear that achieving this ΔV at the perihelion would require us move beyond traditional Solid-Rocket Motor (SRM) or Bi-propellant rocket engine technology. After a detailed propulsion trade study, two propulsion architectures stood out as viable candidates: 1) Nuclear-Thermal Propulsion (NTP [13]) and 2) Solar-Thermal Propulsion.

Further system level trade studies of the NTP technology made it clear that while the technology is being developed for possible future Human Mars mission concepts, it doesn't provide the required ΔV after factoring in the dry mass of the NTP stage. This resulted in selection of a Solar-Thermal Propulsion (STP [11]) based propulsion architecture as the most viable option for this mission concept. Next, we define a notional baseline concept which was a result of a detailed mission-design and multi-day Team-X study. The objective of this Team-X study was to find a feasible point design which allows us to inform further development of the STP technology.

Baseline STP Deep ISM Explorer Concept:

The baseline launch stack for this mission concept consists of the following flight elements:

1. ISM Probe (~550 kg wet)
2. Perihelion Maneuver stage (H2 tanks + Bi-prop system)
3. Solar-Thermal Propulsion System (Heat shield, heat exchanger and 12 engine nozzles)

The basic mission concept is optimized around achieving > 11 km/s ΔV at the solar-perihelion using a STP system. The solar-thermal propulsion concept for solar-system escape application was first proposed in 2002 and relies on using hydrogen (cryocooled) as propellant, which is heated due to spacecraft's proximity to the Sun, using a heat exchanger, which also acts as part of a larger heat-shield, designed to protect the spacecraft.

Figure 9, shows the trajectory (Earth-V-V-E-J-Perihelion-KBO-ISM sequence) for a notional STP mission launching in 2036 (earlier dates might be possible, requires more analysis), flying by the KBO Haumea, before venturing into the deep ISM. The mission concept requires a perihelion ΔV of ~11.2 km/s. The burn time is restricted to be less then 1.5 hrs. to reduce gravity losses. The probe uses a RTG powered EP system providing extra ~2.4 km/s ΔV. The escape velocity achieved is ~19.1 AU/Yr. (~90.5 km/s).

Given the high ΔV requirements, the STP mission concept is very sensitive to mass of the LH2 tank, ISP, mass and support structure mass. Next, we give summarize the main flight system components.

The STP system, as shown in Figure 10, consist of a double folded carbon-carbon heat shield (deployed after launch) with the middle panel also acting as a heat exchanger, 12 rocket nozzles used for producing the

[2] http://kiss.caltech.edu/workshops/ism/ism.html

required thrust and a cryocooled LH2 tank [14]. The heat shield when deployed is larger than the whole stack height, and provides ample cooling and a shadow-zone during the perihelion burn maneuver. The margined LH2 tank mass is calculated using a tank mass factor of 39%. The LH2 cryocooler power requirement of ~1.2 KW are estimated using a thermal model. The heat exchanger + heat shield combination is a multi-layered design and is estimated to be ~4 times as heavy as the one used in the original Thiokol (now Orbital ATK) study [11]. The relatively large factor of safety accounts for details missed at this early stage in the design process.

During perihelion burn (at ~3 solar radii), LH2 runs from the tank (near the bottom in Figure 10) through the heat-exchanger, where it heats up to 3400K temperature and then passes through the 12 rocket nozzles providing ~1350s of ISP. The LH2 plumbing is not shown in Figure 10. The 3400K temperature is close to the Carbon-Carbon melting point of 3800K [11]. This large ISP allows us to achieve the required mission design ΔV without excessive amounts of propellant.

The probe as designed during a Team-X session is a monopropellant based, New-Horizon like probe with ~42 kg of Instruments (consisting of a high speed camera + particles and fields instruments), totaling to a wet mass of ~561 kg. The data rate achieved from ~100 AU is ~200 bps. The probe is powered using the advanced Segmented Modular RTGs (SMRTG[3]), capable of providing ~350W after 15 years of life. Further design assumptions were made in the design which lowered the probe wet mass to 430 kg. This allowed an addition of a RTG powered EP system with ~100 kg of Xenon. The total wet mass of the post Team-X REP probe is ~542 kg.

There is also a Bi-Prop system used for performing launch cleanup and TCMs before the perihelion burn. Note that the total launch stack also consists of a payload adapter and 4 extra SMRTGs connected to it. These RTGs used for cryocooling the LH2 and are dropped off just before the perihelion burn to maximize available ΔV.

The total stack mass allocation (including JPL 43% margin) is ~28,000 kg, which consists of 15,732 kg of LH2, 620 kg of Bi-Propellant, and 11,278 kg of dry mass allocation. The dry mass allocation consists of 542 kg of probe mass (see Table 3), ~1842 kg mass for the heatshield + heat exchanger and rest allocated to support structure and 4 extra SMRTGs. The payload side adapter mass is estimated to be ~369 kg.

Small Satellites to the Local ISM:
Given that the Deep ISM explorer concept requires advanced STP technology development, a more near-term mission concept was also studied using a type 1 mission design along with a NTP system, propelling 3-5 small spacecraft (<160 kg) for rapid exploration of the Local ISM (<150 AU).

The baseline mission consists of launching from Earth and performing a large powered (ΔV >8 km/s) flyby at Jupiter using an NTP stage. During and after the flyby, multiple small probes are released which travel in different directions, allowing us to sample various locations in the ISM and/or flyby one or multiple KBOs. Each probe is designed to carry 1 to 3 instruments for doing various in-situ measurements of the Local ISM. The probes may also have onboard propulsion but it is expected to be limited given the small mass allocation of 160 kg (wet) / probe. Given the large ΔV provided by the NTP stage via a powered Jupiter flyby, each probe would achieve a solar-system escape velocity of ~8-9 AU/Yr. (>2X Voyager). This mission concept is expected to take advantage of low-mass, low-power avionics and deployable telecomm. systems. On-board autonomy can also be employed to add robustness to the concept. Table 2 gives flight system level overview of a deep ISM explorer probe.

Solar Gravity Lens Focus (SGLF) Mission:
The SGLF mission is tasked to reach a distance of ~600 AU and deploy a 1 to 2 m size telescope for multi-pixel imagining of an exoplanet. The spacecraft needs to reach the 600 AU mark in < 40 years from launch. Factoring in the time required to build energy in the inner-solar system for a type 2 trajectory, this results in an escape velocity of requirement > 20 AU/Yr.

Hence, a baseline SGLF mission concept will use advanced low-mass, low-power technologies, on-board autonomy and an advanced STP propulsion stage. Table 4 gives a flight system overview for a SGLF probe.

SUMMARY
This paper proposes a 4-pronged approach to a new program to deploy robotic probes to explore the ISM as a precursor to eventually sending probes to an exoplanet of choice. The work in this paper builds upon the results of the Keck Institute for Space Studies (KISS) study in 2013-2014 on the "Science and Enabling Technologies for the Exploration of the ISM" (Stone, Alkalai, Friedman). Building upon a focused technology development program, we propose a series of small probes to the ISM, probes to the pristine ISM, and probes to deliver telescopes to the SGL to produce multi-pixel high-resolution images of exoplanets before a probe is sent explicitly towards an Earth-like exoplanet.

[3] http://www.lpi.usra.edu/opag/meetings/feb2017/posters/Fleurial.pdf

Table 2: Small Spacecraft Probe (Dual Redundant) to the LISM

Sub-system	MEV (kg)	Comments
Power (without SMRTG)	11	"right-sized" SMRTG
Propulsion	20	REP or E-Sail
Telecomm.	4	Iris level radio, 1m - 2 m deployable HGA
Mechanical	20	Light weight, multi-functional structures
Thermal	6	RTG + RHU and Louvers
Attitude & Control	3	Monoprop + small-sat ACS
C&DH	1	SmallSat Avionics
Science Payload	9	1-2 instruments
Propellant	25	Can be Xenon or extra mass for an E-Sail
System Level Margin	**21**	**According to JPL DP**
SMRTG	40	**No margin needed for RTGs**
Total Allocation	**160**	Wet mass / probe

Table 3: Deep ISM Explorer Flight System (Dual Redundant)

Sub-system	MEV (kg)	Comments
Power (without SMRTG)	47	Ref. bus + batteries
Propulsion	17	Monoprop
Telecomm.	30	Iris level radio, 1m - 2 m deployable HGA
Mechanical	177	Light weight, multi-functional structures
Thermal	29	RTG + RHU and Louvers
Attitude & Control	34	RWA, MIMU
C&DH	15	3U JPL Avionics
Science Payload	42	Fields and Particles + Camera
Propellant	25	Can be Xenon or can be extra mass for an E-Sail
System Level Margin	**74.4**	**According to JPL DP**
2x SMRTG	52	**No margin needed for RTGs**
Total Allocation	**542**	Wet mass / probe

Table 4: SGLF ISM PROBE (Dual Redundant)

Sub-system	MEV (kg)	Comments
Power (without SMRTG)	47	Ref. bus + batteries
Propulsion	17	Monoprop
Telecomm.	30	Iris level radio, 1m - 2 m deployable HGA
Mechanical	177	Light weight, multi-functional structures
Thermal	29	RTG + RHU and Louvers
Attitude & Control	34	RWA, MIMU
C&DH	15	3U JPL Avionics
Telescope	50	0.5-1m Telescope
Propellant	25	Can be Xenon or can be extra mass for a bigger E-Sail
System Level Margin	**80**	**According to JPL DP**
2x SMRTG	52	**No margin needed for RTGs**
Total Allocation	**556**	Wet mass / probe

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