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Science and Technology Steps Into the InterstellarMediumt

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The entry into the Interstellar Medium by the Voyager 1 spacecraft was a milestone of exploration. The surprising results, finding a more complex structure from the data taken at the heliopause boundary, have whetted scientific interest in further exploration and characterization of the Interstellar Medium. Other studies have suggested practical possibilities for interstellar precursors which both advance technology and gather scientific data which might be relevant to eventual interstellar flight. Science of, in and from the interstellar medium is now of interest. Practical and meaningful interstellar flight (i.e. reaching another star system) is at least a century, and probably centuries, in the future. However, its scientific goal of habitable planet exploration, and its probable technological means of accomplishment with solar sails and small spacecraft have now begun to be established. Science rationale and relevant technology are discussed in the paper. A series of three missions is derived from the science and technology considerations, to be accomplished in this century. The furthest of these missions might reach 0.1 the distance to the nearest star (25,000 AU), and thus the series might provide the first incremental steps toward interstellar flight. But even this is a huge challenge. The first mission is the aforementioned Interstellar Medium exploration mission (100-150 AU); the second is a Solar Gravity Lens Focus mission (700-900 AU); and the third is an Oort Cloud explorer (>5000 AU). As a design baseline, each mission would consist of multiple small spacecraft, with a trade-off necessary to consider the possibilities of nano-spacecraft (<10 kg) vs. larger spacecraft (but still smallsats < 100 kg) with more capable payloads. This and other approaches are being considered in a new Keck Institute for Space Studies study. A parametric trade for varying area, mass, perihelion velocity and perihelion distance will be presented to design trajectories with solar system escape speeds >10AU/ year. If such a series of missions proves feasible and affordable, the result will be to begin the path to interstellar flight in an affordable manner in this century, with science and public engagement pointing humankind to the stars.

I. BACKGROUND

In a presentation at the first 100 Year Starship Symposium we laid out the argument that future interstellar travel was likely to be conducted robotically with very small spacecraft incorporating advanced nanotechnology, artificial intelligence and information processing exiting the solar system at high velocities.[1] We then introduced the idea of interstellar precursors – missions far short of interstellar flight (indeed, still gravitationally bound within our solar system) that advanced hundreds of AU into the interstellar medium to conduct missions related to interstellar science and advancing technology that might be applicable to interstellar flight in the future.[2] [*]

Since then the *Voyager 1* spacecraft achieved a milestone of exploration becoming the first emissary from Earth to pass into the Interstellar Medium,[3] which is the area outside the heliosphere, the region where the solar wind and the Sun's magnetic field dominate and repels charged particles from other stellar systems. The results from the Voyager have shown a great deal of complexity around and beyond the heliopause (the boundary of the heliosphere) and this has whetted the appetites of heliophysics researchers for future missions and more investigations.

In addition the interstellar medium is home to a class of recently discovered celestial bodies, Kuiper Belt Objects, important in their own right and for their implications on solar system formation and evolution.[4] A wide range of objects to be explored are being discovered. [5]

Small spacecraft, solar sails and new technologies are opening up more mission possibilities and new scientific discoveries are motivating interest in them.

II. MISSION ANALYSIS

Heliocentric hyperbolic trajectories with very high exit velocities can be achieved by performing a large delta-v at perihelion. The delta-v at perihelion raises

[*] In this work we presented results as a function of area (A) divided by mass (m) of the spacecraft. However, the actual values of A/m were half those stated in the references.

the aphelion of the orbit; if the delta-v is large enough it raises the aphelion to infinity (creating the hyperbolic trajectory) achieving escape from our solar system. As in our earlier paper[6] we are considering solar sail spacecraft which achieve the low perihelion either by direct launch from Earth inward toward the Sun, or by use of Jupiter gravity assist after a launch from Earth to Jupiter. The latter takes longer to get to perihelion but arrives there with higher velocities and eventually surpasses those on the direct launch trajectories. The relevant parameters determining flight time and speed out of the solar system are the thrust from the solar pressure on the spacecraft (proportional to Area/mass ratio, A/m) the perihelion distance (r_p). In our earlier study we were motivated to consider nanosat spacecraft (< 10kg) and thus to carry no on-board propellant. In this study, encouraged by a broader consideration now underway in a new study at the Keck Institute for Space Studies (KISS)[7] we are considering larger spacecraft with more capable payload, power and communications subsystems and the possible addition of propulsion from an on-board radioisotope thermal generator. These ancillary propulsion subsystems, with a nuclear power source, have the potential of augmenting the exit velocity of the spacecraft by tens of kilometres per second and would be employed after 5 AU where the incident light provides negligible acceleration to the solar sail. By presenting results as a function of A/m, we will have them independent of any particular mass assumption.

The two types of trajectories are depicted in Figure 1.

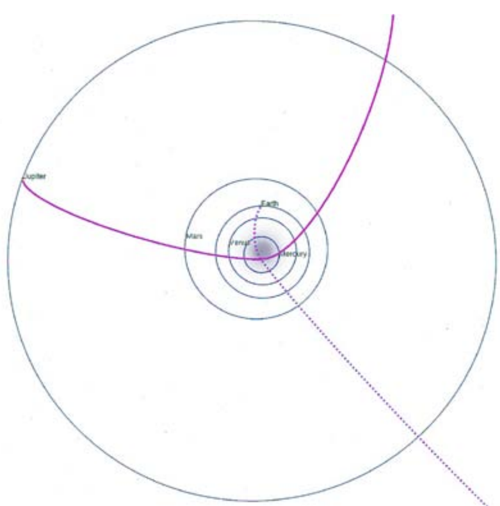

Figure 1: Two trajectory approaches to low perihelion to escape the solar system: Dotted – launch from Earth to perihelion, and then escape; solid – launch from Earth to Jupiter (not shown), then gravity assist to fly in to perihelion and then escape. In both cases sail is deployed after perihelion. Options for additional propulsion include high impulse chemical at perihelion and/or electric propulsion after perihelion added to solar sail.

How fast and how far we can go as a function of the sail size (A) to spacecraft mass (m) ratio for different periihelion disatnces is indicated in figures 2 and 3 for both direct Earth to perihelion and Jupiter swingby trajectories.

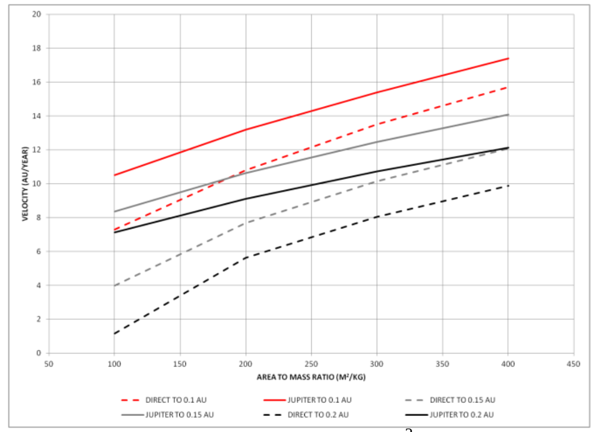

Figure 2: Velocity (AU/year) vs. A/m (m^2/kg) for direct to perihelion (dashed) and Jupiter swingby (solid) trajectories for perihelions of 0.2 AU (black), 0.15 AU (gray) and 0.1 AU (red)

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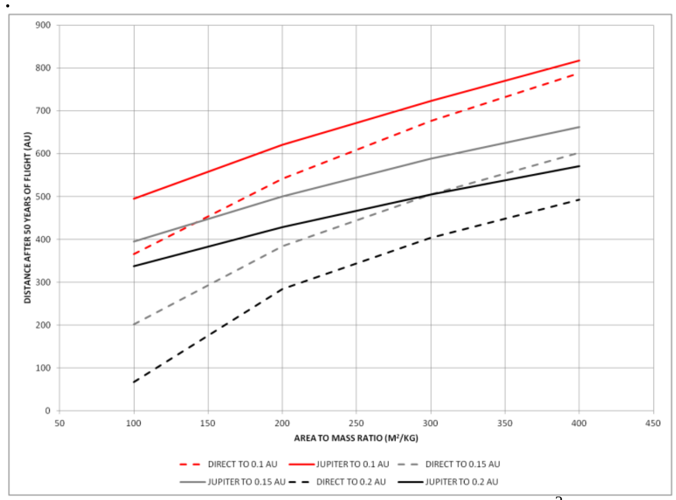

Figure 3: Distance achieved in 50 years (AU)vs. A/m (m^2/kg) for direct to perihelion (dashed) and Jupiter swingby (solid) trajectories for perihelions of 0.2 AU (black), 0.15 AU (gray) and 0.1 AU (red)

Currently The Planetary Society LightSail® has an A/m~ 7 m^2/kg[8] and the Sunjammer Solar Sail spacecraft[†] designed by L'Garde Corp for NASA has A/m~20 m^2/kg[9]. This should be considered the state-of- the-art. In principle the Sunjammer size sail on a 20 kg spacecraft might be considered (although no design of one has yet been done). This would yield an A/m> 100 m^2/kg. The following table lists A/m for a number of solar sail spacecraft which have been studied.

[†] *Sunjammer* has now been cancelled.

Spacecraft	A/m [m²/kg]
IKAROS - JAXA	1.3
Nanosail-D – NASA	2.2
Cosmos 1 – The Planetary Society	5.7
LightSail® - The Planetary Society	7.0
Lunar Flashlight/NEA Scout - JPL	8.0
Sunjammer Developed	22
JPL NIAC Study	368
JPL Near ISM Mission Study	700
JPL Halley Comet Rendezvous Design	711

The JPL design studies have the realism of rigorous analysis, and hence are reasonable design goals – but all of them are extremely large and inherently expensive spacecraft and thus we are motivated to more deeply seek spacecraft <100 kg, with sails (for example) 150 metersx150 neters yielding an A/m >200 m^2/kg. Further in the future (perhaps in the next century) we seek a goal of doubling the linear size of the sail and halving the mass to reach really large A/m, approaching 2000 m^2/kg. Even the nearer term goal is a challenge, when we consider the desired science payload and likely required communications system.

In the KISS study cited above we are considering adding advanced propulsion for small spacecraft. Two types of nuclear powered electric propulsion have been mentioned:

1. Micro-electrospray thrusters capable of generating 20-40 watts of power and 100 micro-newtons thrust per thruster.[10]
2. Miniaturized ion drive Hall thrusters capable of generating 325 watts power.[11]

To estimate how much boost the extra propulsion might provide, we assumed operation of the additional thrust on the outbound leg of the hyperbola once beyond 5 AU for a period of 1-5 years. Such operation would provide an additional delta-v which to a first approximation simply adds to the solar system exit velocity. The micro-electrospray thrusters, even if accumulated into an assembly of many tens of them, adds very little – perhaps at most an additional 1 AU/year if they can operate for a year (which is not yet the case).

However, the miniaturized Hall thruster provides more hope. Assuming values in the cited reference[11] (19 milli-newtons, ISP= 1870s, 43% efficiency, 325Watts) the resulting velocity after a year is ~6 km/s for 100 kg spacecraft. If we can get 5 years operation from such a unit this would yield an extra 6.3 AU/year – extending our range into the Interstellar Medium.

III EXAMPLE INTERSTELLAR MEDIUM MISSIONS

Where should we go? We consider some example missions in this section that address both the scientific objectives in and from the Interstellar Medium (ISM) and the technology that might enable practical and affordable missions there. The KISS study (op. cit.) in which we are participating is specifically addressing science <u>in</u> and science <u>from</u> the ISM.

Heliophysics outside the heliopause is a principal objective. Ideally we would like several spacecraft to explore the ISM at widely space locations – a desire that comes up, as will be seen below, with other science objectives as well. For this reason, coupled with the long trip times involved, we place a high premium on relatively low cost (smaller) spacecraft.

Kuiper Belt Objects (KBO) have been discovered in the region 40-50 AU from the Sun, although at least one has now been discovered at almost 80AU. We might expect ones further away, not yet discovered because of the limitations to seeing that far from Earth. Determining the mass (and hence a density estimate) of a KBO would be extremely valuable. Doing this for two or more KBOs would be even more so. We therefore would recommend investigating the objective of relatively close flybys of one or (if possible) two KBOs on an ISM mission, and also place a high premium on precise tracking and orbit determination in order to measure the gravitational environment in the ISM. This might suggest a spin stabilized spacecraft to fly on as nearly a ballistic trajectory as possible. Again, multiple small spacecraft will be a great advantage.

The KBO and heliophysics mission objectives provide mission goals from 50-200 AU. What next? In our earlier paper we suggested the solar gravity lens focus (SGLF) – the distance at which light (or any electromagnetic radiation) from a distant object is gravitationally bent by the Sun so that all the ray paths focus at the same point. This is a consequence of General Relativity and was predicted by Einstein as one of the confirming tests of the theory. It has been observed many times on Earth when stars occult more distant galactic and extra-galactic objects. The focus however is not a point, but a line extending outward from some minimum distance determined by the mass of the Sun.[12] That distance is theoretically 550 AU, but in practice because of solar corona effects on the bent light rays it is nearer 700 AU.

There have been studies of a mission concept to the SGLF, called FOCAL, primarily by those interested in the search for extraterrestrial intelligence (SETI). The theory is that radio signals from a promising location of extraterrestrial intelligence will be amplified by the SGLF.[13] Currently there is more interest in studying extra-solar planets for signs of habitability than in radio SETI, We hope to investigate whether the SGLF can be sued to amplify observations of extra-solar planets.[14] We take as our solar gravity lens focus mission objective the focal line from 700-1000 AU. An optical or radio observing mission would have much higher mass payload requirements than the heliophysics or KBO missions and the possibilities for nano-spacecraft here are quite uncertain.

Tracking data and orbit determination of the spacecraft could be used to investigate other astrophysical and gravitational questions that might be explored the interstellar medium. We already mentioned deducing mass of KBOs. More generally searches for large masses, gravitational fields of the Oort Cloud, and even possible (now speculative) tests for the presence of dark matter and dark energy should be considered. Measurements of the mass of satellites of a KBO have been proposed as a test for an even more speculative theory of the quantum vacuum.[15]

What next? The next further out ISM milestone is probably the Oort Cloud, the region where comets form and loiter before a few of them are eventually perturbed into or out of the solar system. This region is thought to be between 5000 and 50000 AU – a long way considering that no spacecraft has yet made it to even 150 AU, but not even 20% of the distance to the closest star (Alpha Centauri is about 250,000 AU or 4.3 Light-Years from the Sun).[‡] Space is big, and a lot of it is empty.

Mission ideas are a major goal for the KISS study (op. cit.). We do not yet know what the study results will be – either for spacecraft development recommendations or consideration of future missions. Based on our trajectory studies and the initial consideration of science objectives we suggest that one approach might be to develop a series of (say) three missions probing ever deeper into the ISM that might be accomplished over the next century. On the one hand this is a very ambitious goal both financially and technologically. On the other hand the minimum 50 year transit times are a significant challenge (if not constraint) to those who really are motivated by interstellar travel goals. Again, given our assessment of current technologies we think it is about right for investigating practical mission requirements.

The base mission concepts are

- To the Kuiper Belt and beyond the Heliopause: 50-150 AU. Our design goal should be for A/m ~ 200 m^2/kg (e.g. a 14x14 meter sail with a nano-spacecraft or a 150x150 meter small-sat). This might exit the solar system at 11-12 AU year.
- To the solar gravity lens focus, approx 700-1000 AU. Our design goal for this might be 400 m^2/kg and an exit velocity of 18 AU/year.
- To the Oort Cloud (>5000 AU) with a design goal of 1000 m^2/kg and an exit velocity > 50 AU/year. This is clearly a stretched goal.

IV CONCLUSIONS

Solar sailing with small spacecraft holds unique potential for following up Voyager's interstellar journey with deeper exploration in the Interstellar Medium. There are compelling scientific objectives there – the medium itself, Kuiper Belt objects, using the solar gravity lens focus for observations from distant stars and planets, and astrophysical and gravitation studies of the universe. Sails have to be built with long-life, high thermal and radiation resistance to go close to the Sun, and with deployment systems to permit much larger areas. Continued development of micro-, nano-, and perhaps even pico- spacecraft needs to occur for such long-range missions. The challenges to create practical, affordable and executable missions are great, but the physics suggest that a series of increasing technologically advanced missions with larger and lighter sails, smaller and lighter spacecraft and new spacecraft technologies for communications, power, and control can make a series of missions advancing humankind's exploration beyond the solar system. These are the precursor requirements for interstellar flight, both scientifically and technologically, and maybe (just maybe) they can take us to edge of the solar system.

[‡] The edge of the Solar System, defined by the gravitational sphere of influence of the Sun might be considered a milestone – but a far out and rather ephemeral one: between 30000 and 65000 AU depending on how it is defined and how far the Oort Cloud is found to extend. 1 Light-Year equals 63000 AU.

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